A thermodynamic approach to the assessment of soil ecosystem function: Towards the development of agro-ecological principles rooted in new ecological perspectives

L. M. King

A Thesis submitted for the degree of, PhD

Department/ school of Writtle University College

University of Essex

Date of Submission for examination: April 2024

ABSTRACT

The Anthropocene has been linked to a widespread loss of ecosystem structure and function. It is believed that repercussions of this extend to climate change and agriculture is deemed as a leading industry behind environmental decline. The need for a concise understanding of ecological function is ever more pressing, as well as the development of an agricultural framework that is both productive and ecologically sustainable. Over the last century, thermodynamics has found its place in the development of ecological theory. A theoretical consistency among thermodynamic principles points to circular interaction as a fundamental process in the development of complex systems. Although receiving significant attention recently with the publication of FAO's 'Nature Positive', its application in sustainable agriculture remains a mystery. This requires the development of effective indicators that are equipped to capture the complexity of energy and matter interchange. However, energetics cannot be measured directly and this thesis explores proxies of energy metrics, in the context of sustainable agriculture. Following on from over a decade of research, the study explores soil temperature, as well as a novel measure of soils chemical environment (REDOX potential), discussing their utilization in a thermodynamic approach to the assessment of agricultural soils. The indicators show potential and data corroborates previous research. The greatest limitation is the simplified experimental design; however the research provides a first insight into application of thermodynamics to soil assessment, highlighting a range of potential avenues for future research. To finish, an attempt to reconcile new developments in ecological theory with agricultural practice is made. Referring to results from the experimentation and drawing on the literature, to make some assumptions of the necessary conditions needed, for agriculture to move from the greatest cause of environmental decline, to the biggest driver of positive change.

Acronyms

AMB	Control groups. Subject to ambient temperatures	MEANCoeffVAR	The temperature CoeffVAR, averaged across the whole experiment period
BIN	Biomass, information and networks	MEANDTR	The Diurnal Temperature variation, averaged across the whole experiment period
BJ	*Brassica Juncea*	MEANSTDEV	The mean temperature STDEV averaged across the phase of experiment the whole experiment period
		LNC	Leaf Nitrogen Content
BS	Bare soil	LDMC	Leaf Matter Dry Content
BZ	Belousov- Zhabotinsky	LoMIN	The lowest MIN across the whole experiment period.
CoeffVAR	The coefficient of variation – calculated as STDEV/MEAN X 100	MPP	The maximum power principle
CBD	Convention on Biological Diversity	NP	Niche partitioning
CSR	Competitive, specialist and ruderal	OD	Organic soil at 30cm below surface
DTR	Diurnal temperature range – calculated as the difference between the MAX and the MIN.	OM	Organic matter
EA	Ecological autocatalysis	OS	Organic soil at 10cm below surface
Eco-RAF	Ecological RAF	PAR	Photosynthetically active radiation
Eh	REDOX potential	R	Reduced – irrigation at 25% field capacity (2lph)
EhpH	Eh standardized to pH 7	RAF	Reflexively autocatalytic and food-generated
E⁰	Standard cell potential	REDOX	Reduction/ oxidation reactions
EROI	Energy return on investment	REF	Reference soil – Good loam sterilized at 65°C for 48 hours
Evo-RAF	Evolutionary RAF	ROM	Reference soil with added organic matter

EXP	Experiment, relating to the different experiments within the research relevant to individual chapters	S	Sand
FAO	Food an Agricultural Organisation	SLA	Specific Leaf Area
FC	Fairy Circles	SDG	Sustainable Development Goals
HD	Higher density plant spacing (6 plants per pot)	Sh	Shaded samples
HDF	Higher density plant spacing (6 plants per pot) with water flow rate of 8lph	SR	Specialist Ruderal
HDR	Higher density plant spacing (6 plants per pot) with water flow of 2lph	STDEV	Standard deviation for the 8 hours leading up to solar maximum
HiMAX	Highest MX across the whole experiment period	Sub	Sandy soil (equal clay content to REF, but higher sand and less silt)
IPCC	Intergovernmental Panel for Climate Change	TE	Thermodynamic equilibrium
LB	Biodynamic soil at 10cm below surface	TEA	Terminal Electron Acceptor
LD	Lower density plant spacing (3 plants per pot)	TI	*Trifolium incarnatum*
LOI	Loss on Ignition	WRC	Another Writtle soil
MAX	The maximum temperature per day	WrD	Writtle soil at 30cm below surface
MC	Moisture content of the soil	WrS	Writtle soil at 10cm below surface
MEAN	The average temperature per day		
MEANMAX	The MAX temperature averaged across the whole experiment period	WRT	Sterilized Writtle soil
MEANMEAN	The MEAN temperature averaged across the whole experiment period	YW	Young woodland

MEANMIN	The MIN temperature averaged across the whole experiment period	YWC	Young woodland control
		YWT	Young woodland sterilized
		ΔG	Change in Gibbs free energy (G)

Acknowledgements

Although a little unorthodox to acknowledge ones own achievement, I feel I have been put to the test and I owe it to myself to recognise this accomplishment. Anyone who has endured a PhD programme should be immensely proud of themselves, as I am. To my supervisors, past and present; Peter Hobson, who has been with me since the beginning and a key driver of the research, to Pierre and to John who although parted the programme fairly early on were an inspiration. Then to Christos, who joined late and was challenged with rather quickly coming up to speed, but offered much appreciated insights from his own experiences. I would like to thank the students that supported some of the research and helped with data collection in return for support with their own dissertations. It was valuable to experience supporting students through their dissertations and I learnt an awful lot about research leadership. Finaly, this simply would not be possible without the support of my family friends and especially my partner, Hayley who was a rock through the most difficult and challenging moments.

1 Contents

Appendices

Figures

Tables

Plates

1 Introduction

In less than 100 years, a baseline shift in Earth's functioning has destabilized the planet, moving from the most stable period in the Earth's history, the Holocene, in to a new epoch, the Anthropocene (Steffen *et al*., 2015). The effects of Land use change and degradation of habitats through human activities is well known (IPBES, 2019; Newbold *et al*., 2019). Causing global biodiversity declines (Newbold *et al*., 2015) and a, as well as changes in species composition, with an expansion in generalist species, coupled to a diminishing of specialists (González-Moreno *et al*., 2013; Gaertner *et al*., 2017). All leading to a biotic homogenization within human landscapes (McKinney, 2006; Marull *et al*., 2023). The combined effects of soil degradation and habitat decline are forcing the need for a new paradigms in agriculture (Kassam and Kassam, 2021). What more, the current climate crisis is having an ever-increasing impact on ecological systems. There is an opportunity in agriculture as a land-based sector, to mitigate the devastating effects of land use change and alleviate the pressures of climate change.

In accordance with the latest Intergovernmental Panel on Climate Change (IPCC) report, multiple habitats and continents across the globe have been negatively impacted by climate change (Pörtner *et al*., 2022). It states with high confidence that ecosystems have been exposed to unprecedented conditions over millennia, due to anthropogenically driven climate change, greatly impacting species on land and in the oceans (Pörtner *et al*., 2022). The greatest concern is the shift of species' geographic range and timing of critical life cycle processes (Pörtner *et al*., 2022). These range shifts have impacted ecosystem structure and resilience by lowering levels of biodiversity in the warmest regions, right where it is needed most; as well as homogenizing biodiversity in receiving areas (Pörtner *et al*., 2022). Disproportionate impacts, that homogenize communities, will lead to severe consequences for eco-system function and ultimately human wellbeing (Newbold *et al*., 2019).

In Europe alone the severity of impacts from extreme heat and drought has tripled in the last 50 years (Pörtner *et al*., 2022). This has had a debilitating effect on agricultural productivity, hindering efforts to meet human needs, altering the suitability of growing areas, and disrupting the timing of key ecological events such as pollination (Pörtner *et al*., 2022). With an increasing emergence of climate related food security risks across the globe, the need for adaptable agricultural systems is ever more pressing

(Pörtner *et al*., 2022). Without immediate action the world risks failing to meet the UN sustainable development goals (SDG), many of which are closely associated with soil health; 'no poverty', 'zero hunger', 'clean water and sanitation', 'climate action' and life on land' (Ganlin and Huayong, 2018; Tóth *et al*., 2018; Wang *et al*., 2023).With an estimated 35% of the surface of the Earth altered and degraded, by land conversion to agriculture and rapid urban development (Ramankutty and Foley, 1999) only about 1/5 of land is deemed truly wild (Sanderson *et al*., 2002). The extent of land use change has enabled humans to appropriate an ever-increasing share of planetary resources, and wild animals only now account for approx. 4% of the total biomass of all mammals (Bar-On *et al*., 2018). Global changes to land use are being driven by the need to provide food, fibre, water and shelter to an exponentially increasing human population, but these changes are undermining the capacity of the planet to continue to sustain these resources (Foley *et al*., 2005). At what point will the planet reach a crunch point, and what will this bring?

New protocols to stem the exponential decline of eco-system stability, seek to stay within identified planetary boundaries, to decrease the risk of irreversible and potentially catastrophic shifts in the Earth system. For one, the goal of the Paris agreement set out in 2015 aims to keep global warming below 2˚C (Willett *et al*., 2019). Barry (2014) proposed terrestrial ecosystem loss as the 'tenth planetary boundary', suggesting that the *Ebola* epidemic, California drought and Middle East revolutions, indicate planetary boundaries have been exceeded and biosphere collapse is imminent. Comparisons have been drawn with terrestrial ecosystem collapse at the Triassic – Jurassic boundary and todays increasing carbon dioxide, global warming and fire activity (Williford *et al*., 2014). Planetary boundaries set limits or thresholds, within which ecological function is relatively unaffected. In a quantitative global analysis of biotic intactness, Newbold *et al*., (2016) showed that 65% of the terrestrial surface has seen a decline beyond the 10% proposed safe boundary. With the most significant changes in grassland biomes and biodiversity hotspots (Newbold *et al*., 2016). Biodiversity losses are clearly observed, however uncertainty still remains around safe-limit thresholds (Oliver, 2016). With as much as 3 boundaries already overstepped, more is expected to follow. Especially with the global expansion of industrialised forms of agriculture, that further increase environmental degradation, with potentially irreversible consequences (Rockström *et al*., 2009).

Historical studies and integrated assessment modelling reveal the catastrophic impact that climate change is likely to have on agricultural yield and income (Vermeulen *et al*., 2012). Impinging on the price of food, the general quality of the food produced and more importantly food security as a whole. 1 in 9 people are currently estimated to be undernourished (FAO, IFAD and WFP, 2014) and future populations are predicated to top 9 billion by 2050 (UDES, Population Division, 2015), rising to 11 billion by 2100 (FAO, 2018); requiring an increase of 59 % to 98 % by 2050 (Elferink and Schierhorn, 2016), alongside energy and water demands equalling this figure (Valin *et al*., 2014; Ferroukhi *et al*., 2015). Farmers will need to produce more food per unit land mass and need more resources like water, while the threat of climate change looms, alongside the scarcity of just about every physical factor relating to food production (Giovannucci *et al*., 2012). As pressure on the environment builds with the growing population (Blum, 2005), the need for effective mitigation strategies is becoming increasingly more urgent. Managing these environmental, socio-economic and food security issues will need significant global reforms (Luna Juncal *et al*., 2023).

In a concerted effort to stem the exponential decline of the natural world, the convention on biological diversity (CBD) states in principle 5 of its manifesto, that *conservation of eco-system structure and functioning, in order to maintain ecosystem services, should be a priority target of the eco-system approach*.

At the centre of the water, energy and food nexus, is the soil (Biggs *et al*., 2015; Jónsson *et al*., 2016) and this emphasizes evermore the drive for a holistic management of this precious resource (Weigelt *et al*., 2014; McCormick and Kapustka, 2016). One of the major challenges over the coming years is the need to intensify agricultural production without further impact on the environment (Harmel *et al*., 2004; Luna Juncal *et al*., 2023). This calls for a sustainable intensification of agriculture, that meets the demands of population expansion, whilst still placing the ecosystem framework at the centre of political decisions. Although alternate systems exist, their impact is little understood and some evidence even suggests that practices such as organic may use less energy, but require more land, cause more eutrophication and still emit the same greenhouse gasses as intensive practices (Clark and Tilman, 2017). That said, the definition of sustainable intensification is still very

much under debate (Rockström *et al*., 2017), along with the recognition of a set of practices for land owners to follow.

The shift in agricultural paradigm aims at turning agriculture from the single largest driver of environmental decline, in to being the leading industry behind positive change and global transition to a sustainable world, within safe operating boundaries (Rockström *et al*., 2017). This can only be achieved through a multi-disciplinary approach (Duru *et al*., 2015) to fundamentally re-design agricultural landscapes (Landis, 2017). Researchers should be wiling to learn from the disciplinary knowledge of each other as an innovative way to influence decision making (Brown *et al*., 2023).

Meeting this bold target requires the understanding of progress towards them and it is necessary to find relevant bioindicators. Historically, soil indicators mostly focus on biological, chemical and physical attributes (Jónsson *et al*., 2016). Comprehensive reviews give a detailed overview of existing indicators (Bastida *et al*., 2008; Ritz *et al*., 2009; Cluzeau *et al*., 2012; Havlicek, 2012; Pulleman *et al*., 2012). However, at the international and national level, no standardized soil sustainability indicator suite has yet been established (Ludwig *et al*., 2018, 2018), that can capture the inherently complex dynamic between the physical, chemical and biological components that consists ecosystem functionality.

A new ecological metaphysic presented by Nielsen *et al*., (2019) utilizes thermodynamic principles, that have followed 100 years of research and theoretical development (Lotka, 1922) to provide a new understanding of ecological systems. These concepts have only very recently been explored in the context of sustainable agriculture (Jordan, 2016; Ferri and Arnés García, 2023). The new ecological metaphysic (Nielsen *et al*., 2019) applies a systems perspective to the understanding of ecological function. It recognizes the cyclical and dissipative nature of ecosystems and their tendency to move away from thermodynamic equilibrium (TE), through the storage of Exergy (energy available work). Ecosystems have been hypothesized to develop according to and increases in four separate system attributes (elaborated in the chapters ahead): (1) ascendency, (2) storage of exergy, (3) the ability to dissipate external gradients in exergy and (4) network aggradation (Ulanowicz *et al*., 2006; Nielsen *et al*., 2020). A theoretical consistency among these 4 attributes points to

Ecological Autocatalysis and centripetality as a central principle binding the separate descriptions (Ulanowicz, 1997; Ulanowicz *et al*., 2006).

Exergy has become a valuable tool in the assessment of ecological structure and function (Jørgensen, 1995; Zhang *et al*., 2010; Xu *et al*., 2011; Tang *et al*., 2015). Exergy is often intimated as a thermodynamic explanation of Darwin's 'survival of the fittest' (Nielsen *et al*., 2020), where the fittest are those that can most effectively store energy and matter flows (exergy). Although exergy seems extremely well suited as an ecosystem health indicator by showing changes in structure and function, the greatest issue is that it cannot be measured directly and can only be calculated (Nielsen *et al*., 2020).

Above ground research in forests has drawn patterns that corroborate thermodynamic theory, utilizing a thermodynamic property, temperature, as a proxy of ecological function. Research teams have shown that structure and function correlates rather well with temperature attenuation and microclimate (Norris *et al*., 2012; Michaelian, 2015; Avelar *et al*., 2020). However, the research is limited to above ground structures and little evidence exists for below ground, particularly in agricultural soils.

What differs in the soil is the chemical environment for metabolism, compared to above ground in the significantly less dense atmospheric medium. The soil is a surface catalyst whereby micro-organisms exchange energy and matter with plants and the environment, depended on the conditions present. In the past pH has been used as an indicator of the soils chemical environment and is capable of distinguishing between an array of different soil types and conditions. However, pH has a sibling, the Reduction/ Oxidation (REDOX) potential (Eh), that is much less explored and has the potential to further explain variation in the soil. If pH is a measure of the proton activity (power of hydrogen), then Eh measures the electron activity and is intrinsically linked to microbial activity. Studies have recently confirmed the applicability of Eh as an effective soil measure of agricultural soils (Husson, 2013; Husson *et al*., 2015), however, it has not been explored nor discussed as a thermodynamic indicator. There is also significant variability in soil REDOX that warrants the establishment of deeper understanding (Husson, 2013; Husson *et al*., 2015). Particularly in relation to soil water/ oxygen ratios which correlate to rapid changes in REDOX status (Mattila, 2023).

As a result, its interpretation can be extremely difficult in complex mediums such as soil (Husson, 2013; Husson *et al*., 2015).

In order to effectively inform a new era of agricultural sustainability this research attempts to confirm the application of these novel indicators to soil structure and function, discussing the results in the context of a thermodynamic approach to sustainable agriculture. To begin this thesis sets the framework from which a thermodynamic assessment may develop, starting with a central principle in the new ecological metaphysic; self-organisation.

Aims and objectives:

Aim:

To explore a thermodynamic approach to the development of soil metrics and to inform a new agricultural paradigm rooted in thermodynamics.

Objectives:

1. Examine the plausibility of applying a new ecological-thermodynamic metaphysic to agricultural soil assessment.
2. Devise and qualify methods and techniques for a thermodynamic assessment of soil function and test the efficacy of thermodynamic soil metrics.
3. Begin to reconcile new thermodynamic theories with agroecological principles.

2 Self-organisation: A central principle in non-equilibrium thermodynamic theories of ecosystem growth

2.1 Self-organisation and the origins of life

Self-organisation is where, out of an initially disordered system, some form of order emerges. The concept of self-organisation was first formulated by the cybernetician William Ross Ashby (1947), who believed any deterministic and dynamic systems automatically evolve toward a state of equilibrium. Although, this was somewhat disconnected from the current understanding of natural systems (later discussed), that reside far from equilibrium and are emphatically indeterminate (Peirce, 1892; Elsasser, 1981; Popper, 1990; Ulanowicz, 2009a; Fiscus and Fath, 2018; Kauffman, 2019). It was however, the beginning of a theoretical construct with huge ramifications. Soon after, the brilliant mind of Alan Turing, (1952), conceived a mathematical basis for self-organisation, in his paper on morphogenesis. Turing 'patterns', as they are referred to, are the result of non-linear feedback mechanisms and this theoretical construct has been observed on an unprecedented scale, with application to theories on the origin of life itself (Brakmann, 2001; Hordijk *et al*., 2013; Kauffman, 2019). Darwin had put forth a mechanism for evolution, but Turing had started to describe how life began and why.

Around the same era, Edward Lorenz was starting to experiment with Chaos theory. Bearing in mind that at this time the mechanistic universal views of Isaac Newton were highly regarded, chaos theory took the scientific community by storm. Not that chaos theory invalidates Newtonian physics, it adds significant depth to the understanding of how complex systems, although governed by deterministic laws, can exhibit unpredictable behavior. In tribute to Karl Popper, Ulanowicz, (1999) demanded a reconciliation of the Newtonian world view adopted by eco-system theorists (Hagen, 1992) resonating the need for a new and coherent view of the processes of nature.

Inherently directional (Jørgensen *et al*., 2007) configurations of processes are driven by the trade-off between constraint (order) and flexibility (chaos; Ulanowicz and Abarca-Arenas, 1997). Autocatalysis applies selection pressure to its components and mechanisms, pruning flows and rewarding changes that make components more catalytically sensitive or better catalysts. This choice imposes modifications that bring more material or energy into the participating element, resulting in what Newton in fact

termed "centripetality,". The importance of centripetality to the phenomenon of life cannot be overstated (Ulanowicz, 2011). This chapter discusses recent advances in ecological perspectives and the central role that autocatalysis has come to play. It is time ecology was taken seriously and the new ecological metaphysic truly realized.

2.1.1 Order from chaos

Many features distinguish living matter from non-living; reproduction, self-organisation, evolution, etc. Life's origin is consequence of the prebiotic evolution of organic material (Brakmann, 2001). Theories about the origin of life largely attempt to explain how seemingly inert chemical mixtures can spontaneously evolve into a living, breathing organism. Darwin's origin of species although apt to describe evolution, was criticised by Sir Richard Owen and Adam Sedgwick as he could not use it to explain the origin of life. The first real reference to life origins, was a letter to Joseph Dalten Hooker dated February 1, 1871, which mentions a warm little pond. However, the first documented theory of this aptly named "primordial soup" came from Alexander Oparin in 1924 and J. B. S. Haldene in 1929 and has fascinated the scientific community for almost a century. The theory gained real credibility in 1953 with the Miller-Urey experiment, in which Stanley Miller and Harold Urey formed basic amino acids from a highly reduced mixture of methane, ammonia and hydrogen (see Hill and Nuth, 2003). Unfortunately, the mechanisms behind this almost biblical evidence of spontaneous self-organisation remained a mystery for some time.

Until, a chemist by the name of Boris Pavlovich Belousov stumbled upon what he believed to be a spontaneous oscillating solution (an autocatalytic reaction) and the era of modern non-linear chemical dynamics was born. At the time, Belousov's efforts to publish his findings were rejected, however, nearly a decade later a graduate student named Anatol Zhabotinsky, revisited the reactions and was able to develop a better formulation. Multiple papers were accepted in Russian at first (Zhabotinsky, 1964) and then in English (Degn, 1967), and these publications caught the attention of a number of western chemists (Chance *et al*., 2014). An advancement in the method (Zaikin and Zhabotinsky, 1970), allowed for the study of the Belousov-Zhabotinsky (BZ) reaction in thin layers of unstirred solutions, in which they discovered propagating chemical waves (Plate 1). For the first time spatial and temporal self-organisation was observed in a homogenous system. These oscillations are the result of autocatalytic, intermediate compounds, that catalyze the ingredients of the next

reaction, which subsequently catalyze the first (Rossi and Liveri, 2009). Application to the origins of life, is based in the statistically and thermodynamically favored configurations of autocatalytic loops (Eigen and Schuster, 1979; Morowitz *et al*., 2000; Lincoln and Joyce, 2009; Giri and Jain, 2012; Veldhuis *et al*., 2018). In addition, the heart is known to oscillate in a similar fashion.

Plate 1 - Turing oscillations in Belousov'-Zhabotinsky rection. Source: (Ball, 2015).

Throughout this period of establishment for BZ reactions, a number of papers were published arguing that truly homogenous oscillating reactions were in fact impossible (Epstein *et al*., 2006). This was motivated by what was later to be discovered as an incorrect understanding of the second law of thermodynamics and a failure to appreciate the application of non-equilibrium thermodynamics to spontaneous reactions (Epstein *et al*., 2006). Many chemists failed to distinguish an oscillator from a pendulum (Epstein *et al*., 2006). A pendulum works magnificently in classical thermodynamics, however, oscillating reactions differ in that they never pass through their equilibrium point. In isolated systems, spontaneous chemical reactions proceed to equilibrium and a global minimum of free energy:

$$G = H - TS \qquad [1]$$

Where G is gibbs free energy, H is enthalpy, T is temperature and S is entropy

Chemical oscillations on the other hand operate in open systems and are governed by the laws of non-equilibrium thermodynamics (Groot and Mazur, 2013). Their error stemmed from the believe that reactants converted to products and back again, requiring a decrease followed by an increase in Gibbs free energy (equation 1), violating the second law (Epstein *et al*., 2006). The actual mechanism for this reaction is quite complex and is subject to a number of publications (Field and Foersterling, 1986; Sirimungkala *et al*., 1999), but theoretically the reaction resembles an ideal Turing pattern.

What is different about open systems that reside far from equilibrium is that energy and matter can exchange across the boundary. It was Prigogine (1967) who realised that thermodynamics can be applied to non-equilibrium systems, but a new theory was required. The decrease in entropy that was required to create order, was possible if the net entropy to the universe increased (Prigogine and Rysselberghe, 1963; Prigogine, 2017). Matter can oscillate in a reaction while the free energy monotonically declines and any drop in entropy is compensated by increases from other processes. On the planet Earth, provided entropy export, in the form of infra-red radiation, is much higher than the structural decrease of living things, the order generated by Earth's inhabitants complies with the second law (Henry and Schwartz, 2019).

What Prigogine and his colleagues had started to explain really began at the turn of the century, when the highly revered Alfred Lotka started to put together his theories on the cyclical dynamics of dissipative systems. Lotka (1922) put forth a model of eco-system development (Vallino and Algar, 2016) unlike no other that had been seen, stating that:

'*In every instance considered, natural selection will so operate as to increase the total mass of the organic system, to increase the rate of circulation of matter through the system, and to increase the total energy flux through the system, so long as there is presented an unutilized residue of matter and available energy*'.

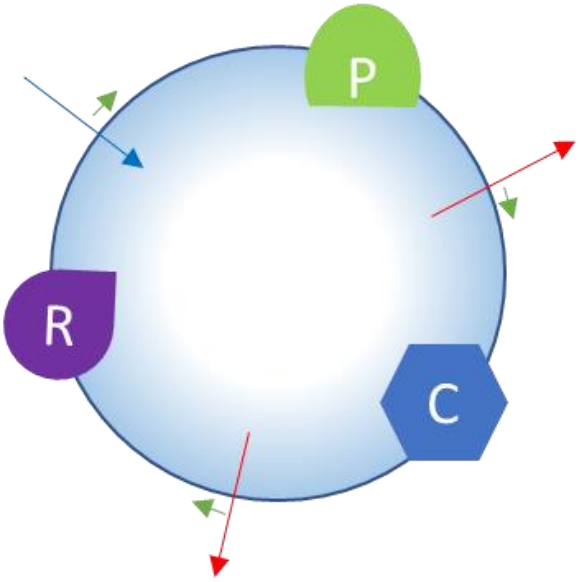


Figure 1 - Ecosystems dissipate incoming photosynthetically active radiation (PAR) (blue arrow) by converting it to infrared radiation (i.e., heat) (red arrows). Phototrophs (P) capture PAR and use available elemental resources (R) to build biomass and release oxygen, which increases chemical potential and decreases system entropy. Heterotrophs and other consumers (C) oxidize phototrophic biomass, producing infrared radiation and recycling resources. The faster the cycle spins, the greater the dissipation of free energy and the production of entropy are, as described by Lotka (1922). Source: (Vallino and Algar, 2016).

2.1.2 Centripetality and the order of selfhood

Understanding the openness and non-equilibrium state of primordial soup, was groundbreaking, however, the origins of life is by no means exhausted here; it is still unclear how simple laws of chemical reactions, manifests properties of life (Joyce, 1979; Luisi, 1998; Peng *et al*., 2020). First, there is the fundamental problem of the 'epistemic cut' that separates the world from the organism (Pattee, 1997). Measuring processes are encoded in the DNA and the cell is the simplest natural case of an observing system (Pattee, 2012). Subcellular entities are not sophisticated enough to count as measuring devices and this epistemic cut position, makes it difficult to imagine life evolving at all (Hoffmeyer, 2001). That said, if the idea that life's semiotic constraints of energy and matter flows, are analogous to more general universal constraints (Christiansen, 1999), it begs the question that Hoffmeyer (2001) challenged, how do physical constraints manifest semiotic controls?

Prebiotic systems, perceived to be abiotic in nature, spontaneously emerging into a biotic system is a baffling concept, as they are fundamentally different in in their organisation in terms of structure, function and complexity. Although abiotic systems can have complex interactions (e.g., atmospheric processes or the hydrologic cycle),

the cycles create predictable and influential patterns, they are however primarily physical or chemical and lack the biologically driven mutual dependencies that biotic systems exhibit (Carnwath and Nelson, 2017; Devi, 2024). Abiotic components influence each other through cycles and physical interactions but lack the mutual dependency that characterizes biotic interdependence. This is an important distinction in ecological organization, where abiotic interactions shape environments, while biotic interdependence actively adapts and sustains ecosystem stability (Shu *et al*., 2022; Devi, 2024). Abiotic systems do not exhibit ecological relationships like symbiosis, competition, or mutualism (Melián *et al*., 2018; Bullock *et al*., 2022).

What Hoffmeyer, (2001) conveyed, is a conceptual reason for how replicative molecules, were preceded by the formation of a semi-permeable membrane, around an autocatalytic chemical system. A membrane creates a point of reference, an asymmetry between the inside and outside, that can move the entity away from equilibrium (Jørgensen *et al*., 2000). For example, by comparing the internal reference with the external environment, a single cell organism such as a bacteria can move in response to nutrient concentrations (Parkinson and Blair, 1993).

A membrane creates a certain individualization, a semiotic niche and a potential internalized environment (Hoffmeyer, 2001), that can exchange energy and matter with its surroundings. Ulanowicz (1997) finds the origins of selfhood in this (box 1); an asymmetry between inside and out (Hoffmeyer, 1998), with even suggestions of a telos (intimation of final cause; Rosen, 1991; Hoffmeyer, 2001).

Box 1

The key to persistent structures, is creating a digital code (DNA), for purposes of coping more effectively with their environment (Hoffmeyer, 2001). What follows is the selfication scheme (Hoffmeyer, 2001):

Interiorization -> communication -> analog maps -> digital maps.

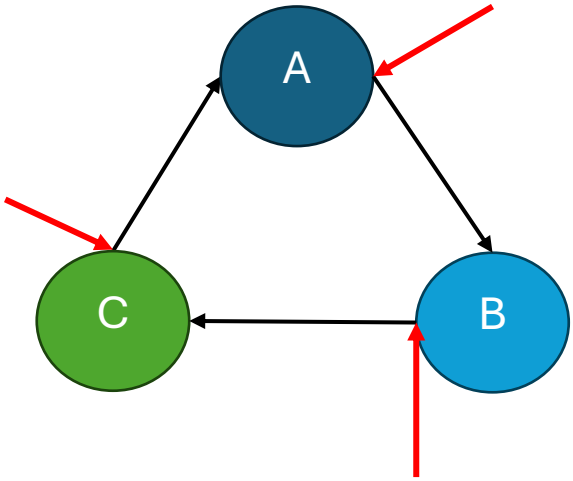
The Common Developmental Road suggests that Eastern philosophy has focused more so on the cyclical, since the enlightenment, whereas, western thought is predominantly linear (Xu *et al*., 2018). Cycles maintain organisation, as state changes are reversible, returning again and again to the same state (Xu *et al*., 2018). Cycles give autonomy and stability (Ho and Ulanowicz, 2005), which is also the case for eco-systems (Ulanowicz, 1983). The above selfication scheme is analogous to four stages of evolution proposed by Xu *et al*., (2018; *sensu* Taoism).

Autognosis -> autocatalytic loop formation -> self-control -> self-realization.

Ulanowicz, (1999) points to autocatalysis, as the unitary agent behind growth. Following from Popper (1990) who took a probability-based approach to replace Newtons mechanistic concept of force, in what Popper (1990) termed 'propensity'. Autocatalysis engenders mutuality among the components and autocatalytic loop formation comes from considering propensities in proximity; in a simple network, of 3 propensities, any one process can have a negative (-), a positive (+) or a neutral (0) effect on the next process, the second can then have any of the three effects and the third similarly (Ulanowicz, 1999). Undoubtedly, 1 of the 9 differs from the rest (e.g. +,+,+) and a mutualistic loop is formed (Ulanowicz, 1999). This supports the widely accepted notion of positive feedback loops being responsible for the self-organized structure in living systems (Eigen, 1971; O'Neill *et al*., 1986; Haken, 1988; Kauffman and Macready, 1995; Peterson, 2000; Haken and Portugali, 2016). In a mutualistic loop of 3 components (Figure 2), A has a positive impact on B, B has a positive impact on C and C on A again. Any increase in one of the components is likely to increase the others (up to the energy capacity of the system). In support of growth it follows, propensities within the loop would support changes that bring ever more resources in

to the loop, in a centripetal fashion (Figure 2). The cycle becomes the epicenter of a centripetal pattern of flows upon which resources converge. This property of an autocatalytic loop, actively creates its own domain of influence (Hoffmeyer, 2001) focusing the centripetal vortex to define its selfhood (Ulanowicz, 2006, 2016).

Figure 2 - Centripetal action as engendered by autocatalysis. A positively impacts B, which positively impacts C and positively impacts A again. The positive reward system selects pathways which actively draw in resources (red arrows). Source: (Ulanowicz, 2006)



Empirical data supports this, when nutrient limiting factors can produce so called 'islands of fertility' (Schlesinger et Aal., 1990; Belsky, 1994; Callaway *et al*., 2002; Bruno *et al*., 2003). Where plant establishment is linked to soil conditions (Maurice *et al*., 2023) and nutrients accumulate beneath the canopy as result of combined abiotic and biotic processes, such as plant cover, litter volume and enzymes (Zhang *et al*., 2022). Research highlights how abiotic factors such as climate, soil composition, and water availability shape the ecological niches that organisms occupy, influencing the diversity and functionality of ecosystems (Carnwath and Nelson, 2017). Plants improve the physicochemical properties of soil through the rhizosphere (Chen *et al*., 2022) and litter decomposition (Zhang *et al*., 2022), both of which affect each other through various feedbacks. The rhizosphere/litter decomposition-influence mechanism is more obvious in arid regions (Mora and Lázaro, 2013; Yang *et al*., 2015). Evidence suggests that fertile island formation is largely driven by soil fungal abundance and plant functional traits (Ochoa-Hueso *et al*., 2018; Martins *et al*., 2024). In particular perennial plants, that create biodiverse hotspots and can determine the structure and functioning of drylands worldwide (Eldridge *et al*., 2024).

Although this centripetal property of autocatalytic reaction networks, does show some level of evolvability (Vasas *et al*., 2010, 2012; Hordijk *et al*., 2012; Hordijk and Steel, 2014; Hordijk, 2016; Goldford and Segrè, 2018), it is still unclear how structures and the complexity that life exhibits, can in fact evolve (Peng *et al*., 2020). In their model, that assumes all reactions reversible, Peng *et al*., (2020) show a fractal relationship between single autocatalytic cycle dynamics and population dynamics of a biological species. However, they challenged existing models of autocatalysis in the origins of life, suggesting its interpretation in models (Gatti *et al*., 2017) can be ambiguous and that they lack realistic chemical kinetics (Peng *et al*., 2020). This presents difficulties in connecting them to plausible prebiotic settings, perhaps due to the complexity in open non-equilibrium systems, contributed by irreversible processes (Peng *et al*., 2020).

2.1.3 Pattern formation and ecological feedback

None the less, ecological feedback mechanisms are credible and have shown to create patterns even at landscape scales! Turing's paper in 1952 explicitly described how patterns in nature, like animal patterns, can arise from a homogenous uniform state (Turing, 1952). Similar processes of pattern formation in nature are starting to show up across the globe. For example the origins of Fairy circles (FC) in Namibia or Mima mounds in Washington state (Plate 2), have long been the subject of controversy (Sahagian, 2017). Many recent theories have argued that it is an emergent phenomena, reflecting an aridity response at the population level; where geometric patterns form, from ecohydrological biomass-water 'feedbacks' (Plate 2; Cramer and Barger, 2013; Getzin *et al*., 2015, 2016, 2019, 2020; Zelnik *et al*., 2015; Cramer *et al*., 2017; Ravi *et al*., 2017). The pattern and wavelength of the gap, is an expression of the spatial scale that water is most limiting to the plants (Meron, 2016; Getzin *et al*., 2020). Getzin *et al*., (2020) concluded that the vegetation gaps maintain ecosystem functioning at lower precipitation values, than if vegetation was uniform in corroboration with Meron (2016). Interestingly, soil temperature plays a significant role in maintaining bare discs, by limiting germination of the grass species within them (Vlieghe and Picker, 2019).

Plate 2 - Fairy circles of Namibia (left). Mima mounds of Washington State (right). Source: (Kelly et al., 2017)

Pattern formation in this sense is an active research area (Rossi and Liveri, 2009; Hsia *et al*., 2012) and while Turing pattern in nature has a robust mathematical background, there are too little field studies. Partly as the phenomenon has more so drawn the interest of physicists over experimental ecologists (Lefever and Lejeune, 1997; Klausmeier, 1999; von Hardenberg *et al*., 2001; Rietkerk *et al*., 2002; Yizhaq and Bel, 2016). Nonetheless, a few studies have empirically linked measured processes, with theoretical modelling, of ecohydrological feedback induced, vegetation self-organisation. In arid grasslands (Getzin *et al*., 2020), African shrublands (Barbier *et al*., 2008), Israelian desert plants (Yizhaq *et al*., 2019), as well as in wetter climates such as Siberian peatlands (Eppinga *et al*., 2008, 2009), where scale dependent, positive feedbacks, were confirmed to drive underlying nutrient concentrations (Eppinga *et al*., 2008). Matching of pattern modelling to empirical data has also been demonstrated for completely different systems, such as the Everglades in Florida (Acharya *et al*., 2015) and even under the Mediterranean sea (Ruiz-Reynés *et al*., 2017). However, more field-work is needed and Getzin *et al*., (2020) called for mutual collaboration between physicists and ecologists, to deepen our understanding of feedback, in complex ecological systems. In particular, investigating timescales of patterns, which in the case of fairy circles, can form over hundreds of years (Caviedes-Voullième and Hinz, 2020).

2.2 Ecological autocatalysis and the evolution of diversity

Cycles provide the dynamical closure necessary for life (Ho, 2003). Nested configurations form (Kauffman, 1986; Hordijk and Steel, 2004; Mossel and Steel, 2005), and the eco-system is a fractal analogue of the organisms that inhabit it. The

same processes of circular interaction found in the prebiotic state, are found in the chains of consumer-resource interactions that organisms partake (Gatti *et al*., 2017, 2018; Veldhuis *et al*., 2018). Philosophers also draw similar analogies between the organisation of cells and of ecosystems (Nunes-Neto *et al*., 2014; Gatti *et al*., 2018). Furthermore, the hierarchal link between chemical autocatalysis and ecological autocatalysis (EA; Veldhuis *et al*., 2018) is akin to the well documented link between chemical stoichiometry and ecological stoichiometry (Elser *et al*., 2000; Sterner and Elser, 2002).

Probably the most profound advancement in evolution, since life rose from the ooze, is the union of two important organisms on the planet; fungi and algae. In a mutual thermodynamic relationship, energy and matter are exchanged between the two organisms otherwise known as Lichen (Plate 3)

Plate 3 - Photo of lichen on a tree trunk (left), on and rock (right). Source: Authors own

2.2.1 Autocatalytic sets and the emergence of niches

The concept of autocatalytic sets was formalized mathematically as 'reflexively autocatalytic and food-generated sets' (RAFsets; Hordijk and Steel, 2014, 2017; Cazzolla Gatti *et al*., 2018). From this, higher levels of autocatalytic sets can emerge at the ecological level, comprising one species guild (Eco-RAF) and the evolutionary level, comprising multiple Eco-RAFs, to form Evo-RAF sets (Cazzolla Gatti *et al*., 2018). Recent studies suggest that natural selection can act on whole RAF sets,

rather than just individual species or genotypes (Calcagno *et al*., 2017; Gatti *et al*., 2017). Through catalytic efficiency selection processes favor reactions that convert reactants to products quickly with minimal loss (Hordijk and Steel, 2017). At higher levels, in terms of resource utilization and competition of multiple RAF sets, selection pressures favor those sets that more efficiently utilize available substrates with minimal waste (Vasas *et al*., 2010). This can lead to the emergence of more complex reaction networks capable of sustaining larger systems, that are more resilient (Smith and Morowitz, 2016). This notion of a single species, enabling multiple species' evolution, contrasts the old natural philosophy, *Natura non facit saltus* (nature does not jump). Something that Darwin used to defend the gradual and minute changes of evolution from one species to another. For example, take a common pest in agriculture, the Aphid. Aphids are part of guild of 5 species that maintain a balance between them (Figure 3). It highlights that species autocatalyze their own and other species' evolution, simultaneously, without the need to partition resources, as in NP theory (Gatti *et al*., 2018). The species in this guild occupy a niche that interacts with a number of RAF sets (Figure 3). And not one species evolved individually, in fact the set evolved together, with the emergence of niches and the set as a whole is the most stable state, given the conditions.

Stability in ecology is defined by the system's (whether a single species guild or whole ecosystem) ability to return to its equilibrium (to be clear this is not TE), state following perturbation (Levin *et al*., 2012). A flexibility often referred to as resilience, however this can over simplify the definition of resilience, which is far more related to ecosystem processes rather than species alone (Zaccarelli *et al*., 2008) and actually depends more on the level of redundancy (Rutledge *et al*., 1976; Naeem, 1998; Elmqvist *et al*., 2003; Petchey *et al*., 2007; Ludwig *et al*., 2018; Biggs *et al*., 2020; Ulanowicz, 2020) and competitive loops driven by environmental conditions (later discussed). Resilience defined by Holling, (1973) is the capacity of the system to absorb disturbance and reorganize, still retaining same structure, function and feedbacks. The IPCC 6th assessment (IPCC, 2022) defines resilience as "not just the ability to maintain essential function, identity and structure, but also the capacity for transformation".

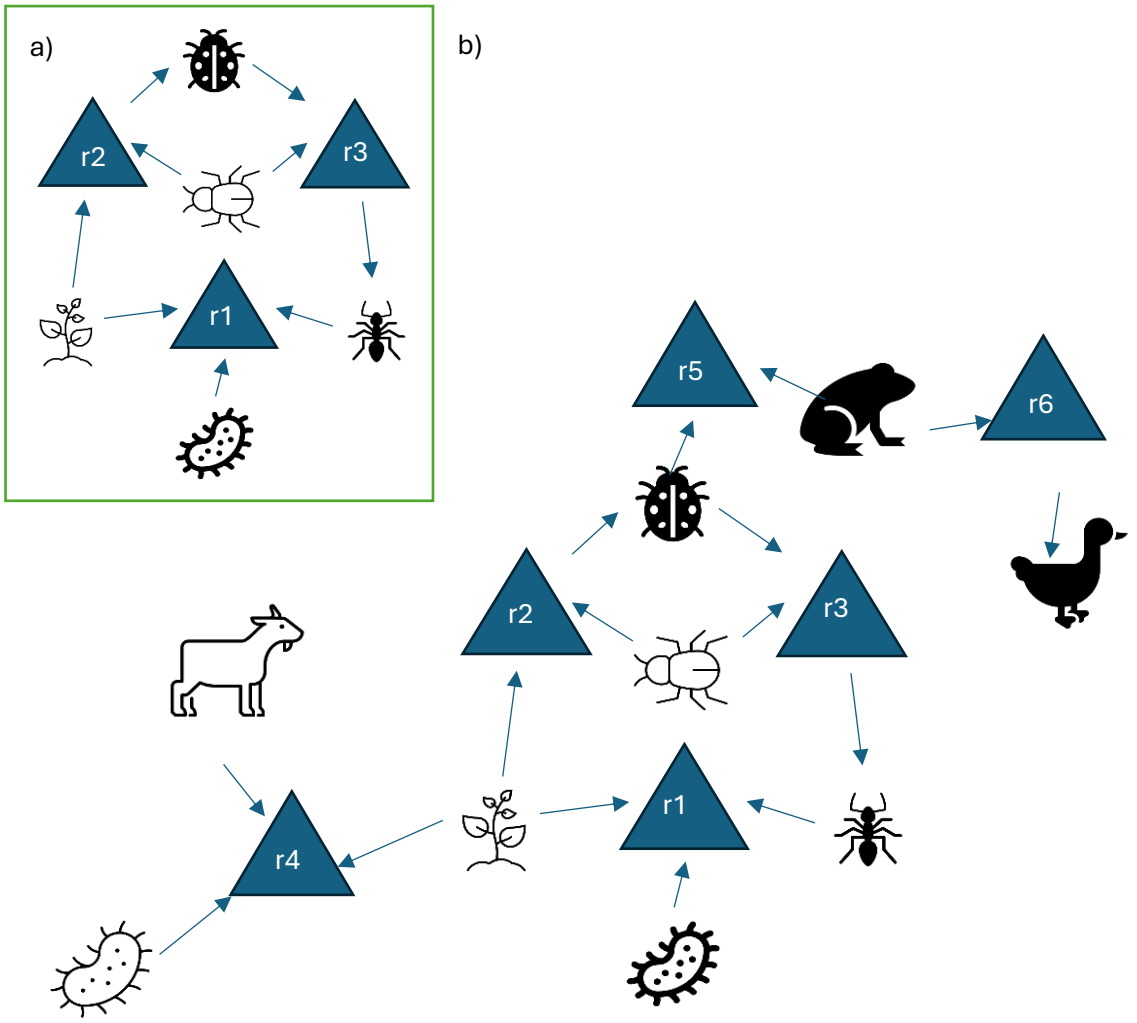


Figure 3 – a) The aphid did not evolve individually to instantly suck on the sap of a plant, in fact the aphid-plant interaction was catalyzed by a bacteria (r1), that eventually found its way in to the gut of the aphid. Following this a mechanism to protect the plant emerged (ladybird; r2) closely followed by an almost behavioral change by ants (r3), to offer protection in exchange for honeydew. These interactions are mediated largely by allelochemical substances from the plant, in stress signaling mechanisms. b) This extends to the wider community, cattle feed on the plants, with the assistance of yet more bacteria (r4) and the energy from aphids propagates throughout the food chain (r5 and r6). Not all interactions are metabolic (ants protecting aphids) and energy flow through autocatalytic interaction is more complex than simple heterotrophic exchange. Niche emergence arises from a fractal expansion of the basal hypervolume. Source: Adapted from, Cazzolla Gatti et al., (2018).

Cazzolla Gatti *et al*., (2018) discuss the concept of how RAF sets can evolve from 'unprestatable' (Longo *et al*., 2012) conditions and are associated with niche emergence and biodiversity. This work builds and extends on theories of eco-systems as complex and adaptive systems, where organisation is central (Levin, 1998). Positive feedbacks are arranged in autocatalytic structures, that operate across scales

and give way to evolutionary outcomes, enhancing biodiversity (Gatti *et al*., 2018). These nested autocatalytic sets now require further quantification and theoretical study, especially with regard to the interplay of ecological and evolutionary dynamics (Gatti *et al*., 2018).

For example, Niche Partitioning (NP) is the process of natural selection, driving species in to differing patterns of resource use (MacArthur, 1955, 1958; Hector and Hooper, 2002). This differentiation, promotes coexistence (Chesson, 2000; Levine and HilleRisLambers, 2009) and NP theories have long underpinned our understanding of biodiversity. However, in NP theory, physical limitations act to restrict niche variables to accommodate a new niche, that is to say, no new resources or conditions can be added through NP alone (Gatti *et al*., 2018). This challenges the classical view that niche differences are key to coexistence and Cazzolla Gatti *et al*., (2018) have proposed, that only Niche Emergence (NE) can push evolution ahead. NP does not allow for the creation of new niches, contrary to archaeological interpretations of fossil records (Brokaw and Busing, 2000; Albrecht and Gotelli, 2001; Silvertown, 2004; Finke and Snyder, 2008; Di Bitetti *et al*., 2010; Cardinale, 2011). With NE New niches emerge from the eco-space following a 'fractal hypervolume expansion', according to Cazzolla Gatti *et al*., (2018); principally derived from the capacity dimension or box-counting dimension, applied to fractal objects (Schroeder, 1991). Put simply, a species can expand from the base resource fractally, through a power law, multiplying available niches (niche emergence; Gatti *et al*., 2017; Cazzolla Gatti *et al*., 2018). Species tend to increase the number of potentially available niches for other species, enhancing the limit of the basal hyper-volume up to the eco-system carrying capacity (Gatti *et al*., 2018).

Examples of this specificity within eco-systems is rife, from the well-known mutual dependency of flowers and a suitable pollinator, to far more curious and obscure interactions such as the fungi, *Ophiocordyceps unilateralism*, zombifying ants for its own propagation. Species posses certain distinguishing traits in order to support the functioning of the eco-system as a whole (Grime and Pierce, 2012). Each species occupies their niche and the emergence and configuration of niches will tend toward that which draws in more resources (centripetality). A niche represents a pathway for

energy flow, with its own individual limitations. Reproduction in plants, for instance, represents the ultimate goal for the individual, to promote longevity for future generations and involves multiple processes and species. The sheer diversity of plant reproduction (flowers, fruits, seeds) suggests interactions between consumer diversity at multiple levels of hierarchy, in evolutionary feedbacks (Georgiadis *et al*., 1989).

2.2.2 From simple laws to complex outcomes.

Species guilds are quite miraculous in themselves, to then place them in the context of the wider eco-system is unfathomable, yet there it is. Here lies the mystery in evolution, the sheer complexity of abundant interaction. It is difficult to comprehend how and where it all came from. However, in a famous thought experiment, the Polya process speculates how from seemingly simple laws, complex outcomes can manifest.

In the generalized Polya process (Cha and Finkelstein, 2018), two colored balls are placed in an urn and one is drawn at random, this is replaced in the urn with another ball of the same color and the process continues (Figure 4). One may assume that the probability of drawing either coloured ball is 50/50 = 0.5. However, what occurs is that the probability never sits at this figure, but instead deviates from it above and below. It can be said that the outcome, although completely indeterminable, is none the less constrained by the previous draws, non-random, yet indeterminate (Ulanowicz, 2011, 2018).

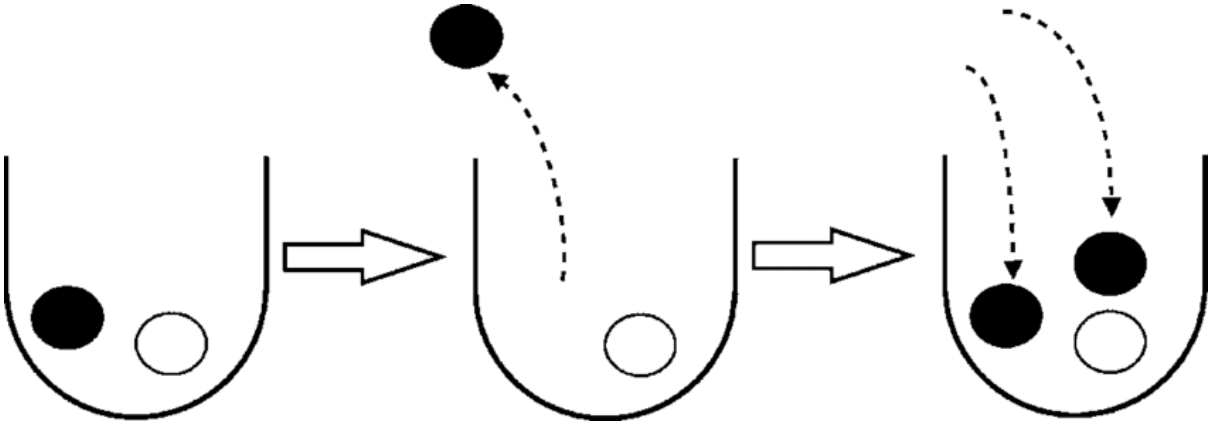


Figure 4 - A depiction of the polya process. For every coloured ball that is pulled from the urn at random, a ball of that colour is added. The ratio of coloured balls is principally driven by chance, however becomes increasingly influenced by the previous draws and actually rarely falls at the expected probability of 0.5. Source: (Cha and Finkelstein, 2018)

What can be ascertained from this experiment is, firstly, the outcome is driven principally by chance and as discussed above, order springs from background chaos, from the many contingencies. Secondly, it involves a kind of self-reference, in the way that a membrane creates an internal reference system, an asymmetry from its surroundings. Finally, the draw is based on a history of previous draws, as too is the final outcome; a necessary tool to create progressive order.

This dilutes to the three dimensions of what (Ulanowicz, 1999) prescribed as, *Life after Newton: An ecological metaphysic*:

- Radical contingency
- Autocatalysis
- Memory

The idea that multiple species can spontaneously evolve into a perfect marriage seems almost supernatural. In Cazzolla Gatti's *et al*., (2018) aphid model (Figure 3), at least one of the autocatalytic sets had to occur spontaneously, prior to inclusion of other catalysts. Although this is always possible, it is much slower compared with if it were catalyzed (Gatti *et al*., 2018). This suggests that the overall probability of an event with constraint (mutualism), is higher than without. True, but unique (rare) events are actually more common than one might think (Ulanowicz, 2004; Jørgensen *et al*., 2007). In fact, the overwhelming majority of events in biology are unique (Elsasser, 1981, 1982; Henning and Scarfe, 2013) and contingency has a spectrum (Ulanowicz, 2004, 2016, 2019). Ecosystems are not causally closed, they are open to non-mechanical agency (Ulanowicz, 2004). As such, spontaneous events may occur at any level of the hierarchy at any time (Ulanowicz, 2004).

For example, Elsasser defines an enormous number as the maximum possible events, that may have occurred in the history of the universe, by multiplying the number of elementary particles in the known universe, with the number of nano seconds since the big bang, to give, $\sim 10^{85} \times 10^{25} = 10^{110}$ (Henning and Scarfe, 2013). Then consider that at the rudimentary level, everything in the known universe is made up from a concoction of the 100 or so naturally occurring elements, the number of contingencies among them can be calculated as a factorial, $100! = 9.3 \times 10^{157}$. It's clear that the probability of a unique contingency is extremely high, as this many possible configurations ensures non-repeatable events; as the number of types increases, the possible combinations grow, which engenders the unprestateability of the phase space (space of possibilities; Longo *et al*., 2012). This expresses the depth of possibilities from the known elements on Earth. Now of course the vast majority of reactions are not thermodynamically possible and would not happen, however it provides the necessary heterogeneity for autocatalysis to occur.

In fact, as little as 75 distinct types is all that is required to equal the same number of individual events since the big bang (Elsasser, 1969; Henning and Scarfe, 2013; Ulanowicz, 2019). This heterogeneity of distinct types, vastly increases probability of autocatalysis to occur (Kauffman, 1986; Ulanowicz, 2019). 75 distinct components, non specific, is all that is required to have enough interactions to reach Ellassers number. If the interactions discussed in the formulation of Elassers number created everything in the Universe, then as little as 75 components has the potential to do the same and in fact likely will tend to do so. Ecosystems regularly exceed 75 components and many exceed 75 species, l*et al*one other physical and chemical components that they interact with, depending on what one considers a "component". The probability demonstrates the extent and almost necessity of unique events in natural systems. It defines what Ellasser referred to as 'Ontic Openness' (Ulanowicz, 2006; Nielsen and Emmeche, 2013). All living systems are ontologically open, implying the extremely high level of uncertainty that guarantees a system to develop (Nielsen and Emmeche, 2013). It also reveals difficulty in determining what that system may actually develop in to. Laws constrain evolution, but cannot determine outcomes (Ulanowicz, 2009b). Complex systems, as causal circuits (Bateson, 1980), can react non-randomly to random stimuli (order from chaos; Prigogine *et al*., 1984) and autocatalysis is molded by a stream of unique events, behaving like a propensity rather than a mechanistic force (Popper, 1990). There is none more apt example of this than the self-organising oscillations of Turing's (1952) patterns, where order emerges from chaos.

What more, this legion of uniqueness allows for the residency of weaker flows to continue as redundant pathways (Ulanowicz, 2020). In this sense redundancy in the form of response diversity (Elmqvist *et al*., 2003; Ludwig *et al*., 2018) is crucial to sustaining ecosystem growth, primarily through enhancing the temporal stability of associated ecosystem function (Naeem, 1998; Petchey *et al*., 2007; Biggs *et al*., 2020). This is biodiversity at its finest! A balance between constraint and flexibility (Ulanowicz, 2020), where simple rules can create complex outcomes (Ulanowicz, 2007). It is why primary production of a given area can vary so tremendously; as it is dependent on the traits of the photosynthetic individuals involved and the availability of limiting resources (light, nutrients and water; Jänes *et al*., 2017). Biodiversity influences ecosystem function and high diverse communities tend to be capable of higher productivity. The effect of biodiversity on ecosystem function, is then also

dependent upon the temporal and spatial scale of the interactions within these complex systems (Barry *et al*., 2021).

2.2.3 Temporal and spatial scales

Uniqueness provides a platform for species to inhabit a diverse range of environments. Habitats where the conditions change dramatically, either daily as in tidal areas or even seasonally as in flood lands, are tasked at providing the necessary energetic pathways to sustain both scenarios, or succumb to significant energy losses and the poor ability to export entropy (Prigogine and Nicolis, 1985). This creates a heterogenous landscape, as these habitats are exposed to the fluctuating environmental conditions. Feedback modifications of Eco-RAF sets, promote alternative niche constructions (Post and Palkovacs, 2009; Kylafis and Loreau, 2010; Odling-Smee *et al*., 2013). Interactions of organisms modulate the resources, by causing state changes (Veldhuis' *et al*., 2018) and certain species have key roles; keystone species (Power *et al*., 1996), ecosystem engineers (Jones *et al*., 1994) or foundation species (Whitham *et al*., 2006).

Veldhuis' *et al*., (2018) give an example through flooding, where a macro detritivore dominated grassland loop, switches to a microbe dominated grassland loop. With increasing rainfall, grazing intolerant grasses, evolve to cycle nutrients and energy

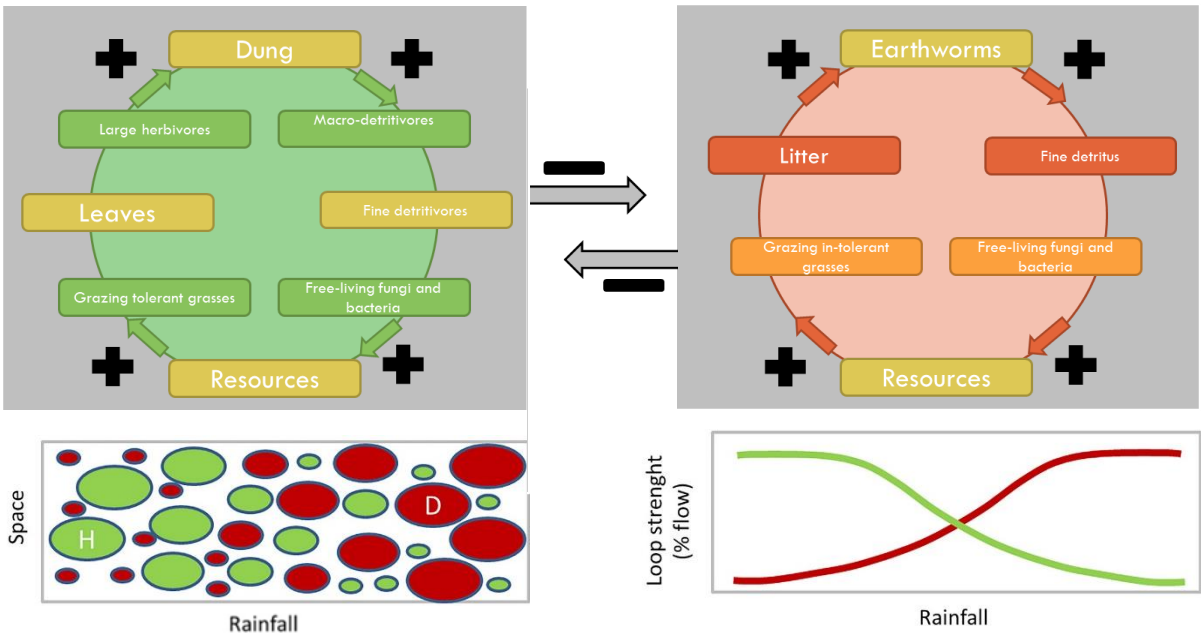


Figure 5 - Conceptual model of two competitive autocatalytic loops, in a semi flood land habitat. With water as the limiting factor, two stable states have been established to ensure energy dissipation prevails. With rainfall, loop strength for detritivore pathway (D; red) increases and heterotrophic pathway (H; green), diminishes. This is reversed when rainfall is minimum.

through a leaf litter and earth worm path; shifting from grazing tolerant plants and a macro detritivore path (Figure 5). The evolution of either grazing tolerance or intolerance, is simple to see here and either strategy generally contributes to enhanced nutrient cycling or conservation (McNaughton *et al*., 1997; Steinberg *et al*., 1997; Loreau, 1998; Mazancourt *et al*., 1998; Belovsky and Slade, 2000; Veldhuis *et al*., 2018). Like the fairy circles the system finds the most stable situation based on the limitations of the environment (in both cases water).

Competition between loops (Ulanowicz, 1999) generates negative feedback, with the extreme hydrological cycle. The system flips backwards and forwards between the two 'alternate stable states' and as a whole, maintains stability in the limiting conditions (Howison *et al*., 2017; Veldhuis *et al*., 2018). During times of extreme conditions the less tolerable loop becomes redundant but still exist, with reduced flows, until the event that conditions become more favorable again. This may be visible as a grazing mosaic and Howison *et al*., (2017) proposed that the alternating patches, are governed by the interplay between the two biotic processes. The patches expand the range of conditions, under which grazing mosaics can persist (Howison *et al*., 2017). Smit *et al*., (2023) go on to produce a patch dynamic model that confirms how feedbacks between large herbivores, vegetation and soil fauna alter patches over space and through time. Grazing tends to have a non linear, both a negative and positive effect on species diversity dependent largely on the grazing intensity. Overgrazing can disrupt positive associations between biodiversity and nutrient availability (Wang *et al*., 2020), where as abeyance can lead to homogenization of food webs and biodiversity loss (Schrama *et al*., 2023). Traditional methods that employ light – moderate grazing management, tend to be more sustainable and lead to sustainable grazing management and promote biodiversity (Mu *et al*., 2016; Dong *et al*., 2020).

This presents the existence of both a positive (facilitative) and negative (competitive) interaction between species (Bruno *et al*., 2003), that contributes resilience. Maestre *et al*., (2005) observed, through density data, that in low and high abiotic stress levels, the net effect of neighbours can be positive or negative, respectively. The combined positive feedback within loops and negative feedback between them, results in competition between sets (autocatalytic loops) of species (Ulanowicz, 1997; Verhoef and Morin, 2010; Veldhuis *et al*., 2018). This self-reinforcing nature, of coexisting loops, can explain spatial and temporal heterogeneity (Veldhuis *et al*., 2018). It follows

that the higher the amount of resources a species can produce or acquire, the greater amount of loops it can participate in. This balance between positive feedback within loops and negative feedback between loops, corresponds well with interaction–redistribution models of vegetation dynamics (Lejeune *et al*., 2002; Rietkerk *et al*., 2002; Veldhuis *et al*., 2018). Furthermore, it can be used to explain the competitive exclusion principle. As previously mentioned the centripetal property of an autocatalytic system actively selects paths that draw in the most resources, weakening flows across others making them redundant (Ulanowicz, 1997; Ulanowicz *et al*., 2006). For example, two species competing for the same resources will undoubtedly result in the more efficient one outcompeting with the other establishing a positive feedback loop, that further reinforces its occupation in the niche (Jørgensen and Fath, 2004). In the above grazing example, the competitive traits of the two systems exclude them from one another and as a result the overall landscape achieves a semi stable state. A species can cross a threshold and become dominant (the herbivore or the detritivore in this example), which can alter the ecosystem structure and function, until such a time as conditions allow the other to cross a threshold in to dominance (Vasas *et al*., 2010).

What this demonstrates is that natural selection is not only driven by the competitive exculsion principle and natural selection, acting in a downward motion to shed components not participating as effectively in autocatalysis, it is also working in an upward motion to build efficient loops. Veldhuis *et al*., (2018) goes on to postulate, that this also confirms how nutrients and their availability are in fact emergent properties that arises from the fractal eco-space (Gatti *et al*., 2018), contrary to classical accepted views that it determines community structure (Veldhuis *et al*., 2018). Food web models are shown to stimulate nutrient flow rates (de Ruiter *et al*., 1994), food web structure is an important factor in nutrient mineralization (Berg *et al*., 2001) and macro-detritivore identity drives leaf litter diversity (Vos *et al*., 2011). Community structure then, is not only consequence of functional traits and assembly rules but also loop formation and competition (Veldhuis *et al*., 2018). Emergent properties such as resilience and alternate stable states, are then consequence of competition between autocatalytic loops and mutualism within them (Veldhuis *et al*., 2018). This can be adaptive both ecologically and evolutionary under certain conditions (Loreau, 1998; Mazancourt *et al*., 1998). However, the interplay between

ecological and evolutionary outcomes is so complex, it requires redefining mutualism (Mazancourt *et al*., 1998; Gatti *et al*., 2018).

In this sense evolutionary cycles across both space and time, alternate between long periods of aggradation, (accumulation of exergy , evidenced by movement from TE) and short periods of innovation, with abundant opportunity (Gunderson and Pritchard, 2012). They are 'adaptive' (Gunderson and Holling, 2003) and this is a fundamental concept for understanding complex systems. The adaptive cycle as proposed by (Gunderson and Holling, 2003) exhibits two major transitions (Figure 6). The first, r to K is a time of slow incremental growth and accumulation (the fore loop), the second, Omega to Alpha, is a time of rapid renewal and reorganisation following collapse. As in the transitional habitats described above, the two competitive systems collapse and re-organise with the changing conditions. This of course propagates up to the highest scale (the biosphere). Cycles are nested and the concept extends to what Gunderson (2002) termed, panarchy (nested adaptive cycles). Gunderson (2002) proposed that panarchy operates within distinct spatial and temporal scales, shaped by a limited number of key processes (Sundstrom and Allen, 2019). Subsequent research has provided substantial evidence supporting this idea (Allen and Holling, 2008; Wardwell *et al*., 2008; Sundstrom, 2009; Nash *et al*., 2014; Spanbauer *et al*., 2016; Sundstrom and Allen, 2019).

The k phase is the most vulnerable stage, although highly efficient the system is brittle with low resilience but high resistance. A strong enough perturbation (such as flooding, or drought) is enough to drive the system to collapse and it will reorganises in a different stable state. Extreme events can completely tip the scales and throw the system back to a previous successional stage, it is forced to remember the configuration (Figure 6). Similarly, the accumulation of fast events at smaller scales can overwhelm larger slower ones and processes, structures at the lower scales then overthrow those at higher scales. The revolt may lead to new processes and structures at those higher scales (Figure 6).

The adaptive cycle metaphor gives a qualitative description of processes, characteristic of a complex system (Castell and Schrenk, 2020). In accordance with Gunderson and Holling, (2003), complex systems pass through the two unique phases as a means to adapt and evolve.

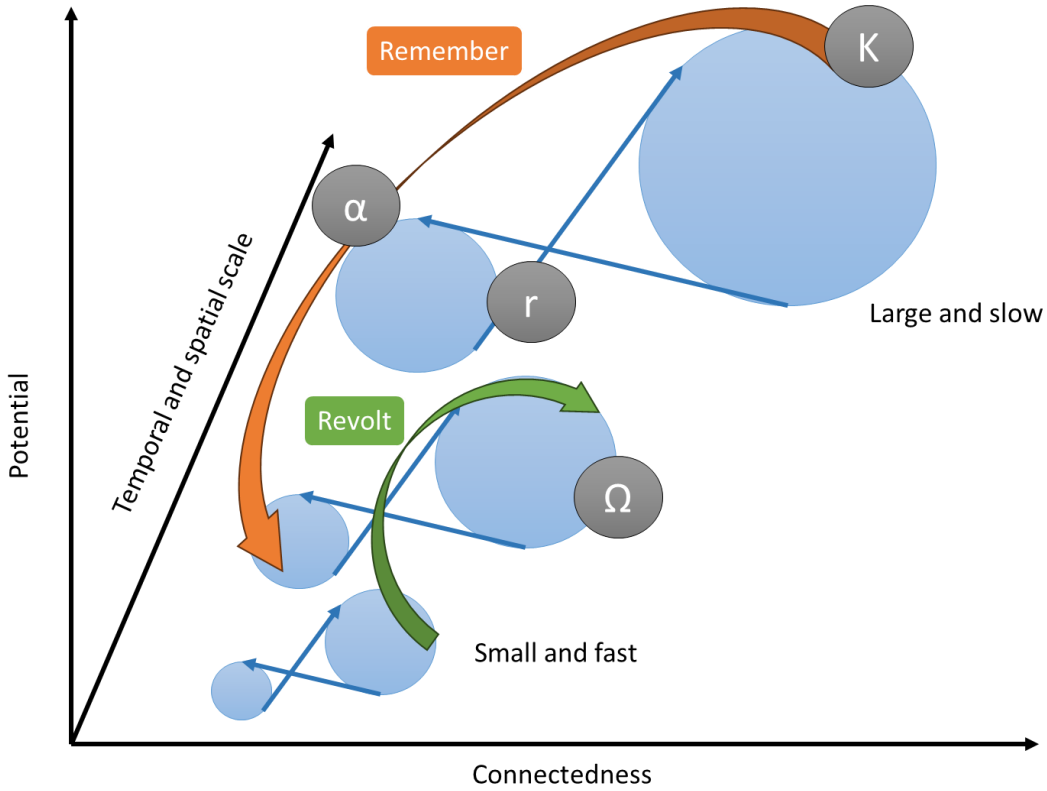


Figure 6 - The cross-sale interaction of the adaptive cycle. Introducing a 3rd dimension of spatial and temporal scale, where the larger (biosphere) scales are slower and smaller (organism) scales are faster. 4 distinct phases plot the trajectory of an adaptive system: The r phase (r), a period of rapid resource exploitation and growth, with innovation and flexibility, but low stability. The system is experimenting and expanding and energy and resources are plentiful. In the K phase (K), energy efficiency and accumulation dominate, accompanied by high stability, however this creates rigidity and the system is vulnerable to collapse (Ω). Ω is a rapid breakdown where accumulated resources and structures are released, trigger by perturbations that push the system beyond its threshold. Finally, the organisation phase (α), is a period of high uncertainty, but a window of opportunity, as the system prepares for a new growth cycle. The two cross-scale interaction that facilitate systematic change are revolt and remember. Remember exerts a top down influence and occurs during the α phase, where legacies from larger, slower systems remember past structures and influence faster smaller systems. The revolt, has a triggering effect and occurs during Ω, where a faster smaller system in collapse can cascade up to the next scale.

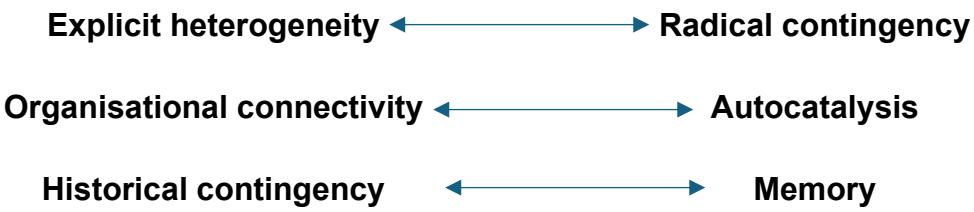
Complexity and order emerge from relative simplicity and disorder through “periodic but transient setbacks involving relaxation and restructuring of organization” (Kurakin, 2011). Thermodynamic principles, used to investigate the dynamics of change in

complex adaptive systems, such as exergy, infrared thermal measurements, and electron and proton transport in autocatalytic processes (E.D Schneider and Kay, 1994; Jørgensen and Fath, 2004; Kurakin, 2011; Sundstrom and Allen, 2019), align closely with the concepts of adaptive cycles and panarchy. These authors argue that setbacks to the trajectory of increasing complexity, occurring across all spatial and temporal scales (e.g., small forest fires, mass extinctions, or the decline of civilizations), have not altered the overall trend of increasing complexity. While individual components may change, the underlying organization and relationships tend to persist and evolve over time (Kurakin, 2011; legacies form).

2.2.4 Complex systems as webs of autocatalytic loops

Complexity in the context of its raw definition, although extremely apt to describe the intricate and complicated state of natural systems, has far deeper connotations; moving in to a whole scientific field of its own. Ecological complexity embodies the study of diverse components, connectivity and emergent properties, encompassing key eco-system variables, like trophic interactions and functional diversity (Bullock *et al*., 2022); referring to structural complexity and complex behaviors (Peipoch *et al*., 2015). Complexity at the landscape scale is contingent on variation in biological form and function at finer scales and the relationship between diversity and complexity has been the focus of ecological theory (Hutchinson, 1957; Rutledge *et al*., 1976; Peipoch *et al*., 2015). The literature surrounding ecological and/or biological complexity find an accessible ground for ecologists, physicists and systems theorists alike to explore the fundamentals of complexity, with ecological structure as the entry point for the framework (Cadenasso *et al*., 2006).

In spite of the relatively recent general increase of interest in complexity, the theory and associated concepts such as non-linear dynamics, self-organisation, irreversibility, emergence, etc., have been a rich topic for study in physics, thermodynamics and systems theory (Kay and Schneider, 1994, Bak, 1996, Auyang, 1998, Milne, 1998). This framework is based on three dimensions of complexity; spatially explicit heterogeneity; organisational connectivity; and historical contingency (Cadenasso *et al*., 2006). There is something reassuringly familiar in the three dimensions of complexity, with the new ecological metaphysic (Ulanowicz, 1999).



2.2.5 Developing the necessary structures for effective energy dissipation

Autocatalytic systems undergo a centripetal migration of material and energy towards the loop itself (Figure 2), rewarding modifications that provide additional material or energy to aid operations. This selection applies to all aspects of the loop, making the cycle the focal point of an inward migration of energy and matter (Ulanowicz, 1997; Ulanowicz *et al*., 2006). However, this flow of resources leads in the siphoning of essential elements away from system members that do not engage in autocatalysis as effectively (Ulanowicz, 1999; Jørgensen *et al*., 2007). The total mutual information (ascendency) increases as a result of the steady pruning of exchanges connecting system elements, while flows over remaining links rise due to the acceleration of autocatalysis (Ulanowicz, 1999).

Autocatalytic interaction imposes increasing constraint and channels system flows along fewer, but more efficient, paths that are more beneficial to the process. This "pruning" increases the occurrence of these flow events (Jørgensen *et al*., 2007). That said, autocatalytic cycles are not always rigorously coupled, to return to Figure 2; A's action does not always reinforce B's. Instead, they are variable biotic constituents and processes. Autocatalysis is a mechanism in simple chemical systems, but when chance and variation enter the picture, it exhibits nonmechanical characteristics. Autocatalysis among indeterminate processes causes selection pressure, where a change in a process B's characteristic improves B's catalytic influence on C or makes B more sensitive to A. Changes in process B, on the other hand, reduces its effect on C or makes it less responsive to A, resulting in atrophy (Ulanowicz, 1999). This selection is not the same as natural selection (Ulanowicz, 1999), which operates downwardly (Veldhuis *et al*., 2018) to strip redundant components. The selection pressure from self-organisation acts in an upward fashion, building ecological feedback structures (Veldhuis *et al*., 2018).

Take the energy characteristics of a desert, largely it is the movement of water that separates a desert from a rainforest. Evapotranspiration is a fundamental process that drives photosynthesis and primary productivity (Fisher *et al*., 2017). Heterogenous features enable the increasing ability to draw in resources like water and dissipate energy. Through entropy transfer tools Yuan *et al*., (2021) showed that information transfer from solar radiation and vegetation activity to evaporative fraction, increased in forested areas compared to non-forested areas. Indicating that energy dissipation is enhanced through transpiration in increased vegetation. Similarly, transpiration helps to build the energy into biomass of the plant, or at least to maintain the vigor of the plant so that it can effectively dissipate energy. In the fairy circles (Plate 2) energy dissipation is maximized on the perimeter of the ring, as resources converge there (Meron, 2016; Getzin *et al*., 2020).

Desert	Rainforest
	
Aridity in a dessert is by far the greatest limiting factor and although species have developed specialized structures and functions, to harvest energy in the extreme conditions, the habitat remains largely homogenous with poor interconnectivity that lets a large fraction of the available energy go to waste.	*Higher surface area, interconnected network and increased biomass, develops the necessary structures for effective energy dissipation. Largely through evapotranspiration.*

Figure 7 - The difference in energy flow through evapotranspiration between a desert and a forest. Dense vegetation has more surface area and greater thermodynamic mass, leading to greater evapotranspiration and energy dissipation. Source: Stock images

If given the right information, a configuration that allows a more efficient path for energy flow will be favored and promote greater energy dissipation. In a chrono sequence of soil pedogenesis and ecological succession, a homogenous substrate (like a desert sand) lacks the necessary structure, to retain valuable resources such as water, nutrients, etc. With limited prospects for autocatalytic interaction, energy dissipation is poor. What is crucially important is that this is only dependent on the ability of the components to access resources. Hence why biodiversity is so important. Abundance and diversity in living biomass, is representative of an abundant and diverse departure from TE (Jørgensen *et al*., 2000). Where it becomes extremely important to understand, is the environmental impact that simplification of landscapes, like agricultural ones, may have. Climate change is often attributed to greenhouse gases and the role of biodiversity in mitigating climate change is given to carbon sequestration (Pörtner *et al*., 2022). However, diverse eco-systems are an effective climate buffer by reducing surface temperatures and climate regulation is a significant eco-system service (Landis, 2017). Eco-systems cool themselves, through self-organisation, exporting entropy to the atmosphere as heat and these transformations are mainly achieved by water movement (evapotranspiration; Pokorný *et al*., 2010). As such, afforestation could significantly reduce surface temperatures and contribute to the positive change needed to mitigate climate change (Ellison *et al*., 2024).

The role of water vapour from evapotranspiration, in cooling ecosystems forms an integral part of understanding energy dissipation and is discussed in more detail in chapters 4 and 5. Its cooling effect is primarily the result of the proportion of sensible and latent heat (Norris *et al*., 2012; Michaelian, 2015; Avelar *et al*., 2020). It is also true that aerosols contribute to a net cooling effect (Myhre *et al*., 2013), however this is largely through the formation of cloud condensation nuclei, enhancing cloud formation and albedo effect (Merikanto *et al*., 2009; J *et al*., 2016; Rejano *et al*., 2023; Kubečka *et al*., 2024) Interestingly, water vapour in the atmosphere is thought to have the opposite effect and makes up 50% of known greenhouse gases. However, atmospheric water is far more a result of global warming increasing sea temperatures, as a mere (yet considerable) 10% of atmospheric water vapour is from evapotranspiration. Interestingly, Patel *et al*., (2024), found strong relationships between an increase in atmospheric water vapour and desert greening. Also, (Laguë *et al*., 2023) used global climate models to show how terrestrial evaporation can

increase atmospheric water vapour through generating cloud feedbacks; the suppression of evaporation, increases energy input to surface and surface moist static energy over land (the thermodynamic state of an air parcel). This emphasises the dual local and global effects of water vapour in cooling and warming the planet, further promoting the role of ecosystems in terrestrial cooling and the importance of complex ecosystems across the planet. It is clear that research in to evapotranspiration and energy dissipation is needed and this will become increasingly more evident as the thesis progresses.

2.3 Conclusions

Although science is still some distance from a 'unified theory' of ecology, it is clear that autocatalysis plays a pivotal role. Theoretical models and empirical evidence is changing our understanding of nature and evolution, where concepts such as niche partitioning and natural selection, that have thus far underpinned knowledge, are found to be only part of the story (Gabora , 2006; Gatti *et al*., 2018). Autocatalytic loops are consistent across theories of the origins of life, to complex systems.

Empirical evidence of Turing (1952) patterns in ecological phenomena such as FC, are for the first time being realized. However, too little field studies exist and there is poor communication between ecologists and physicists. Although it is still unclear how simple laws of chemical reactions, manifests properties of life, new research is emerging.

Autocatalytic loops are found to be the unitary agency behind growth and EA is identified as the central principle in the development of complex systems. There are two timescales at work and positive mutualism at the faster scale is abetted by negative competition at the slower scale, creating a heterogenous landscape that maintains stability in limiting conditions. In addition, nutrient cycling is an emergent property of the combined effects of positive and negative feedback at the faster and slower timescales, respectively.

Through autocatalysis, species and communities develop toward a state of the most effective energy dissipation within the limitations of the system. Complexity, through the development of structure and function will always maximize this as it is intrinsically linked to thermodynamic laws, in particular entropy production (the second law). Scale becomes extremely important in the context of energy flows in managed landscapes.

In agriculture for instance, the individual that is the crop has certain needs to build biomass and provide a competitive yield, in order to facilitate economic gain. The factors that denote that profit margin are related to the ability of the farmer to supply those needs.

Diversion of critical ecosystem services, for the benefit of mankind (from higher scales), is resulting in significant environmental decline and ability to supply those resources sustainably. In order to progress, a deeper understanding of energy and matter flows in managed systems is needed. This first requires the development of effective indicators and is the premise of the following chapters.

3 Developing a framework for the thermodynamic assessment of structure and function in agricultural soils

3.1 The pitfalls of contemporary soil bioindication

An indicator is a metric that enables a verification of the soil's situation in respect to its conservation state, pollution, productivity, or any other characteristic that offers information about its existing and potential status (Bonilla *et al*., 2002; Camacho, 2008; Tapia-Báez, 2015; Huera-Lucero *et al*., 2020). Multiple reviews have been carried out on existing bioindicators (Bastida *et al*., 2008; Ritz *et al*., 2009; Cluzeau *et al*., 2012; Havlicek, 2012; Pulleman *et al*., 2012) alongside EcoFINDERS (Faber *et al*., 2013; Griffiths *et al*., 2016; Stone *et al*., 2016) and outputs of recent international initiatives for soil monitoring, ENVASSO (Bispo *et al*., 2009). Yet no standardized soil sustainability indicator suite has been established (Ludwig *et al*., 2018). Soil indicators tend to focus on the biological, physical and chemical characteristics (Vallejo-Quintero, 2013; Jónsson *et al*., 2016; Huera-Lucero *et al*., 2020). Approaches either focus on a single indicator or a suite of indicators (Zhou and Ang, 2008). A single indicator is often unfavorable, as it is not believed to capture the complexity of natural systems (Nourry, 2008). On the other hand too many is timely, costly and messy to say the least (Ludwig *et al*., 2018). As such an indicator set requires careful crafting. One of the greatest potential causes of error is in the estimation of data from other parameters, which ultimately are considered as true values, such as estimating moisture content from a collection of parameters like precipitation, soil structure, texture and land use. This can make their true connection with reality questionable (Baveye, 2017). Furthermore, some indicators are scale dependent and become unpredictable when scaling up (Baveye, 2017).

The need for further data on the condition of our soils is well acknowledged (Shepard, 2015) and crucial to effectively create policies and programs, that safeguard this vital resource. As such, they are central to land-based decision making. In a recent and very comprehensive systematic review, Bathaei and Štreimikienė, (2023) inspect a myriad of current indicators with only a small handful related to soil. Jónsson *et al*., (2016) provide a transdisciplinary approach for indicator development. Wang *et al*., (2023) discuss progress and perspectives in remote sensing of soil degradation. Details of these studies has not been included here, but they provide great detail to the plethora of soil bioindicators available to the scientific community. In addition,

technological advances have made soil sampling more precise and has enabled access to vast data sets through satellite imagery. The most current data sets were collected in the 1980s as part of the National Soil Inventory (LandIS, n.d.). However, there are limitations with satellite data, such as spatial and spectral resolution, temporal constraints, atmospheric and environmental interferences, data costs and access, integration challenges and uncertainty in measurements, all which are discussed in detail in the comprehensive reviews by Karakuş, 2023; Vitousek *et al*., (2023). These limitations highlight the need to complement satellite data with other sources, such as ground-based observations or aerial surveys, to create a more comprehensive understanding of the phenomena being studied.

Soil sustainability indictors cover a broad spectrum of ecological processes and functions, and consider factors related to species richness, biodiversity, invasive species etc; as well as vulnerability to stressors and other chemical factors such as nutrient content and contamination (Bastida *et al*., 2008; Bispo *et al*., 2009; Ritz *et al*., 2009; Havlicek, 2012; Pulleman *et al*., 2012). However, in an agricultural setting, due to its inherently modified environment from intensive management regimes, it is difficult to make an assessment with these measures. Species are often predetermined, resilience is often artificially created (Ludwig *et al*., 2018) and fertility is often fabricated. These factors can take time to stabilize following conversion to regenerative or ecologically based practice and so far, there is no existing monitoring approach that can directly monitor the progress of sustainable transition.

Indicators that compartmentalize biological, chemical or physical compartments of the soil (Huera-Lucero *et al*., 2020; Bathaei and Štreimikienė, 2023), do not have the necessary reach to capture the flow of energy and matter that defines a natural system, residing far from equilibrium. Soil sustainability indicators must reflect the capability of the soil to continue to function under the pressure of anthropogenic disturbances such as farming. As the previous chapter began to discern, ecological function relies on the thermodynamically open characteristic. Unlike isolated systems that have specific mass and energy, thermodynamically open systems are subject to fluctuations as they transfer energy to and from the surroundings.

For example, the majority of terrestrial plants get their energy from the sun. Energy from the suns radiation crosses a boundary when photons hit Photosystem 1 and the

catalysis of electrons across the thylakoid membrane (Meredith *et al*., 2021), converts that energy in to mass and eventually fuels the growth of the plant. This is happening across the whole of the community or ecosystem in question and further exemplifies the fuzzy boundaries that exist in the natural world, that are largely scale dependent (Post *et al*., 2007). Boundaries are perhaps much better understood from a from a quantum understanding of the universe, based on probabilities and Holling (2002), began to discuss this with the panarchy concept. Nested systems in panarchy exhibit boundaries as multiscalar, hierarchal entities and from a thermodynamic perspective these boundaries persist in time by contributing to the energy production at higher hierarchal levels (Yarrow and Salthe, 2008). Ecosystems such as forests are typical thermodynamically open systems (Lisitsyn and Matveev, 2022), evidenced by the flux of energy, matter and entropy used to build and organize matter (Svirezhev, 2000) Failing to appreciate this fundamental prerequisite for complex systems and compartmentalizing chemical physical and biological components (Huera-Lucero *et al*., 2020; Bathaei and Štreimikienė, 2023), instead of capturing the multiscalar, hierarchal flux of energy, mass and entropy, is where soil bioindication will fail.

It is important at this point to stress that agricultural systems are too thermodynamically open and should be considered nothing other than thermodynamic systems.

3.2 Recognizing the farm as a thermodynamic system.

Humanity has undergone several revolutions in the last 200 years or more, which have increased productivity and prepared the ground for the current exponential population growth. England's total land area is 13,031,001 hectares (GOV.UK, 2013), of which around 70% is utilized for farming (GOV.UK, 2017), mostly for improved grassland, horticulture, and arable land. 11% is used for urban development and 10% classified as forest (National Statistics, 2023); which more than halved between the Domesday book of 1086 and the start of the industrial revolution (GOV.UK, 2013). This has since improved, however, it will be difficult to return to the ancient state of England’s land, where agricultural development has replaced forests for thousands of years and the long-term impact of which is very much an unknown.

The only energy sources available to farmers prior to the 19th century were man and animal, who used stick-like ploughs to score the soil's surface. At the turn of the

industrial revolution, devices like the mouldboard plough, drawn by steam-powered tractors, improved cultivation of crops, encouraging the growth of towns and a range of occupations. These developments, nevertheless, paled in comparison to what transpired following World War II, when petroleum replaced other energy sources, powering machinery and enabling the synthesis of herbicides and fertilizers. This led to an explosion in the sector as higher-yielding crop types were developed. Both scientists and agronomists saw enormous promise and the end of world hunger. However, The World Bank estimates that although the green revolution significantly reduced world hunger (from 34% in 1950 to around 7% in 2022) it has not, by any means, put an end to it and it has come at a great cost to the planet (John and Babu, 2021).

Farms like natural systems are open and self-organising, in that they convert solar energy into biomass that can be extracted as yield; supplying energy in the form of food, feed or biofuels, to humans and animals. However, what differs from natural systems is they subsidize energy inputs in the form of fuels, fertilizers, pesticides etc, to maintain “order” (Jordan, 2016). They use external, non-metabolic energy sources, otherwise known as exosomatic energy (Odum *et al*., 1979), which is unique to humans (King and Jones, 2023), to boost production by essentially pumping energy into the system. In natural systems the energy that ultimately and successively leads to the production of biomass, is achieved through autocatalytic interaction (Chapter 2). These processes are predominantly metabolic or endosomatic (embodied in an organism) and are linked to physiological activities, providing a range of ecosystem services.

According to the Office for National Statistics, the agriculture, fishing and forestry sector utilizes over 3% of the national fossil fuel consumption and this is predominantly Gas Oil (ONS.GOV.UK, 2023). In commercial agriculture, 50% of energy consumption is for production, logistics and application of fertilizers (Woods *et al*., 2010; Paris *et al*., 2022) and 55% is from indirect sources (Paris *et al*., 2022). Although modern fertilizer production and application techniques have significantly slashed the energy demand, the environmental impact remains and has increased with the rising demand for food . As long as agriculture is dependent on fossil fuels, food prices will be driven

by energy costs and agriculture will continue to contribute to greenhouse gas emissions (Woods *et al*., 2010).

The ratchet tightens ever more as humanity advances technologies in agriculture. The adoption of fertilizers has enabled and will continue to enable population growth and lessen world hunger. However, due to the economic model of demand, increases in yield from multiple farmers adopting new technologies results in lower profits as supply increases. There is no turning back as demand meets supply through population increase and to overcome profit losses, farmers seek newer and newer technologies; the cycle continues. There are examples of agricultural related environmental decline all over the world; nutrient pollution in the Gulf of Mexico, the Baltic Sea, the Adriatic Sea, and the Black Sea (Mitsch *et al*., 2001) and similarly for India's soil and water resources (Pingali, 2012). Numerous strategies have been put forth to relieve the burden on the environment, owed to the increasing scientific and media coverage. Nevertheless, despite the significant financial and ecological costs to society, there is little adoption and the issue appears to persist, largely a result of poor knowledge transfer from extension agents (people and infrastructure designed to synthesise and disseminate scientific information to agricultural practitioners; Pham *et al*., 2021).

According to (Jordan, 2016) industrial agriculture's objectives and environmental preservation are mutually incompatible. In order to maximize output while preventing agricultural degradation, energy subsidies are needed. For instance, successional species (weeds) might supplant the crop in the absence of pesticides or the organic alternative (E.D Schneider and Kay, 1994). An economic model of short-term efficiency, i.e. money in/ money out, is ill equipped to consider the environmental fallout of pseudo natural systems like agriculture. Instead, a favourable management, is one that increases endosomatically derived feedback and in turn the exosomatic energy use efficiency (Figure 8; Jordan, 2016). Recently the Food and Agricultural Organisation (FAO) published a substantial paper on agricultural thermodynamics (Ferri and Arnés García, 2023), bringing it in to the light of the public eye. 'Nature positive' proposes three most critical structures, in accordance with three main features and ecosystem components affecting productivity, which is embedded into the endosomatic feedback (Figure 8).

Above-ground and below-ground biomass for energy storage *- More biomass means more energy units available within the system.*

Soil biota, soil fertility and trophic levels for energy mobilization *- A rich soil and longer food chains ensure more efficient recycling and longer residence time within the system for each energy unit.*

Landscape diversity and biodiversity for systemic complexity *- Diversity of habitats, species and gene pools increase.*

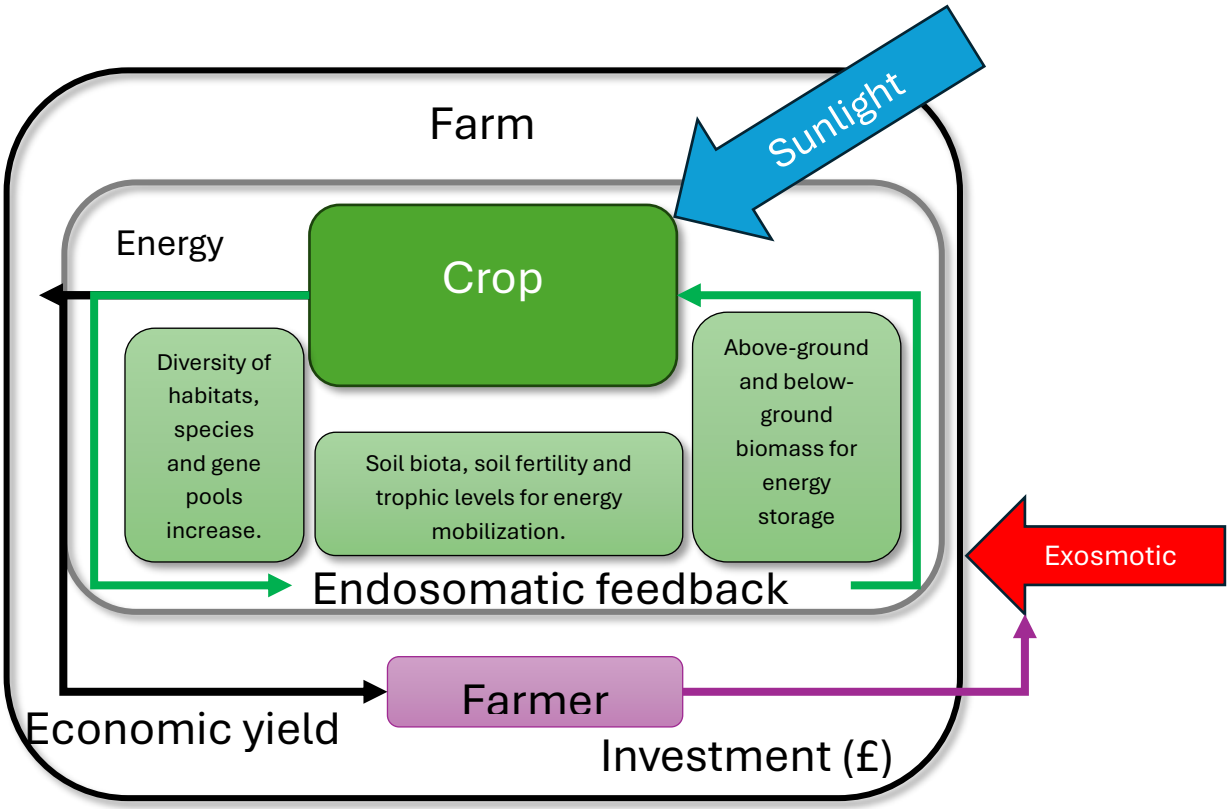


Figure 8 - A thermodynamic model of a farm. Farmers extract crops from the system (Energy out), for financial gain (Economic yield), investing a proportion of this (Investment (£) in to energy subsidies (Exosomatic energy). However, soil functioning is dependant on a positive feedback loop linking to soil communities (endosomatic energy), possible through the three main components affecting productivity. Source: Adapted from, Jordan (2016) and Ferri and Arnés García (2023)

3.3 Toward a thermodynamic approach to ecological assessment

Lotka, (1922, 1925) stated that natural selection will operate to increase total mass, increase circulation of matter and increase energy flux through the system; so far as compatible with the constraints to which the system is subject. This is the golden thread anchoring thermodynamic theories of ecological function. The maximum power principle (MPP), which states that effective systems are those that maximize the flow of usable energy (Figure 9), served as the foundation for (Lotka, 1922, 1925) research. A theory that Odum employed to explain a great deal of the architecture and functions of eco-systems (Odum and Pinkerton, 1955).

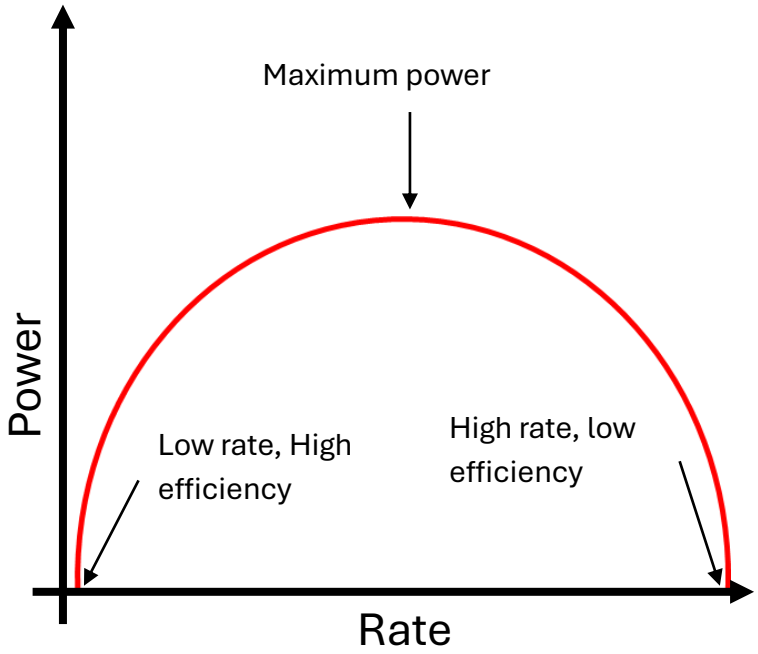


Figure 9 - The maximum power principle, there is a trade-off between high power and rate, which means the extremely efficient systems would run infinitely slowly.

Much earlier Boltzmann (1905) had observed that life is a fight for free energy that may be used for labor. Similarly, Schrödinger, (1944) pointed out that organization is maintained by extracting order from the environment. A consistency among these statements and the MPP is that successful eco-systems are ones that can gain the most free energy under the given conditions, e.g. move away from TE. Lotka, (1922, 1925) and those that followed made invaluable contributions to the development of modern ecological theory, however, the insights remained largely descriptive. That is until Schneider and Kay (1994) put forth a model of ecosystem growth, that could bring ecological theory in to the realms of predictive science, founded on the most basic

principles of physics. Survival of the fittest shapes ecosystem structure and function, with the fittest species being those that achieve a balance between channeling energy in to their own production and reproduction, as well as contributing to autocatalytic processes (chapter 2), that increase the total dissipation of the eco-system, as a whole (E.D Schneider and Kay, 1994). In essence, ecosystems choose development paths that systematically increase their ability to degrade the incoming solar energy (E.D Schneider and Kay, 1994), this is evidenced by movement away from TE. As such a healthy system configures itself to this limitation, which must be reflected in any development of a thermodynamic indicator suite.

In his book *Maximum Power: The ideas and applications of H. T. Odum,* O'Neill and Hall (1996) use some real-life examples of how MPP works. The principle recognizes a tradeoff between a high rate and high efficiency that yields most useful energy or work. O'Neill and Hall (1996) use a seminatural experiment to illustrate this. Streams were stocked with different levels of predatory cut-throat trout and it was deduced that maximum production occurred at intermediate stocking rates. At a low predator density, an abundance of invertebrate food meant the fish used relatively little maintenance energy on the hunt, where as in high densities, food was less available and the fish had to use more energy searching. In another example O'Neill and Hall (1996) mention how leaf area index, can be predicted from the MPP applied to net energy from Photosynthesis, where deciduous forests and wet climates tend to have a leaf area index of about $6m/m^2$. This is because higher leaf area index produces more photosynthate, less efficiently, due to the higher metabolic demand of the extra leaves, whereas lower leaf area indexes are more efficient but draw less power. Furthermore, this concept applies to the basis of all thermodynamic enquiry, the Carnot engine, well known for its application to modern physics. High efficiency is of course possible, but the engine would run infinitely slowly, and mankind would have much more use for a machine that is less efficient but delivers a lot more power. These examples display just how embedded MPP is in the irreversibility of the universe. High efficiency can be achieved through endoreversible processes (internally reversible and externally irreversible), however, they operate far too slowly and increasing the rate increases the irreversibility which must decrease the efficiency (Hoffmann, 2008; Nielsen *et al*., 2019)

Odum later revised the MPP, replacing power with Emergy, stating Emergy is the available energy of one kind previously used up directly and indirectly to a service or product" (Odum, 1995). Total flow of Emergy is its 'empower' and can be regarded as the work required for maintaining an eco-system's steady state. System configurations that maximize empower will inevitably prevail (Odum, 1995). What started with Lotka (1922) had now evolved into one of the first quantifiable indices of eco-system function, derived from thermodynamics (Nielsen *et al*., 2019). Empower calculates the solar cost to obtain a unit of biomass, accounting for the quality of the energy by measuring the path that was taken to reach a certain configuration (Odum, 1995). It measures the flow of energy and is calculated by first identifying all energy inputs (solar, wind, water, chemical enery, etc). converting them in to emergy units, using conversion factors known as transformities. The sum of all emergy calculations is the Empower and equates to the level of reliance on renewable energies, a positve figure in favor of a more efficient ecosystem (Odum, 1969, 1995).

As the application of thermodynamics in ecological assessment became more evident, multidisciplinary researchers began integrating thermodynamic principles from physics with ecological theory. A key realization was that ecosystems maintain a steady state far from equilibrium by working against gradients (Müller 1998). The formation of such gradients distinguishes classical from non-equilibrium thermodynamic systems, and life utilizes these gradients to perform work. Müller (1998) introduced the gradient concept, rooted in the non-equilibrium thermodynamic principle, supported by empirical evidence from a study in Northern Germany. He proposed that ecosystem function is defined by the dynamics of these gradients, despite many theoretical hypotheses relying on non-measurable variables.

Another important consideration here is that non-equilibrium systems require openness. The definition of an open system is that it exchanges energy, information and mass with its environment, compared to an isolated system that exchanges nothing (Nielsen *et al*., 2019). Isolated systems would eventually die, they would reach a maximum entropy event in which they are in TE with their surroundings (Nielsen *et al*., 2019). What more, an open system like an ecological one is only kept alive by a continual in flow of energy (Nielsen *et al*., 2019). Due to the irreversible process of dissipation, energy is always degraded in to heat and matter is always spread out in the universe, hence why entropy always increases in accordance with the second law

of thermodynamics. What is interesting is that the same flow of energy can both evolve a beautiful garden or turn it in to a crater, the big difference is in one case entropy decreases and in the other it increases, respectively. This is the truly wonderous feature of biological and ecological systems, is how they use energy flows to create organization and structure (chapter 2).

It is the basis of Lovelock and Margulis (1974); Lovelock (1995) Gaia hypothesis, where in a closed system (like the universe perhaps), the second law dictates that Entropy is always increasing, however, living matter evades decaying to TE (a maximum entropy event) by investing in negative entropy (Schrödinger, 1944; Figure 10). Lovelock and Margulis, (1974), presented a CoEvolutionary concept not unlike the Aphid example in Chapter 2 (Gatti *et al*., 2018), where life and environment evolve in a coupled way and the Homeostatic concept, where life maintains the stability of the planet and enables life to exist and more importantly evolve. This is of particular importance when reflecting upon the declining biodiversity, habit destruction and soil degradation.

Because entropy production is an irreversible process, entropy has an energy term plus a time term. Energy and mass are reversible and have no temporal constraints. Entropy reveals the direction of events, the arrow of time (Blum, 1951). The dead Dear Analogy (Figure 10) represents the asymmetry of living systems, from the moment after the dear takes its last breath, the energetics of the organism shift from its steady state, toward TE (Tiezzi *et al*., 2007). Energy and mass stay the same (law of conservation), however entropy increases, and information is lost. Entropy can change irrespective of energy and mass, seen in many naturally occurring phenomena in the universe, not only that, but it also inevitably increases. Life demonstrates the intrinsic evolutionary characteristic of entropy and the fate of the universe (Henry and Schwartz, 2019). Entropy has the broken time symmetry (Blum, 1951), necessary to sustain the directionality of eco-systems (chapter 2). What the dead dear analogy illustrates, is that classical thermodynamics breaks down far from equilibrium systems and a redefining of entropy and other energy terms is required, for non-equilibrium thermodynamics.

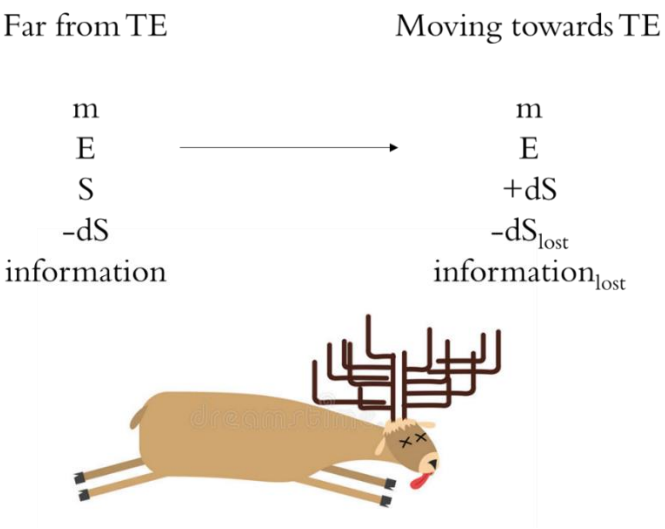


Figure 10 - Dead deer analogy. m = mass, E = energy, S = entropy, -dS = negative entropy. Following death mass and energy stay the same but entropy increases, negative entropy is lost and information is lost. Source: (Tiezzi et al, 2007)

3.4 The dimensions of energy flow.

The second law of thermodynamics is crucial in understanding the development of self-organizing systems, as observed by Prigogine and his colleagues (Prigogine *et al*., 1972; Prigogine and Nicolis, 1977, 1985; Nicolis and Prigogine, 1989). However, application of thermodynamics to complex system behavior, requires a full comprehension of current thinking in non-equilibrium thermodynamics (Kay and Schneider, 1992). The key difference of non-equilibrium systems is that at steady states they can reduce their structural entropy, in fact it is a prerequisite for life. Prigogine (1955) pointed out that open systems could create order and decrease entropy, by dissipating energy to their surroundings (Prigogine, 1967; See definition of thermodynamically open and ontologically open above and in chapter 2 respectively). In the natural world, a reduction in structural entropy is more than matched by an increase from other processes. Closed systems, as they plunge to equilibrium, exhibit only transient oscillations (like the Belousov- Zhabotinsky reactions; Chapter 2). The sustained oscillations required for life demand openness, coupled to a continuous flow of new reagents and removal of waste products (entropy; Epstein *et al*., 2006).

An ecosystem will choose growth pathways that most consistently promote a deviation from TE. The mechanisms of this are synthesized in three growth forms: Biomass, Information and Networks; a distillation of Von Bertalanffy and Odum's attributes for

ecosystem development and Constanza's six descriptors of ecosystem health (Jørgensen, 2006b). All are reflected in a single measure '**Eco-Exergy'**. This metric captures the abundance and diversity of biomass as a divergence from TE.

If numerous development routes are available from a given starting state, those yielding highest exergy storage are more likely to occur, because these demand the most energy dissipation to construct and sustain, consistent with the second law (Jørgensen *et al*., 2000). The autocatalytic assembly (Chapter 2) acts as a center on which to centripetally concentrate increasing quantities of exergy that the system absorbs into itself (Ulanowicz, 2000; Jørgensen, 2002). Energy storage alone is insufficient, but the increase in specific exergy, or exergy/energy ratios, that indicates improved usability, reflects an increasing ability to perform work (Jørgensen *et al*., 2000).

Exergy was first defined by Zoran Rant in 1956, an idea already developed by J. Williard Gibbs in 1873 (Gibbs, 1948), however it was Jørgensen and Svirezhev (2004) who provided a concise explanation (Vihervaara *et al*., 2019). The contributions of Jørgensen and his co-workers on the establishment of eco-exergy models is highly regarded (Jørgensen, 1992; Jørgensen *et al*., 1995, 2005; Marques and Jørgensen, 2002; Marchi *et al*., 2011; Wu *et al*., 2017). Eco-exergy has been successful as a thermodynamic variable in the assessment of eco-system health (Jørgensen, 1995; Zhang *et al*., 2010; Xu *et al*., 2011; Tang *et al*., 2015) for various ecosystem types (Jørgensen, 2010; Zhang *et al*., 2010; Draganovic *et al*., 2013; Molozzi *et al*., 2013; Puzachenko *et al*., 2016), including agricultural systems (Chen *et al*., 2009; Zhang *et al*., 2019; Amiri *et al*., 2020; J. Wang *et al*., 2021; Valero *et al*., 2022).

More recently, The FAO brought to light a number of methodologies for ecosystem health and sustainability assessment in agriculture (Ferri and Arnés García, 2023), in reference to material and energy flows, or *Energy return on investment* (EROI). It reflects the capacity of the system to generate rather than consume energy, ranked by efficiency. The basic EROI indicators interestingly do not account for the solar energy intake from primary producers, taking the standpoint that the sun is a given environmental factor. As such inclusion of an indicator for photosynthetic production is suggested, that can be measured through remote sensing. The net primary

production, which when divided by the EROI can indicate the amount of energy units fixed into new biomass per unit of total input by farmers.

Both Emergy (empower) (Odum, 1995) and Eco-exergy Jørgensen, 1992) are long established tools used to help explain energy and matter flows (Bastianoni and Marchettini, 1997; Sciubba and Ulgiati, 2005; Bastianoni, 2008; Buonocore *et al*., 2020, 2021; Grande *et al*., 2023). Also, EROI has been proposed as the most suitable indicator to assess ecosystem recovery activities in farm landscapes (Ferri and Arnés García, 2023). However, they lack a certain practicality which maybe holds back their effective uptake. Calculations of energy terms such as Eco-exergy and Emergy will never be exact, as it is not possible to measure the concentrations or determine all possible contributions to it. Eco-systems are far too complex to discern every detail (Sven E. Jørgensen and Nielsen, 2007) or to grasp the contribution of all the elements (Jørgensen *et al*., 2000). EROI requires thorough data collection and processing, there may be challenges in accounting for human labour, energy for machineries, fuel and other energy inputs and a risk of double counting energy flows. In addition, these indicators also tend to have more application to sustainability, in the context of renewable energies, rather than ecological health. Although valuable in the assesment of ecosytem growth due to interrelationship with energy flow, Emergy is burdened with a number of rather important limtations too. Such as, subjectivity in transformities, challeges in accounting all inputs (Odum, 1969, 1995), lack of consideration of transience in ecosystems that are in a constant state of flux (Ulgiati and Brown, 2009). That said, although exergy seems well equipped for ecosystem diagnostics, the fundamental issue here is that it cannot be measured directly (Nielsen *et al*., 2020). Application of thermodynamics to assessing agroecological intervention would benefit from the development of metrics that could serve as a proxies for energy and material flow.

3.5 Conclusions

Traditional soil indicators are ill equipped to encompass the complex dynamical nature of ecological systems and a new framework for soil assessment is required. Ecological thermodynamics has found itself as one of the foundational columns in systems ecology (Jørgensen, 1992; Jørgensen *et al*., 1995, 2005; Marques and Jørgensen, 2002; Marchi *et al*., 2011; Wu *et al*., 2017) and agricultural systems like ecological systems are emphatically thermodynamic. What makes thermodynamic

indicators distinct from conventional metrics, is they are concerned not with static quantities of components, but with flows of energy and material. A framework rooted in thermodynamics shows promise and the efficacy of thermodynamic indicators is quite robust, in particular the well evidenced application of Eco-exergy to a variety of eco-systems including agriculture. Exergy is both qualitative and quantitative of a system's flow of energy. On one hand, it refers to the quality of the energy and declines as it is utilized in processes. On the other, it measures the distance from TE, that the system is in reference to its surroundings (Sven E. Jørgensen and Nielsen, 2007; González *et al*., 2023). Features that give eco-exergy great credence as a holistic measure of eco-system development (Jørgensen, 2006b). However, supported by Nielsen *et al*., (2020) the author argues that direct measurements of energy terms are not possible and will always require estimates of the systems variables. Many indicators require complex calculations, using estimates of energy flows. What is outlined in the proceeding chapters is the exploration into novel indicators that may serve as proxies of energy and matter flow.

4 Application of temperature to asses structure and function of agro-ecological soils.

4.1 Introduction

4.1.1 The loss of soil structure and function in the Anthropocene

The Anthropocene is regarded as a period of significant ecological simplification, defined as a loss of landscape complexity and ecological integrity (Peipoch *et al*., 2015). The resultant reduction of plant species diversity leaves the soil exposed to erosion and other forms of degradation, especially on already vulnerable land such as sloped ground (Berendse *et al*., 2015). With the expansion of anthropogenic developments (Ramankutty and Foley, 1999) and through misuse of the land, 24 billion tonnes of fertile soil is lost every year worldwide (Bartz *et al*., 2015). The global annual loss of topsoil is approximately twice that of formation (Verheijen *et al*., 2009; Borrelli *et al*., 2017). One hectare of soil provides habitat for 15 tonnes of organisms, or 1.5 kilograms of biomass per square metre (Bartz *et al*., 2015), distributed in the biomass of millions, if not billions of individuals. Therefore, soil loss undoubtedly impacts species global biodiversity (Pimentel, 2006). This in turn can impact fundamental processes such as nutrient cycling (Naiman *et al*., 2005; Hatten and Liles, 2019), microbial activity (Weil and Brady, 2017) and plant productivity (Hatten and Liles, 2019).

This isn't to say that degradation is not a natural phenomena (Gunderson and Pritchard, 2012). On the contrary, disturbance is woven into the evolution of the planet. The cyclical and adaptive processes of collapse and reorganization drive evolutionary jumps (Cazzolla Gatti's *et al*., 2018). Collapse is a necessary process. Following collapse, eco-systems shift from high biomass building early stages, through to high efficiency mature stages. However, large enough disturbances (fire, volcanic eruptions or heavy storms) can revert the system to an earlier stage of development, causing the loss of ecological niches (Gunderson and Holling, 2001). Stages of growth (Fath *et al*., 2004) do not necessarily follow a linear trajectory and while individual organisms may appear to have a linear growth direction, from birth to death (dead deer analogy; chapter 3), ecosystems themselves tend to stabilize at dynamical states (chapter 2).

Agroecosystems can be held in an early stage of development, with low biodiversity, due to the continuous removal of biomass (Ferri and Arnés García, 2023) and sterilization of the soil. Whether a single pulse disturbance or gradual multiple press disturbances; agricultural soils can be held in to highly depleted conditions known as a poverty trap, or a state of artificial resilience, where the system is no longer self-organised and high performance cultivars rely on fertilizers and other inputs; known as a rigidity trap (Gunderson and Holling, 2003; Ludwig *et al*., 2018). Through a loss of structure and function, poor resilience impairs agricultural system's ability to reorganise (Gunderson and Holling, 2001; Aoki, 2012) ultimately impacting on their delivery of services to support human wellbeing (Johnson *et al*., 2017). However, it is believed that holistic agricultural practices, such as the use of cover crops and low tillage that minimizes disturbance, can maintain at an intermediate stage of growth with the potential to increase energy cycling in the form of biomass (Ferri and Arnés García, 2023).

4.1.2 Unique and functional ecosystems

It is important to draw attention to the uniqueness of species and landscapes (Elsasser, 1981, 1982; Henning and Scarfe, 2013). The more unique and heterogenous an assemblage of species is, the more likely autocatalysis (chapter 2) will occur (Kauffman, 1986; Ulanowicz, 2019) and the greater the exergy storage (Chapter 3). Each organism has its role for the period it exists, the species however, plays a bigger evolutionary role, spanning multiple lifetimes. Species exhibit functional traits, which are characteristics (either physiological, phenological or morphological) that influence growth and development (Violle *et al*., 2007; Lueder *et al*., 2022). They fall into a spectrum along three axis in what (Grime and Pierce, 2012) coined as Universal Adaptive Strategy Theory or CSR models, referring to Competitive, specialized and ruderal traits, respectively (Figure 11). Ruderal plants tend to be annuals, with an investment into genetic adaptations (genotypic plasticity; seeds) over generations, whereas competitive species have more phenotypic plasticity and can change their structure dependent upon environmental conditions. Specialized species tend to live in very harsh environments and have specialized adaptations to survive. Traits are expressed in numerous ways, such as specific leaf area, leaf nitrogen content, etc. Agricultural succession tends to be dominated by ruderal 'weeds' due to the high disturbance and high stress environment (Figure 11), unless in the case of

low intensity agriculture, where it is likely that more competitive or specialized species are able to establish.

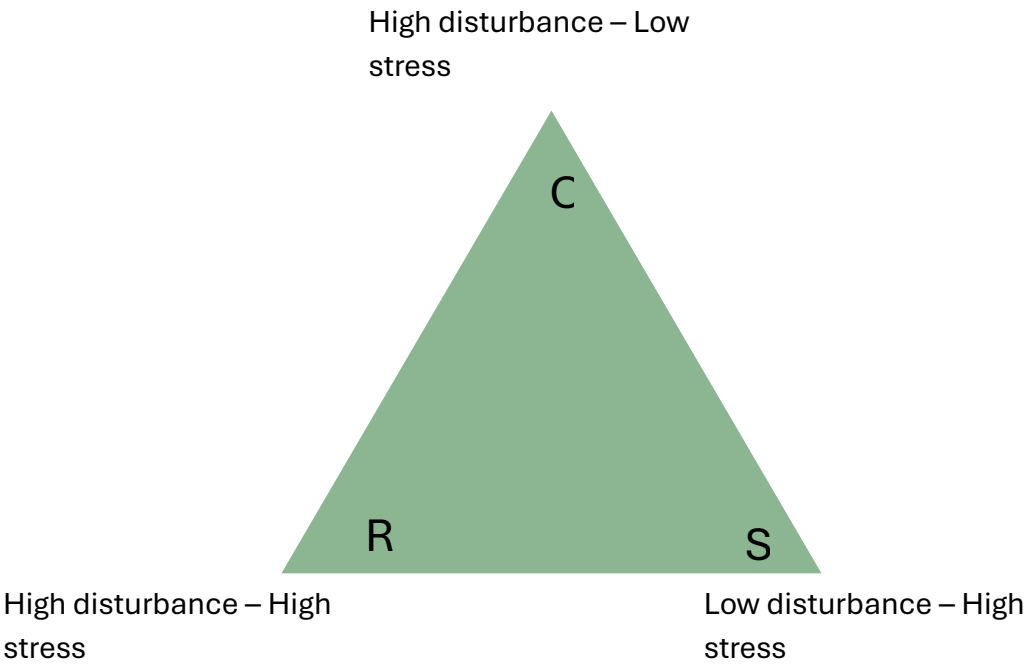


Figure 11 – Grimes CSR model. A tri axis of species traits, evolved through adaptation to stress and disturbance. The framework is built around the 3 main environmental pressures that plants face: Competition for resources, stress from harsh environmental conditions and disturbance events that damage or destroy biomass. The three primary plants strategies according to Grime and Pierce (2012), are competitors (C), who are adapted to low stress low disturbance environments, their strategy to maximize resource acquisition. Stress tolerators (S), are adapted to high stress low disturbance environments, tending to be slow growing, long lived and capable of surviving with limited resources. Ruderals (R) are adapted to low stress and high disturbance conditions and invest in rapid growth, with high seed production and short life cycles.

The enormous variety of organisms in the soil, through their moving and feeding activities, influence multiple soil processes such as the aggregate stability (Rillig an d Mummey, 2006) and the infiltration of water (Wall *et al*., 2015), playing a significant role in soil structure and function (Orgiazzi and Panagos, 2018). Through typical feedback processes, vegetation and soils develop together (Chapin *et al*., 1998; Hooper *et al*., 2000; Ehrenfeld *et al*., 2005; Bardgett and van der Putten, 2014). A micro-topography of mounds in vegetated and unvegetated patches can develop throughout landscapes (similar to fairy circles in Chapter 2) resulting from an array of mechanisms that shift soil particles and transform the soil matrix (Barth and Klemmedson, 1978; Sanchez and Puigdefabregas, 1994; Martinez-Turanzas *et al*., 1997). Like in fertility islands (Chapter 2), the centripetal vortex, created through mutual interaction draws in resources (Ulanowicz, 1999, 2006, 2016). Then in the

absence of feedback loops, predominantly following plant death, the fertility diminishes (Tiedemann and Klemmedson, 1986; Butterfield and Briggs, 2009). Remove the phytomass (biomass generated from photosynthesis) and the micro-system breaks down. Evidence of the requirement of effective energy dissipation pathways to sustain a complex system. A product of CSR is that species richness and spatial heterogeneity, tend to fall within conditions at intermediate stress levels, for example, how both high and low level halophytes coexist at intermediate salinity levels (Chen *et al*., 2015).

4.1.3 Applying thermodynamics to soil health in agriculture

Soil health is deeply intertwined with ecological thermodynamics, as both involve the flow and transformation of energy and matter within ecosystems. Life on Earth advances through the necessity to maximize the dissipation of solar energy and convert in to exergy (chapter 3; Jørgensen *et al*., 2000). Biodiversity and the complexity of species interactions are a manifestation of the investment in to eco-exergy, identified through the three growth forms; biomass, information and networks (BIN; see chapter 3; Jørgensen, 2006, 2008a). Following maintenance and growth, any remaining usable energy is utilized to move the system away from equilibrium, evidenced by BIN (E. D. Schneider and Kay, 1994; Fath *et al*., 2004; Jørgensen and Fath, 2004; Jørgensen, 2006a; Schick, Porembski, Peter R. Hobson, *et al*., 2019). Furthermore, following a non-equilibrium thermodynamic view of natural systems and due to their inherently open character, growth and development is only possible through a continual flow of energy to and from surroundings (Chapter 3; Boltzmann, 1905; Schneider and Kay, 1995; Vihervaara *et al*., 2019).

About the time that Darwin was compiling his theory of evolution (Darwin, 2003 (1859)), Boltzmann the physicist, took a keen interest in the second law of thermodynamics, under which natural systems in the universe inevitably decay in to complete disorder, seeking an equilibrium (Chapter 3; Boltzmann, 1905; Schneider and Kay, 1995; Vihervaara *et al*., 2019). Boltzmann realised on the other hand, that what Darwin proposed was quite the opposite, living systems form organised structures, with complexity and specialisation, that brings order from chaos, moving away from TE (Boltzmann, 1905; Schneider and Kay, 1995; Vihervaara *et al*., 2019). Natural systems reduce their structural entropy, exporting it to surroundings to create order (Chapter 3; (Lotka, 1922; Schrödinger, 1944; Prigogine and Nicolis, 1985;

Martyushev and Seleznev, 2006; Henry and Schwartz, 2019). They form dissipative structures, accumulating highly complex organic compounds to store energy (Eco-exergy) and dumping entropy, as low complexity biomass (Ferri and Arnés García, 2023). In photosynthesis plants absorb low entropy photons (see chapter 6) and emit radiation at a lower temperature, then most animals feed on the lower entropy matter they have built, producing higher entropy waste (Epstein *et al*., 2006; Virgo and Harvey, 2007). Schrödinger (1944) described this as “feeding on negative entropy” in the environment (Virgo and Harvey, 2007).

Exergy informs us of the complexity of an eco-system in relation to its energy stored in organic matter (OM) and genetic information (Vihervaara *et al*., 2019). Complexity follows a successive trajectory (Figure 12) and reflects the increase in 3 separate variables related to heterogeneity; number of components, number of connections and emergent properties (Bullock *et al*., 2022). Specific exergy increases throughout the succession however the growth forms themselves can be distinguished in stages (Fath *et al*., 2004). Structure dominates early stages of growth (biomass). In middle stages, energy throughflow increases between components and boundary, indicating informational advancement (information). In maturity, internal cycling in complex networks typically dominates and specific dissipation decrease, indicating advanced organization (networks), see Figure 12. During a collapse, declines in energetic states like energy storage, entropy production, specific dissipation, and specific exergy, reflect an ecosystem returning toward equilibrium (Jørgensen *et al*., 2000). As in the dead dear analogy (Chapter 3).

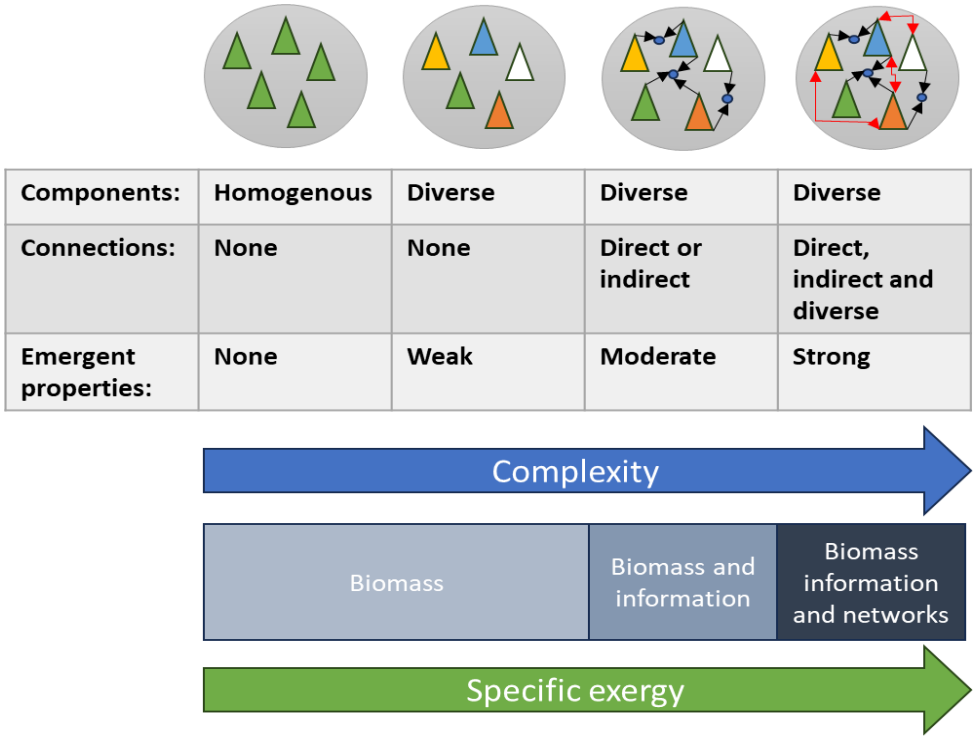


Figure 12 – The increase in number of components, number of connections and emergent properties increases with complexity. This succession is mirrored in the increase of specific exergy and the 3 components of eco exergy (biomass information and networks) emerge separately in stages. Source: Adapted from Bullock et al., (2022) and Fath et al., (2004)

Plant-soil development of a given area reflects the trajectory of complexity and exergy (Figure 12). Within the constraints of the local environment diverse environmental conditions give rise to diverse communities. Exergy losses from various biological processes like photosynthesis, microbial activity, and nutrient cycling, are often linked with inefficiencies in these processes (Bararzadeh Ledari *et al*., 2020). In soil ecosystems, microbial diversity and network complexity are crucial for sustaining ecological functions and supporting the stability of the soil-plant system (Griffiths and Philippot, 2013; Chen *et al*., 2023). As environmental factors affect soil microbial interactions, the complexity of these networks can influence the system's response to changes in biodiversity or external stressors, such as climate shifts or land-use changes (Chen *et al*., 2023).

According to Jørgensen and Mejer, (1977), the amount of exergy conserved among ecosystem components can indicate the directionality of succession. They predicted that as ecosystems age, they collect more stored exergy, which may be measured by studying species biomass densities, chemical potentials, and genetic diversity

(Jørgensen, 2006a; Jørgensen *et al*., 2007). In fact, exergy has been found to quite accurately quantify changes in structure and function, capturing coherent structural changes in biological communities (Molozzi *et al*., 2013) and has been valuable in informing the health of ecosystems (Jørgensen, 1995; Zhang *et al*., 2010; Xu *et al*., 2011; Tang *et al*., 2015). However, due to the structurally complicated and unknown thermodynamic properties of biomass (Qian *et al*., 2017), the total eco-exergy cannot be measured directly (Nielsen *et al*., 2020), approximations are needed, not all the components of life processes are known and more often than not a simplification of the eco-system is used (Doty, 2021). Exergy calculations often assume that the system is in a static condition, that the inflow and outflows are balanced over time, simplifying the calculations and measuring as if the system components remain constant (Odum, 1969). Temperature and pressure figures are often set at ambient conditions and considering the inherent fluctuations of these factors, it can make Exergy calculations unmanageable (S. E. Jørgensen and Nielsen, 2007). Furthermore, as this thesis has explained in detail, ecological systems are emphatically non-linear and these processes are often linearized, for practical purposes, introducing approximations (Jørgensen and Fath, 2004). This has driven the quest for effective proxies of exergy, rooted in thermodynamics. Of particular interest is temperature.

Radiant, thermal and latent energy exchange processes primarily take place at the surface and vary soil temperature responses, the effects of which propagate through the soil profile, at rates affected by soil physical properties (Hillel, 2003). These include, bulk density, texture, structure, water content, etc and affect thermal properties such as specific heat capacity, thermal diffusivity and thermal conductivity (Van Wijk and De Vries, 1963; Al-Kaisi *et al*., 2017). Table 1 displays the average thermal properties for two soil fractions as well as moisture properties. Clay particles tend to have a higher thermal conductivity than sand particles alongside their ability to hold moisture (Abu-Hamdeh, 2003). Wet clay soils respond better than dry sands due to the structure and moisture retention. Soil temperatures are determined by transport processes of heat and exchange with atmosphere. This is through either convection, conduction or radiation (Koorevaar *et al*., 1983). Convection with phase change can increase heat transfer, especially for water which has very high values for latent heat

(Koorevaar *et al*., 1983). In addition, the evaporative process of moisture from the soil is known to follow three distinct stages. Going from a relatively high rate in stage 1, followed by a lower rate in stage two and a very low rate in stage 3 (Han and Zhou, 2013). Evaporation rates are high for a wet soil, but a dry soil layer (a crust) forms in later stages that limits diffusivity and slows evaporation (Lehmann, 2023).

Table 1 – Thermal properties of two soil fractions, sand and clay. Clay has a reduced thermal conductivity, however, has the same volumetric wetness and volumetric heat capacity compared to sand. Source: (van Wijk and de Vries, 1963).

Soil Type	**Porosity**	**Volumetric Wetness ($cm^3\ cm^{-3}$)**	**Thermal Conductivity (10^{-3} cal $cm^{-1}\ s^{-1}\ deg^{-1}$)**	**Volumetric Heat Capacity (cal $cm^{-1}\ s^{-1}\ deg^{-1}$)**
Sand	0.4	0.0	0.7	0.3
	0.4	0.2	4.2	0.5
	0.4	0.4	5.2	0.7
Clay	0.4	0.0	0.6	0.3
	0.4	0.2	2.8	0.5
	0.4	0.4	3.8	0.7

Plants respond to abiotic changes, such as extreme events and the sum of changes constitutes the eco-system's thermodynamic function. Through evapotranspiration, plants remove the heat of dissipated photons and convert it into latent heat. Much of the free energy dissipated by plants is constituted by photon dissipation and transpiration, and can be measured by micro-climate (Norris *et al*., 2012; Michaelian, 2015; Avelar *et al*., 2020). In the case of soils, dynamics of free energy dissipation, heat flux and latent heat is similarly controlled, primarily by moisture content (Abu-Hamdeh, 2003), as water has a greater specific heat (Howe and Smith, 2021; later discussed in chapter 5). Water and heat flows are interactive and the moisture potential, alongside the movement of liquid and vapour are affected by temperature gradients (McInnes, 2002; Al-Kaisi *et al*., 2017). Moisture in the upper living layers of the soil affects energy fluxes at the interface between land and atmosphere

(Srivastava *et al*., 2013; Chaube *et al*., 2019; Suman *et al*., 2020) directly impacting the flow of energy through the system. Water is a primary limiting factor to crucial energetic transformations such as in photosynthesis (Green *et al*., 2019; Y. Zhang *et al*., 2020; Hu *et al*., 2023; Peng *et al*., 2024) and microbial mediated nutrient cycling (Bauke *et al*., 2022; Lv *et al*., 2023). As such, soil moisture is a key variable in exploring temperature as a proxy for exergy.

Soil temperature is further influenced by ground cover and habitat type (Howe and Smith, 2021), affecting the reflectance of incident shortwave radiation (Chapin *et al*., 2002; Santos *et al*., 2019). In the case of agricultural systems, the higher surface albedo from lower vegetation will have the effect of increasing warming compared to highly vegetated habitats. This is well documented (van Wijk *et al*., 1959; Lal, 1974; Jiménez *et al*., 2007; Savva *et al*., 2010; Santos *et al*., 2019). Previous studies that have made connection between ecosystem structure and temperature, mainly focus on the positive impact that biodiversity has on micro-climate (Jiménez-Gutiérrez *et al*., 2021; Maillard *et al*., 2022; Vopravil *et al*., 2022). However little research makes the connection with ecological structure and function and the use of temperature as an indicator of structure and function.

In a thermodynamic model of soil structure and function, species form interactions with other system components (Autocatalysis; Ulanowicz' (1997; 2009; chapter 2), that impact on the dissipation of energy through the system. For example, nodulation on legumes, enabling the more efficient uptake of nutrients in exchange for carbon. Systems effectively select pathways with the least resistance, pruning the flows (Ulanowicz, 1999; Jørgensen *et al*., 2007) in favor of interactions that better move away from TE (Chapter 3; Boltzmann, 1905; Schneider and Kay, 1995; Vihervaara *et al*., 2019). What more, species unique traits (Grimes CSR) enable specialization and the fulfillment of niches to maximize the dissipation of solar radiation (Jørgensen *et al*., 2000). Any energy that cannot be converted to exergy, is lost as heat to the environment, at the temperature of the environment (Jørgensen, 2008b). Which presents the case for temperature as a proxy indicator of exergy and so soil health.

This principle has been applied in studies on forest ecosystems to test for differences in thermodynamic function between old growth and new plantations (E. D. Schneider and Kay, 1994; Norris *et al*., 2012; Avelar *et al*., 2020). More impressively, is the

inclusion of thermal imaging and satellite data to conclude the correlation between NDVI and TIR (Avelar *et al*., 2020). Avelar *et al*., (2020) made a valuable contribution to the field, utilizing satellite imagery to detect thermal differences between natural and human induced disturbance. Agricultural systems, through there intensive management, abate effective energy dissipation (Jørgensen *et al*., 2000) and alter the thermodynamic signature. This and along with many other studies, fundamentally highlights how structure and function can affect local abiotic habitat conditions (Norris *et al*., 2012; Aalto *et al*., 2013), as well as how new technologies such as satellite imagery can improve rapid assessment of eco-system health (Avelar *et al*., 2020; Xu *et al*., 2020). These studies have focused on surface temperature and research is yet to investigate this in the soil, especially in an agricultural setting. The soil is inherently complex, with tightly coupled physical, chemical and biological processes that often behave in nonlinear, counterintuitive ways, and must be better understood if scientists aim to progress on issues of sustainable land management (Turner, 2021).

The hypothesis of this study is that, through the development of structure and function and coupled progression of complexity, soil has increasing rates of entropy production and greater exergy storage leading to lower and attenuated temperatures (Figure 13); (Ulanowicz, 1997; Jørgensen and Fath, 2004; Ulanowicz, 2009c; Norris *et al*., 2012; Molozzi *et al*., 2013; Michaelian, 2015; Avelar *et al*., 2020).

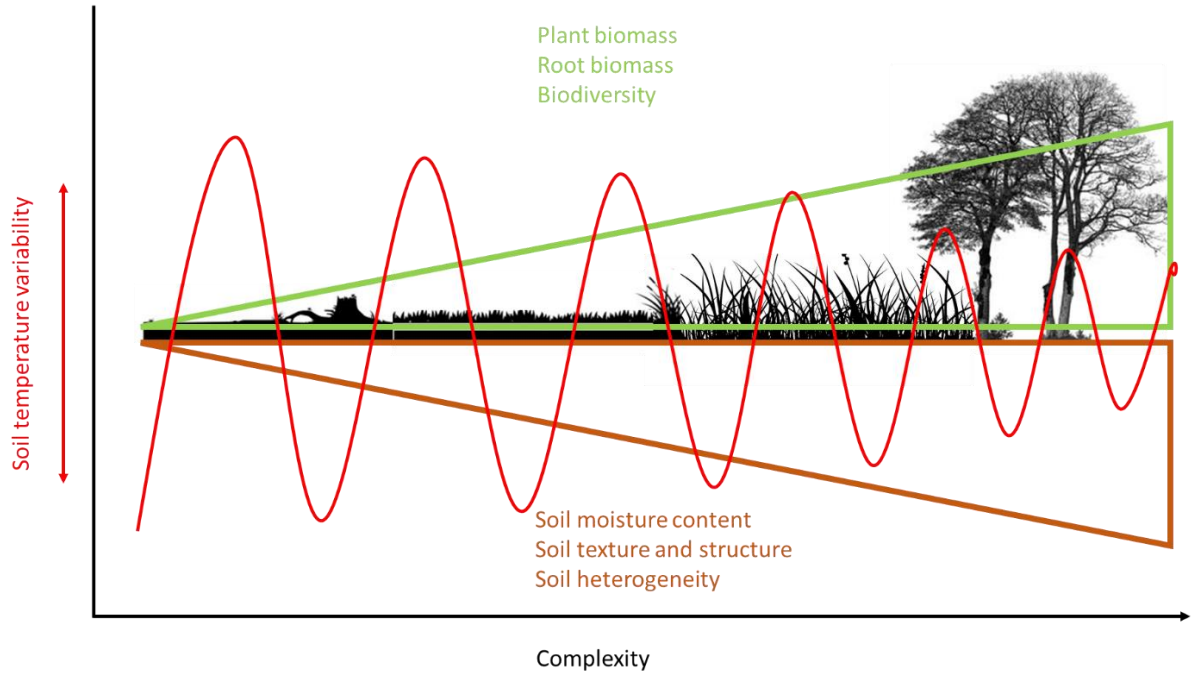


Figure 13 - Model of complexity against soil temperature variability. In lower complexity configurations, the above ground structures are limited and the soils structure is poor, this gives rise to a highly fluctuating temperature regime. With increasing complexity, temperature attenuation occurs. This is reflected by the improved soil structure and increased biomass, information and networks.

4.2 Methods

4.2.1 Experimental design

A series of experiments (EXP1, EXP2, , EXP3 and EXP4) were carried out utilizing temperature as an indicator to explore a thermodynamic approach to soil health, a summary of the experiments is presented in Table 2. The experiments were designed to represent different stages of eco-system development (Jørgensen *et al.*, 2000; Gunderson and Holling, 2001; Jørgensen and Fath, 2004). They consisted of 3 controlled environment experiments and one field trial, with a consistency among them that they all contained a bare soil example, which was later used in analysis to compare them all together. Each controlled experiment followed the same layout, with pots containing soil and different species in a randomized pattern, all attached to drippers on an irrigation system (Plate 4). These pot trials represented different degrees of early stages of development and experimentation focused on structure and function as an entry point to design. Structure was distinguished in two ways; one, the structural properties of the soil itself, as in the textural class; and two, the structure of the plant-soil system, where the addition of plants adds biological structure. Function

Plate 4 – Left - pots in glasshouse experiments laid out in a randomized pattern connected to two irrigation drippers. Right, a close up of one of the pots with plants young Brassica Nigra plants growing.

can be related to structure, in that different structural properties may influence the function of the system, but also functional traits of different plant species were included in the comparison. All experiments used a bare soil scenario as control group (later used as baseline to compare between experiments). The key differences are that

EXP1 included pure Sand and used a different soil to EXP2 and EXP3, which both used the same soil. EXP2 included more plant models and EXP 3 used the same plant but changed the soil moisture. Then finally in EXP4, removal of all plant material and high disturbance through rotivation in an established meadow served as a bare soil comparison to the undisturbed meadow.

The controlled environment trials were carried out in a glasshouse at Writtle University College. The trials were situated in the warmest compartment of the glasshouse, in the South East corner and the analysis period for the most focused on specifically the vegetative growth period (growth phase) using 5l pots that were assessed prior to the experimentation, to see if that pot size was sufficient to capture temperature differences from ambient temperatures in the glasshouse, without the influence of radial heat transfer to the surroundings. The soil was first dried and heat sterilized in an oven at 65°C for 72 hours, before being ground to 4-6mm, to allow for consisted filling of the pots and at the same time preserving the integrity of macro-aggregates (Kravchenko *et al*., 2015; Zhou *et al*., 2020). Before filling the pots, a fine woven pourous membrane was placed in the bottom of the pot to stop soil erosion form the irrigation.

After the pots were filled a set up phase followed in order to let the samples settle and test equipment, to ensure the pots were filled correctly and the experiment is functional. Drip irrigation maintained soil moisture where needed and the timing was determined during the setup phase, by slowly increasing 1 minute per day over 4-7 days, until the moisture content stabilized at moisture levels that were not too much that overwatering would occur. This was estimated at twice that of permanent wilting point (PWP) for the given soil (Ratliff *et al*., 1983) and separate irrigation lines were installed for different soils that reduced the flow rate but delivered water for the same amount of time. For information on the irrigation and other variables considered in the trials please see Table 2 - Due to the limited access to resources and a multitude of variables that were considered important. Multiple experiments were carried out in different scenarios, detailed in the table below.Table 2.

Moisture measurements were carried out using ExTech Moisture Metre, by inserting the probe in to 3 locations in the soil and averaging the 3 readings. This was carried out at the outset of the experiment and was then checked a 2nd or 3rd (see appendix).

The measurements were minimized as they were quite destructive. A visual assessment of soil was carried out regularly and in the event that plants showed signs of wilting or that soil surface was very dry, in which case, 1-2 mins were administered to recover moisture levels; this occurred on one occasion during EXP2 on the 11th MAY when MAX temperatures peaked at 5°C above the Mean for 3 consecutive days. If in the case of EXP1 (16th June) where soil moisture consistently appeared too dry, the irrigation time was increased by 1 min. Then in the event of over watering (as in EXP3 on the 4th May), where the samples all fell outside of the range of the moisture metre (0><50%), time was decreased by 1-2 min.

Following the setup phase, in pots with added plants, seeds were sown before they were thinned to the desired density (see Table 2), this marked the beginning of the experiment and when the moisture levels monitored to visually maintain at field capacity. Shading in EXP2 (Table 2) was created by placing an oversized opaque plastic cover (visible in Plate 4). This allowed air flow but fully blocked the solar radiation.

The 5th field trial was carried out in a meadow in Sussex that had been managed for grazing until 2019 where it has since been left undisturbed. This was included to represent a more intermediate stage of development that might be seen on agricultural systems. The site slopes to the North East and 5ft strips that followed the contours of the slope, visible from satellite image (Plate 5), were alternated between undisturbed and heavily rotavated and maintained for bare soil, before temperature loggers were distributed randomly across the two treatments, at 10cm and on the surface of the soil, 5 for each (n=20).

Table 2 - Due to the limited access to resources and a multitude of variables that were considered important. Multiple experiments were carried out in different scenarios, detailed in the table below.

Experiment (EXP)/ ID code	**Plant spacing**	**Plant -soil combinations**	**Soils**	**OM (%)**	**Water threshold (%)**	**Irrigation**
EXP1	Normal spacing	Bare soil (BS), Sand (S),	Black soil	>20	35-40	5 mins per day

	(5-6 plants per pot)	*Brassica Juncea* (BJ), *Trifolium incarnatum* (TI)	Sand	<0.1	5-10	
EXP2	Normal spacing (5-6 plants per pot)	*Bare soil (BS), Sub soil (Sub), Brassica Juncea* (BJ), *Trifolium incarnatum* (TI) and Shade treatment (Sh)	Tops oil	~ 4.2	20-25	5 mins per day
			Subs oil	~ 1.5	15-20	
EXP 3	Sparse - 3 plants/ pot (LD) and Normal spacing - 6 plants/ pot (HD)	*Bare soil (BS) Brassica Juncea* (BJ)	Tops oil	~ 4.2	20-25	2 mins per day. Flow rate reduced to half for reduced watering samples (R)
EXP4	None	Disturbed and Meadow	*In-situ*	None	N/A	N/A

Plate 5 - Satellite image of the field trial site (EXP4). Shows the boundary of the field and the slope. Strips are visible where the Disturbed areas were.

4.2.1.1 Drought simulation

On two occasions a drought scenario was simulated by switching off the water and desiccating the samples. The experimental setup followed EXP 2, however following the 20 days growth period the drought simulation was carried out. The reason for drought simulation was to explore the role of soil water in energy dynamics (Srivastava *et al*., 2013; Chaube *et al*., 2019; Suman *et al*., 2020;. Soil drying has a direct relationship with exergy, as it affects the availability and flow of energy within the soil-plant system, influencing biological processes and ecosystem functionality (Green *et al*., 2019; Y. Zhang *et al*., 2020; Hu *et al*., 2023; Peng *et al*., 2024; Bauke *et al*., 2022; Lv *et al*., 2023). The lack of water diminishes energy flow and storage capabilities, impacting microbial activity, plant growth, and nutrient cycling, ultimately leading to a loss of ecosystem efficiency and resilience (Chapter 3).

This was undertaken at two different times of the year (Drought1 and Drought2), which captured a broader range of seasonal variation. In Drought1 , desiccation was carried out over 4 days in May 2022, three moisture readings were taken on the first, second and fourth day of desiccation (24th, 25th and 27th May). Maximum local temperatures were 17˚C for the 24th, 18˚C for the 25th May and 19˚C for the 27th May. In Drought2 ,

desiccation was carried out over 4 days in July/August 2022. Three moisture readings were taken on the first, second and fourth day of desiccation. The hottest local temperatures were experienced on the 30th July and the 2nd August (days 1 and 3), reaching 26˚C.

4.2.2 Analysis methods

4.2.2.1 Temperature

Continuous collection of temperature data was the key measurement framework, identified as a proxy of exergy storage and energy dissipation (see above). Temperature is a measure of heat and is often discussed with association to entropy. Temperature and entropy have long had a place in describing the universe. After all everything in the universe has a temperature. Temperature is not a surrogate of entropy by any means, it can however allude to energy dissipation through its relationship to entropy production. As previously described, ecosystems dissipate energy to the maximum of the entropy production (Martyushev and Seleznev, 2006), building order in structures through the accumulation of exergy. This moves the system away from equilibrium. A degrading system, lacks the necessary structures to maintain its steady state, plunging toward equilibrium. The corresponding reduction in entropy production and exergy storage, cumulatively hamper energy dissipation, resulting in a build-up of high entropy wastes (Epstein *et al*., 2006). As all energy inevitably degrades to heat, temperature is affected. Heat is best considered as a measure of the movement of particles, where an increase in entropy is calculated from the decrease in organization of the particles. When measuring the temperature of the soil, we are in fact measuring the heat flux from the soil to its surroundings; the proportion of degraded (longer wavelength) energy from the sun. It is the average kinetic molecular energy of the soil system, it is not a direct measure of the thermal energy, but the transfer of thermal energy, as it comes into equilibrium with its surroundings. Driven by the energy flux created in diurnal solar fluctuations. Effective energy dissipation leads to a lower amount of degraded energy (greater exergy) and an attenuation of temperature (Norris *et al*., 2012; Schick, Porembski, Peter R. Hobson, *et al*., 2019; Avelar *et al*., 2020).

For the glasshouse trials a custom-built temperature array was designed using Arduino hardware and coding. The array utilized the DS18B20 temperature probe, logged time with the DS3231 real time clock and stored the data on an SD card. Prior

to utilization the temperature array was tested against Hobo data loggers (a high-quality research grade temperature logger) and the probes were found on average to be have a maximum deviation 0.631°C from these precision instruments, across a temperature range of 15-25 degrees C. The experiments presented here focused on soil temperatures at 10cm below the surface, both in the pots and the field; surface temperatures were also recorded in the field and utilized the Hobo data loggers. In the field, loggers were distributed at 20m transects. In all 5 trials temperature was logged every 15 mins.

4.2.2.2 Moisture content

Moisture content was measured using an ExTech moisture probe inserted so that the tip of the probe was at 10cm in the soil. This was consistent across all experiments. 3 measurement were taken at different locations within a 20cm radius. The pot trials were limited to 3 sets of measurements per pot, as each time a hole was left in the soil and too many started to impact upon the structure of the soil.

4.2.3 Species selection

In the controlled experiments plants, were used to represent a slight advance in complexity by introducing higher level organisms, with more complex structures to dissipate energy. Bare soil for example is only dependant upon photosynthetic microorganisms (cyanobacteria, mosses, etc). Two different species were selected representing different traits.

Grimes CSR model recognises that species display measurable traits, in a universal three-way trade off to produce adaptive strategies that facilitate the survival of the species. In agriculture, several semi wild plant species have been utilized as cover crops in a new wave of sustainable agriculture. The leaf functional traits of a select few of these species were identified and used in the experimentation here (Table 3 ; Tribouillois *et al*., 2015). In accordance with universal adaptive strategy theory, *Brassica Juncea* is more of a competitive species, whereas *Trifolium incarnatum* is more of a ruderal species. Functional traits dictate the organisms ability to assimilate energy in the form of biomass, dependant upon the abiotic factors. In EXP1 and EXP2, dry weight of the samples was measured and averaged per plant, to give the average biomass per plant.

Table 3 – Difference in trait expressions between Brassica Juncea and Trifolium incarnatum. Brassica juncea shows lesser SLA (specific leaf area) *by 6.1 m^2kg^{-1}, greater LDMC (leaf dry matter content) by 16.6Mgg^{-1}, greater LNC (leaf nitrogen content) by 5.5mgg^{-1} and much greater LA (leaf area) by 60.1 cm^2*

	SLA (m^2kg^{-1})	LDMC (mgg^{-1})	LNC (mg g-1)	LA(cm^2)
Brassica juncea	24.2 ±2.8	116.6 ±8.9	47.7 ±6.9	79.4 ±31.6
Trifolium incarnatum	30.1 ±3.7	101.0 ±7.9	42.2 ±4.6	19.3 ±4.2

For the field trial a species survey was carried out to indicate the diversity (Figure 14). Frequency and abundance was estimated using DOMIN scale and the C-S-R plot was determined using the C-S-R signature calculator, from UCPE Sheffield (Hunt *et al*., 2004). The community was quite central to the plot, but sat more on the specialist/ ruderal axis and the nearest strategy type was Specialist ruderal/ competitive, specialist, ruderal (SR/CSR).

BSBI species name	**% Abun**
Rubus fruticosus	<0.1
Trifolium repens	<0.1
carduus crispus	2.0
ranunculus acris	0.2
Rumex obtusifolius	0.2
Lotus corniculatus	<0.1
Rumex acetosa	2.6
Stellaria graminea	4.3
Urtica dioica	0.6
Taraxacum officinale	0.1
Senecio jacobaea	<0.1
Sisymbrium officinale	<0.1
Anthoxanthum odoratum	36.6
Poa trivialis	32.0
Festuca pratensis	21.4

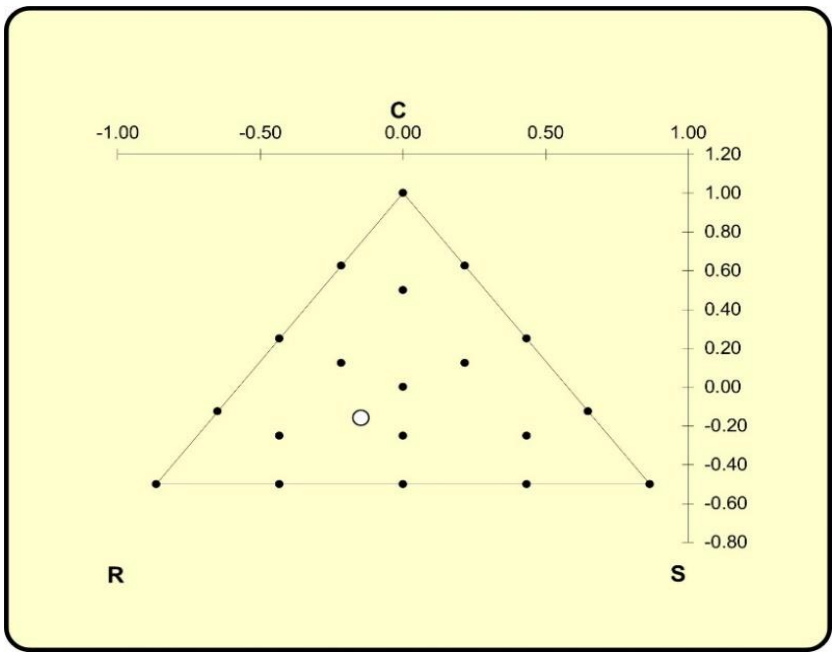


Figure 14 – Left, results from species and abundance survey, showing the species and the % abundance estimated from the DOMIN assesment. Right, the C-S-R plot generated from UCPE C-S-R signature calculator. The nearest strategy type was SR/CSR.

4.2.4 Soil selection

4 textural classes were examined in the glasshouse trials (Figure 15). Ranging from an extremely homogenous, pure sand, representative of a genesis state of soil, to a sub soil with very high sand content and low clay and silt content, a good loam soil and furthermore a sandy silt soil with high OM content, manufactured for optimum plant growth (Black soil). Although not all soils were included together due to sample size constraints an attempt was made to compare them across experiments.

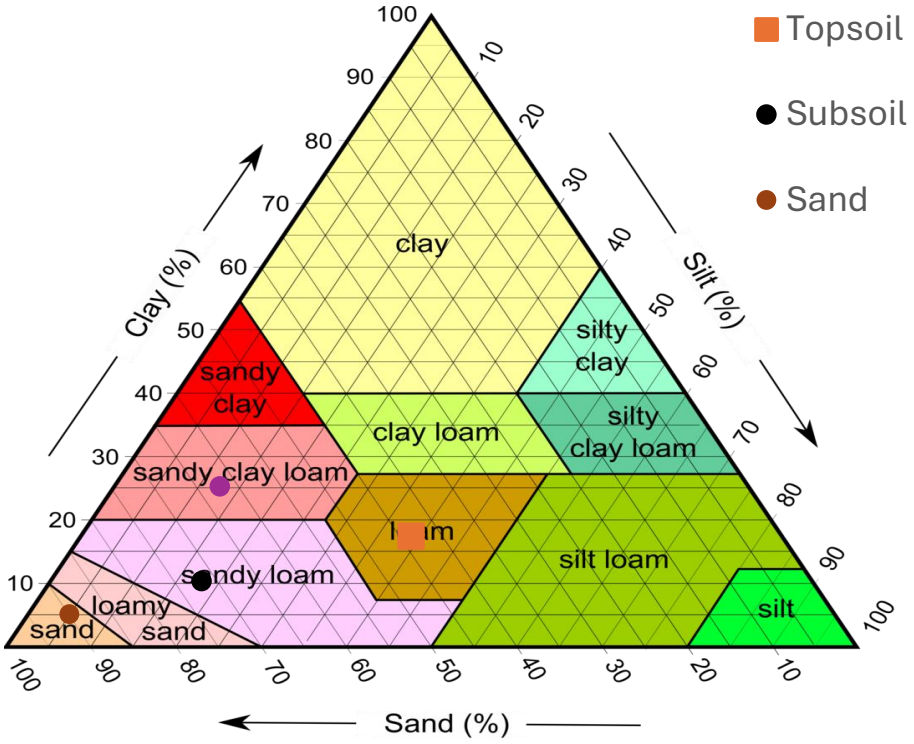


Figure 15 – Ternary plot for soil textural classification, taken from particle size distribution analysis of the soils. The analysis identifies the soils distinct textural classes.

4.2.5 Statistical analysis and variability calculations

It is important to note here that due to the frequency and volume of temperature data points, the analysis of these vast data sets would have been extremely time consuming without the use of a bespoke python script developed to extrapolate the key variables and measures, derived from ecosystem thermodynamics. Furthermore, the RAW data sets have not been given in appendices as it would take up many

hndreds of pages, however one experiment was exported as the RAW data it would take up many hundreds of pages; instead summary statistics and any statistical tests have been provided (Appendix A through F) where relevant.

The study is primarily concerned with the flow of energy from solar radiation through the system (soil). As such the rising sun is of particular interest as it represents the increasing input of energy. The soils response to that energy input can then be measured in the form of several temperature-based metrics. Taking the maximum temperature (MAX) as the solar peak, the mean (MEAN) was calculated for the 8 hours leading up to that point. Also, the ability of the system to dissipate and store exergy is related to the rate of heat loss and as such, the daily minimum temperatures (MIN) were considered. These were averaged across the experiment periods (MEANMAX and MEANMIN) as well as calculating lowest MIN and the Highest MAX (LoMIN and HiMAX respectively).

The 8 hours before the MAX was used as the key sampling zone and measures of variability during this period were calculated; the temperature variability, measured as the standard deviation of the 8 hours before MAX (STDEV); the diurnal temperature range (DTR), measured as the average difference between the MAX and the MIN; and the intra diurnal variation, measured as the coefficient of variation (CoeffVAR), which was calculated by $\frac{STDEV}{MEAN} \times 100$ (see Elagib, 2010).

STDEV In statistics, is a measure of the amount of variation of a random variable about its mean. It shows the variability of temperature within the timeframe. CoeffVAR is a relative measure of variability that indicates the size of a standard deviation in relation to its mean. It shows the extent of variability in reference to the MEAN, the higher the CoeffVAR the greater the level of dispersion around the mean. DTR shows the amount of change over the time period.

4.3 Results

4.3.1 Temperature indices of growth phase for controlled experiments

The following graphs are a sample of data for each of the temperature metrics across 3 experiments (EXP1, EXP2 and EXP3) , summary data and statistics are given in Appendix A. To simplify the results not all data sets were included for all experiments and representative plant-soil combinations were chosen for each graph. Above all, soils with more homogenous structure (less particle heterogeneity), such as sand and sub soil were more variable (Figure 22 and Figure 24), alongside higher MAX temperatures (Figure 16,Figure 17 and Figure 18) and lower MIN temperatures (Figure 19). Shaded soils responded more similarly to plants and on some occasions were less variable than those with plants (Figure 22). In EXP3, a higher input of water (8lph compared to 2lph), resulted in less variable (Figure 23) and lower MAX temperatures (Figure 18), however there was no statistical difference between water regimes or plant-soil combinations for MIN temperatures (Figure 19). The data consistently oscillates about the average trendlines throughout the experiments (Figures 16 through 24) and often, the more complex plant-soil combinations (samples with plants and even bare soil) showed least deviation from the line of best fit compared to sub soils and sands (Figure 20). Furthermore, STDEV and confidence limits tended to be greater in samples with plants (see appendices). Table 4 summarizes the soils and plants in each of the graphs, relative to the temperature metric they are representing.

Table 4 - Summary of the soils and plants used for each of the graphs, from what experiment they are from and what metric they will represent.

Metric	**EXP1**	**EXP2**	**EXP3**
MEAN		Subsoil (Sub), Bare soil (BS) and *Brassica juncea & Trifolium incarnatum* (BJ&TI)	
MAX		Subsoil (Sub), *Brassica juncea* (BJ), *Trifolium*	6 plants per pot with 8lph watering (HDF), 6 plants per pot with 2lph watering (HDR)

		incarnatum with inoculant (TI+)	
MIN	Sand (Sand), Bare soil (BS), *Trifolium incarnatum* (TI)		
STDEV	Sand (Sand), Bare soil (BS), *Brassica juncea* (BJ)		3 plants per pot with 8lph watering (LDF), 3 plants per pot with 2lph watering (LDR)
DTR		Shaded soil (Sh), *Brassica juncea* (BJ)	Bare soil with 8lph watering (BSF), Bare soil with 2lph watering (BSR)
CoeffVAR		Subsoil (Sub), Bare soil (BS), *Trifolium incarnatum without inoculant* (TI)	

4.3.1.1 MEAN

MEAN temperatures (calculated as the daily temperature mean for the 12 hours preceding daily MAX), tended to differ very little between soils and with and without plants (Figure 16). This was irrespective of soil type and particularly evident in lower values (Figure 16). The glasshouse conditions as expected intensified the thermal regime evident by the difference between ambient temperatures and the average glasshouse soil temperature (Figure 16). The glasshouse soil was on average 5.4°C (+/-0.66°C) hotter than the recorded ambient temperature from Writtle weather station.

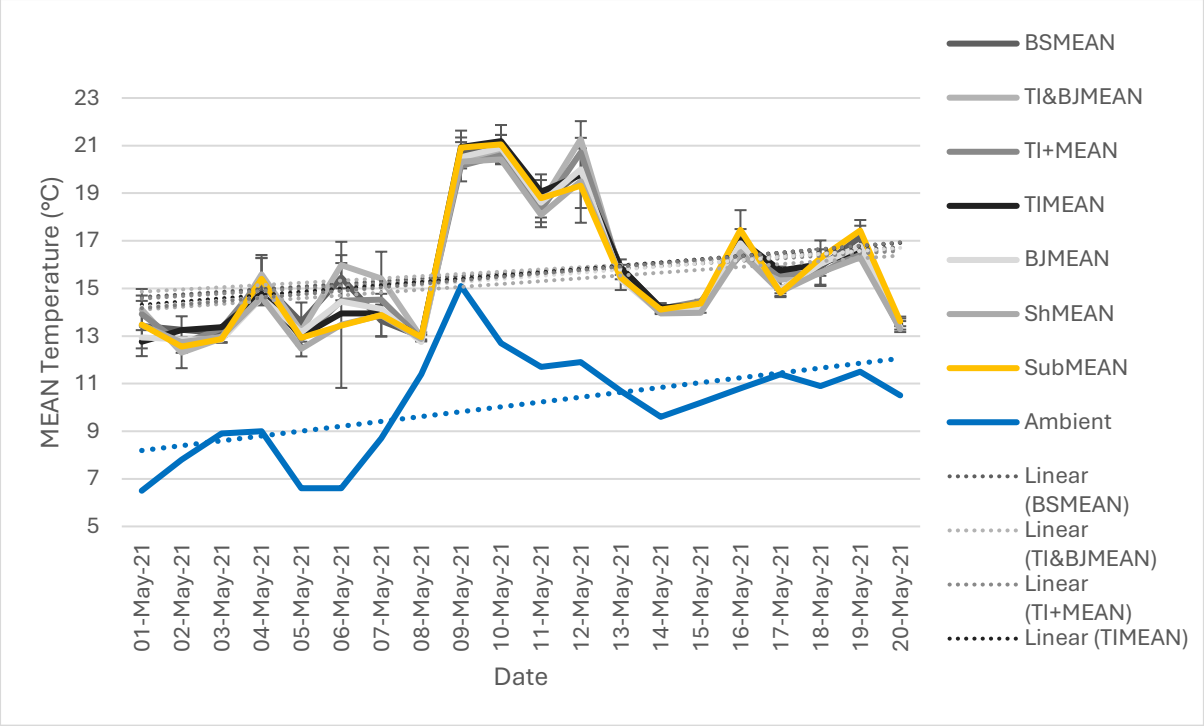


Figure 16 – Daily MEAN temperatures for Bare soil (BS), Subsoil (Sub) and Trifolium incarnatum (TI) & Brassica Juncea (BJ), Results are from EXP2, where two soils were compared and multiple plant models. No statistical difference was evident between Sub and other plant-soil combinations (TI and BJ) for MEAN temperatures. Daily mean ambient temperatures, taken from Writtle University College weather station, were plotted (Blue Line) and show how the glasshouse conditions affect soil temperatures, with an increase between 4.74˚C and 6.06˚C, compared to the ambient temperature recorded at the weather station. Error bars are confidence limits. Total N = 60 across 20 days.

4.3.1.2 MAX temperature

MAX temperatures, as the daily maximum temperature averaged for each plant-soil combination, tended to be higher in soils with more homogenous structure (Figure 17) or reduced water content (Figure 18). As in the MEAN, MAX temperatures in the glasshouse were much higher than ambient temperatures (Figure 17) Individual plant species such as TI+ and BJ, were similar and the Sub soil was statistically far hotter for average MAX temperatures ($p<0.001$, t test; Figure 17). In samples with reduced water input (60ml per day), were on average hotter at the peak compared to samples receiving a sustained water input enough for field capacity 266ml per day.

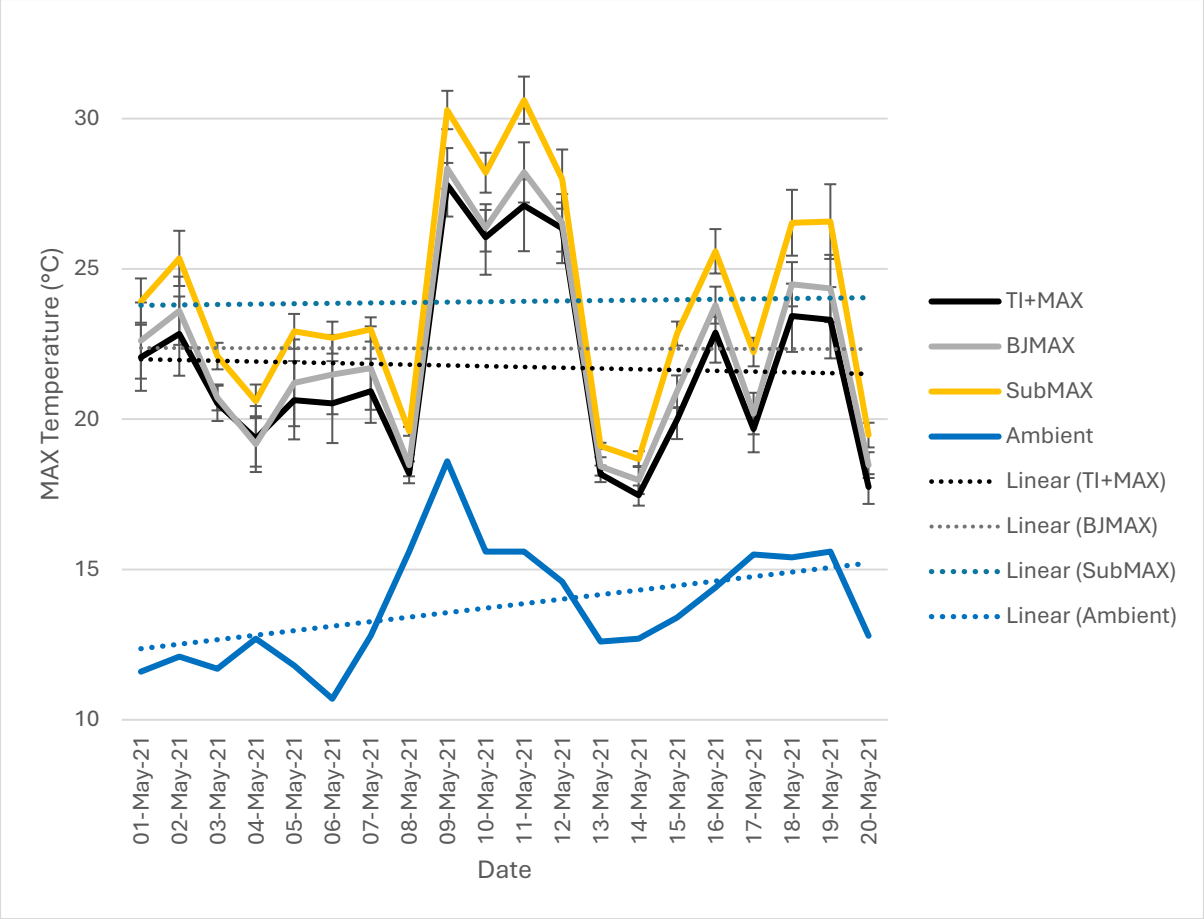


Figure 17 – Daily MAX temperatures overtime and averaged for Trifolium incarnatum with inoculant (TI+ in topsoil), Brassica juncea (BJ in topsoil) and Sub soil (Sub). Results are from EXP2 where two soils were compared and multiple pant models. MAX temperatures were statistically greater for Sub, than both TI+ ($p<0.0001$, t-test) and BJ ($p=0.002$ t-test) and there was no statistical difference between TI+ and BJ. Error bars represent confidence limits The daily maximum ambient temperatures, taken from Writtle university college weather station and show a difference of between 8°C-10°C (+/- 0.95°C) and as much as 12°C for Sand on 9th May (+/- 0.6°C). Total N=60, across 20 days.

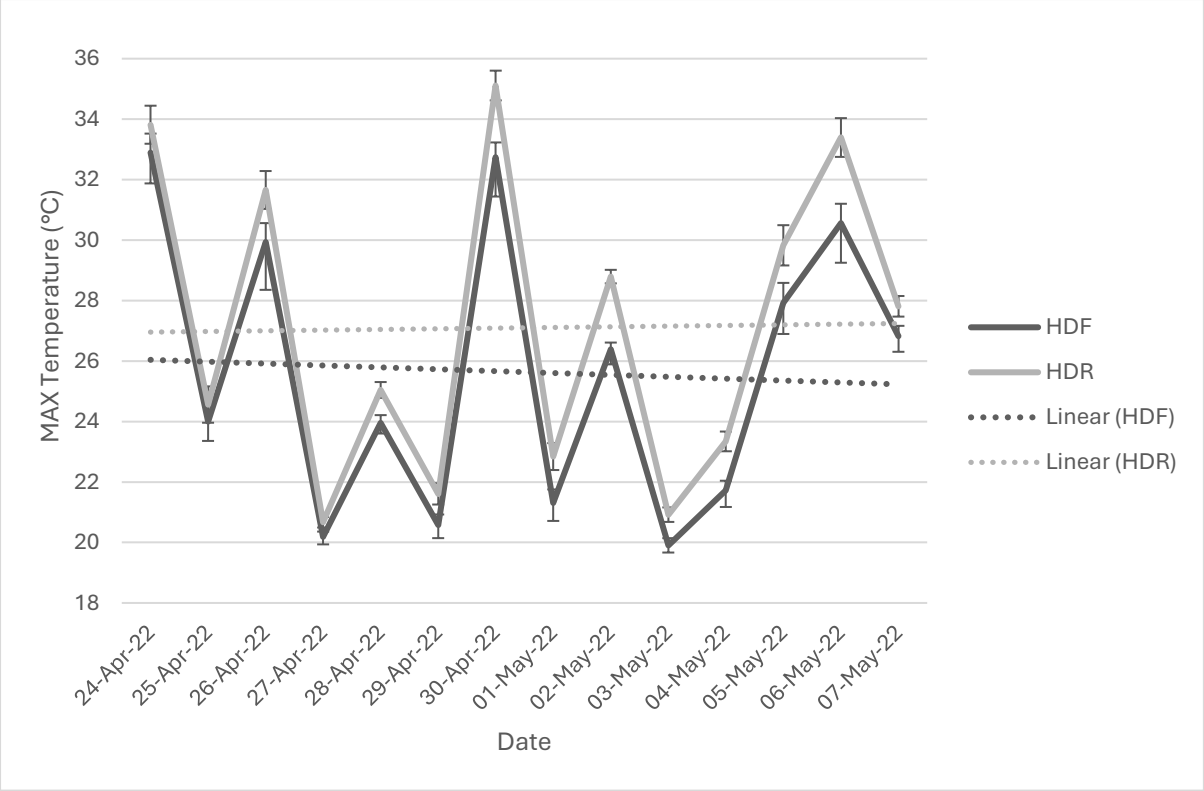


Figure 18 – Daily maximum temperatures (MAX) over time for EXP3, which compared two different watering regimes and two different plant spacing compared to control of bare soil. This graph shows the two watering regimes for higher density spacing of 6 plants per pot (HDF and HDR). Reduced watering, compared to standard watering (HDF) exhibited generally greater MAX (p=0.02, t-test). Error bars are confidence limits. Total N=30 across 14 days.

4.3.1.3 MIN temperature

Minimum temperatures (MIN), calculated as the daily absolute minimum had the opposite effect in that more homogenous soils were for the most part lower than other plant-soil combinations. Although not shown here in EXP2, MIN temperatures were statistically lower in the Sub compared to the TI+, but not with any other samples (p=0.02). In Figure 19, Sand in EXP1, compared to BS and BJ, tended to reach lower minimums and was on average 1.19°C to 1.46°C cooler. Confidence limits are less in MIN data, indicating a greater variability between samples in hotter temperatures (Figure 19).

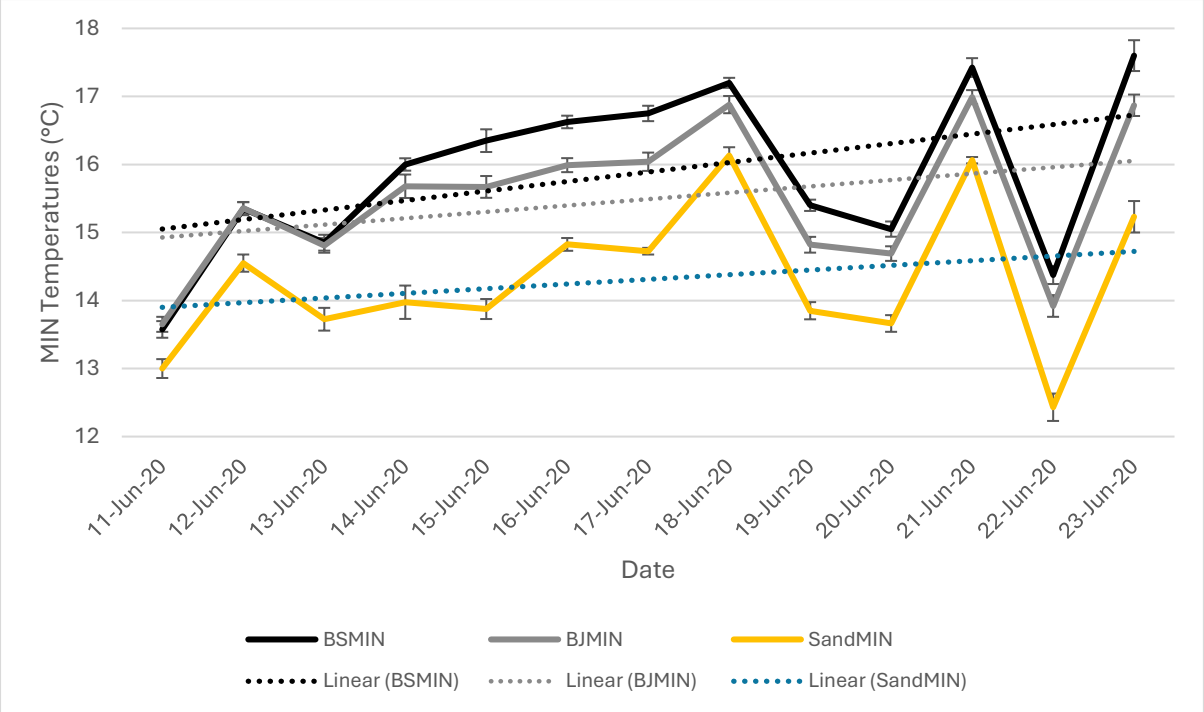


Figure 19 - Minimum temperatures (MIN) graph for EXP1, where Sand was compared with 3 other plant soil combinations. This graph shows the averaged MIN temperatures were lower in both the Sand (p<0.0001), Mann-Whitney) and Brassica juncea (BJ;p=0.04, Mann-Whitney) compared to Bare soil (BS) and the Sand was also statistically lower than BJ (p<0.0001; Mann-Whitney). Total N=39 across 13 days

4.3.1.4 STDEV

More homogenous soils tended show greater STDEV when compared to other plant-soil combinations. For example, In EXP 1 the BS and the Sand were both statistically greater STDEV (Figure 20) than the soils with plants ($p<0.002$ for Sand and $p<0.03$ for BS). Sand differed by up to 2.68°C (+/- 0.57°C) and the BS by up to 1.05°C (+/- 0.42°C).

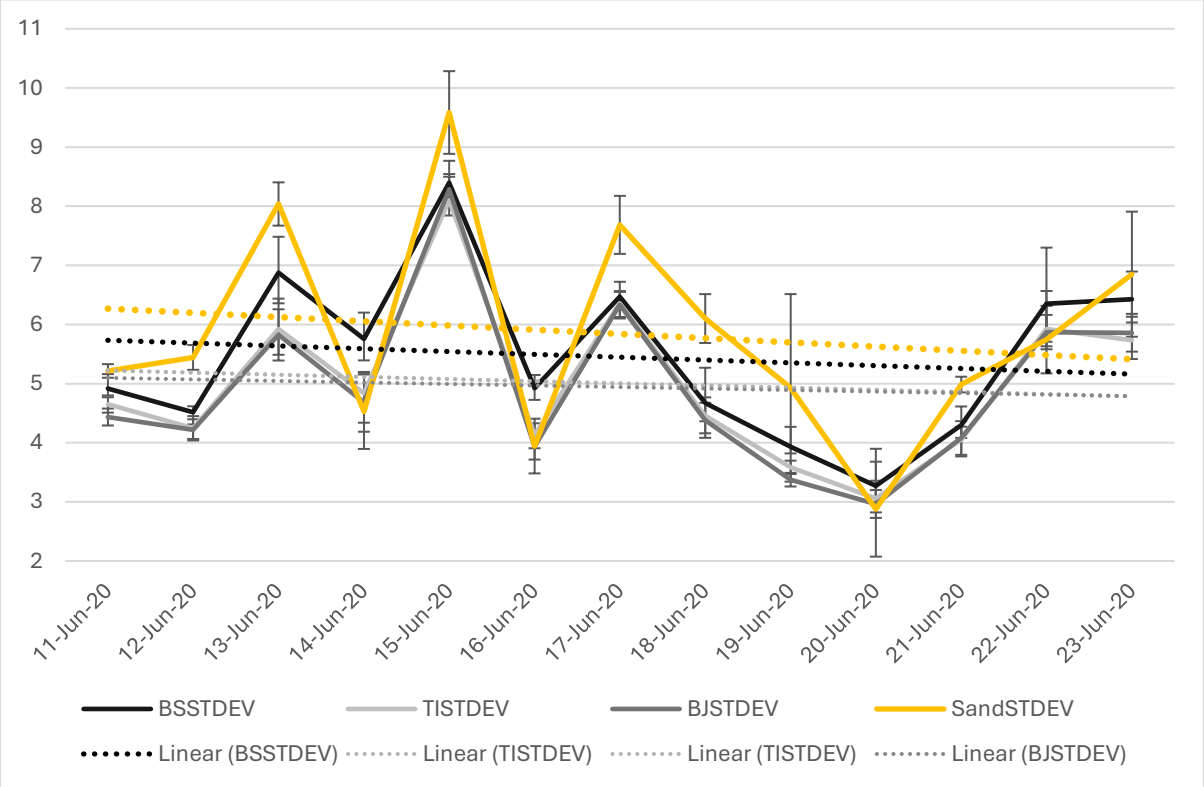


Figure 20 – Temperature STDEV over time for all soils and plants in EXP 1, where a pure sand (Sand), was compared with the bare black soil (BS), black soil with Trifolium incarnatum (TI) and black soil with Brassica Juncea (BJ). Linear trend lines stack in order, Sand, BS, then TI and BJ, error bars are confidence limits. Total N = 351, across 13 days.

Soil moisture also tended to reduce STDEV, for example in In EXP3, the STDEV (Figure 21) was greater for BS ($p=0.02$, Mann Whitney) in the reduced irrigation (2lph) compared to irrigation that sustained the water threshold (Table 2; 8lph) . With the reduced irrigation STDEV differed on average between 0.184°C and 0.866°C.

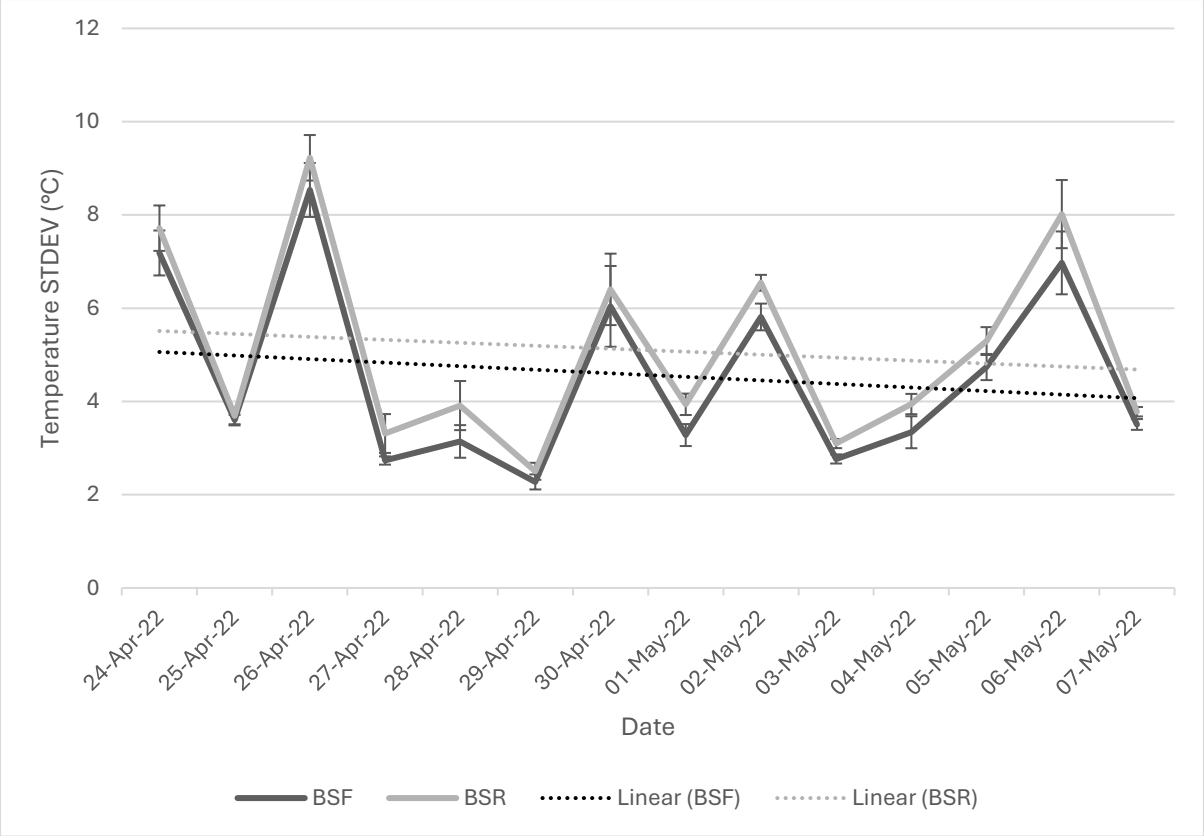


Figure 21 - Temperature STDEV over time for EXP3, which compared two different watering regimes and two different plant spacing with control of bare soil. This graph shows the two watering regimes for bare soil, where reduced watering (BSR) exhibited greater STDEV (p=0.02, Mann Whitney), compared to standard watering (BSF). Error bars are confidence limits BS higher by as much as 1.25°C. Total N=28 across 14 days.

4.3.1.5 DTR

In EXP2, shaded soils (Sh) were statistically lower in DTR (Figure 22) than both BS (p=0.009, Mann-Whitney) and Sub (p<0.001, Mann-Whitney). Although not significant (p=0.056), DTR for LDF was slightly lower on average compared to LDR (Figure 23). On the hottest day (11th May), where temperatures reach over 30°C (Figure 17), the difference in DTR between Sub and Sh was 3.79°C (+/- 0.72°C). Interestingly, DTR on the 11th May was ~2°C greater than on the 9th May, despite both days reaching a similar MAX (30.28°C on 9th and 30.61°C on 11th; Figure 17) evidence of the progressive and high variability of the temperature data.

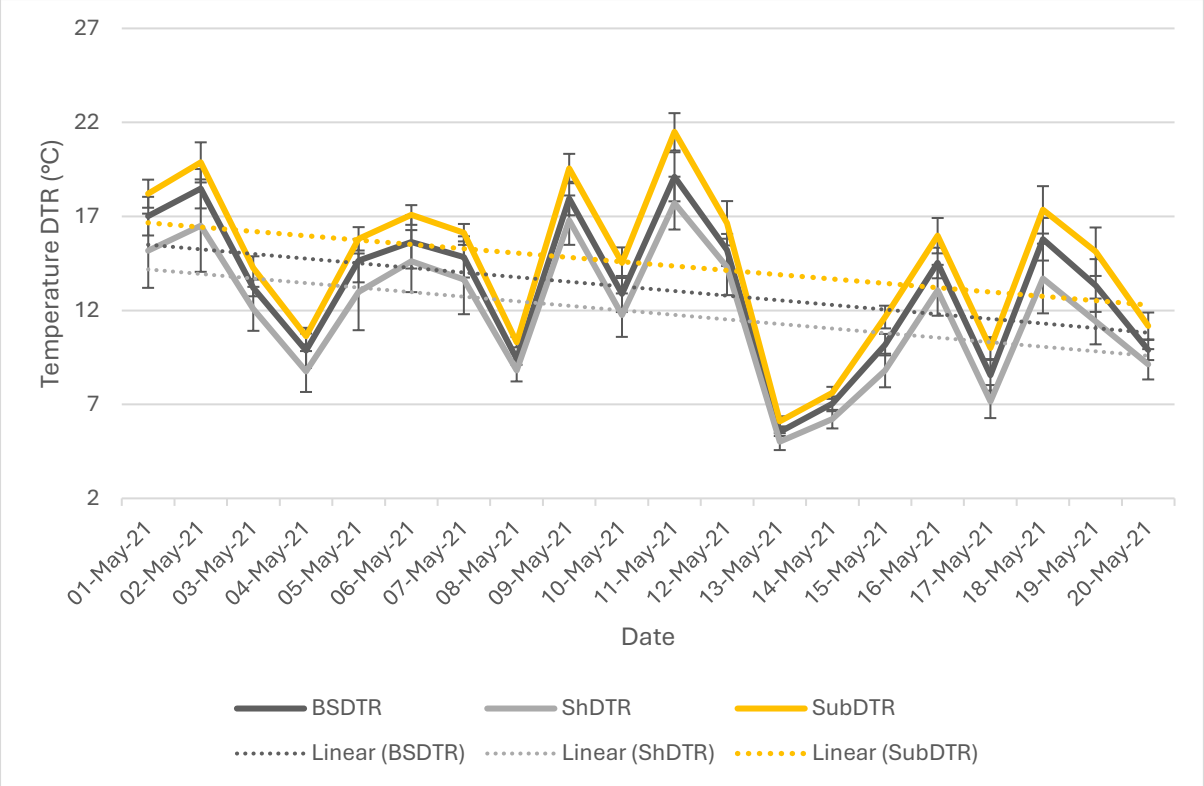


Figure 22 – Diurnal temperature range (DTR) for EXP2 where two soils were compared and multiple pant models. DTR was statistically greater for Sub, than both bare soil (BS; p<0.0001, t-test) and Shaded soil samples (Sh; p=0.002 t-test). Error bars are confidence limits. Sub soil greater than BS and Sh less than BS by as much as 1.4°C and sub by as much as 3.7°C. Total N = 80 across 20 days

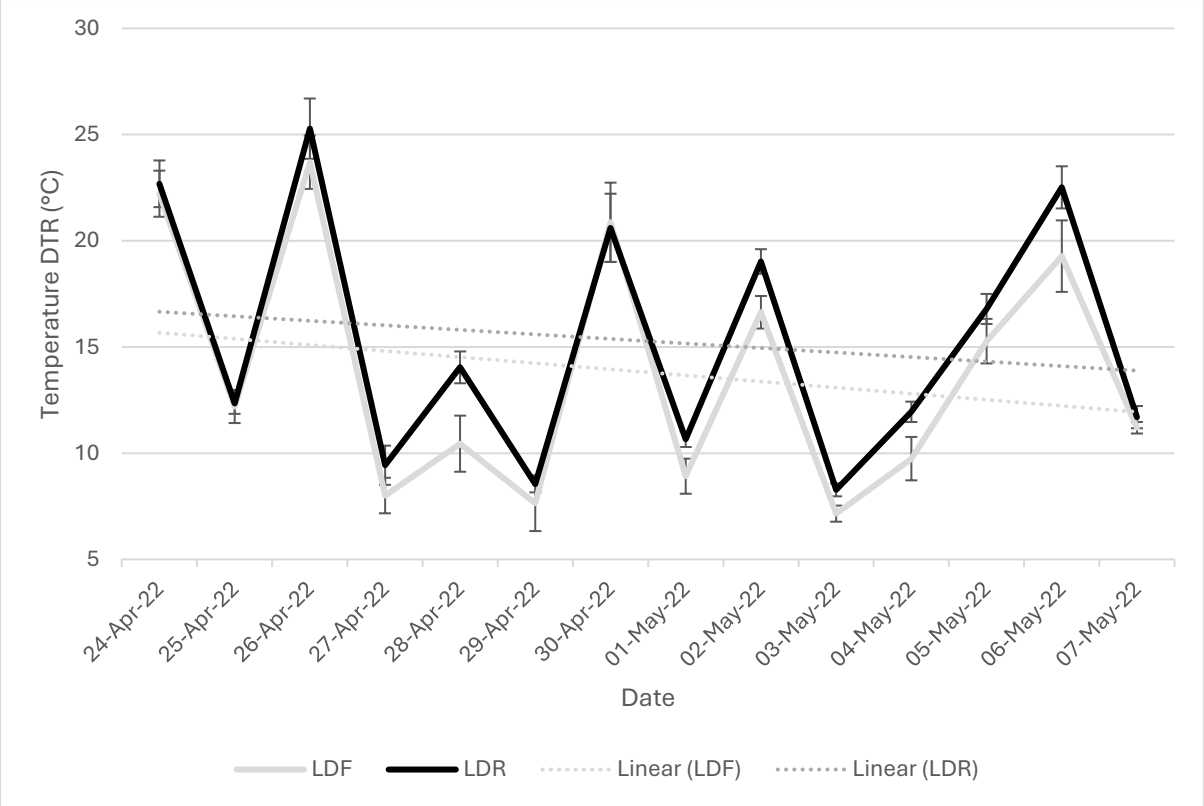


Figure 23 - DTR for EXP3, which compared two different watering regimes and two different plant spacing with control of bare soil. This graph shows the two watering regimes for low density plant spacing of 3 plants per pot, in the two watering regimes; where reduced watering (LDR) exhibited greater but not significant (p=0.056, Mann-Whitney) DTR compared to standard watering (LDF). Error bars are confidence limits. LDR for the most part higher than LDF by as much as 3.3°C. Total N=28 across 14 days.

4.3.1.6 CoeffVAR

On average CoeffVAR for Sub soil in EXP2 was significantly higher than both the BS (p=0.03, Mann-Whitney) and TI (p=0.001, Mann-Whitney), however BS and TI did not differ (Figure 24). As for DTR and STDEV, CoeffVAR (Figure 24) tended to have confidence limits with more crossover compared to MAX (Figure 17 and Figure 18) and MIN (Figure 19), indicating that MAX

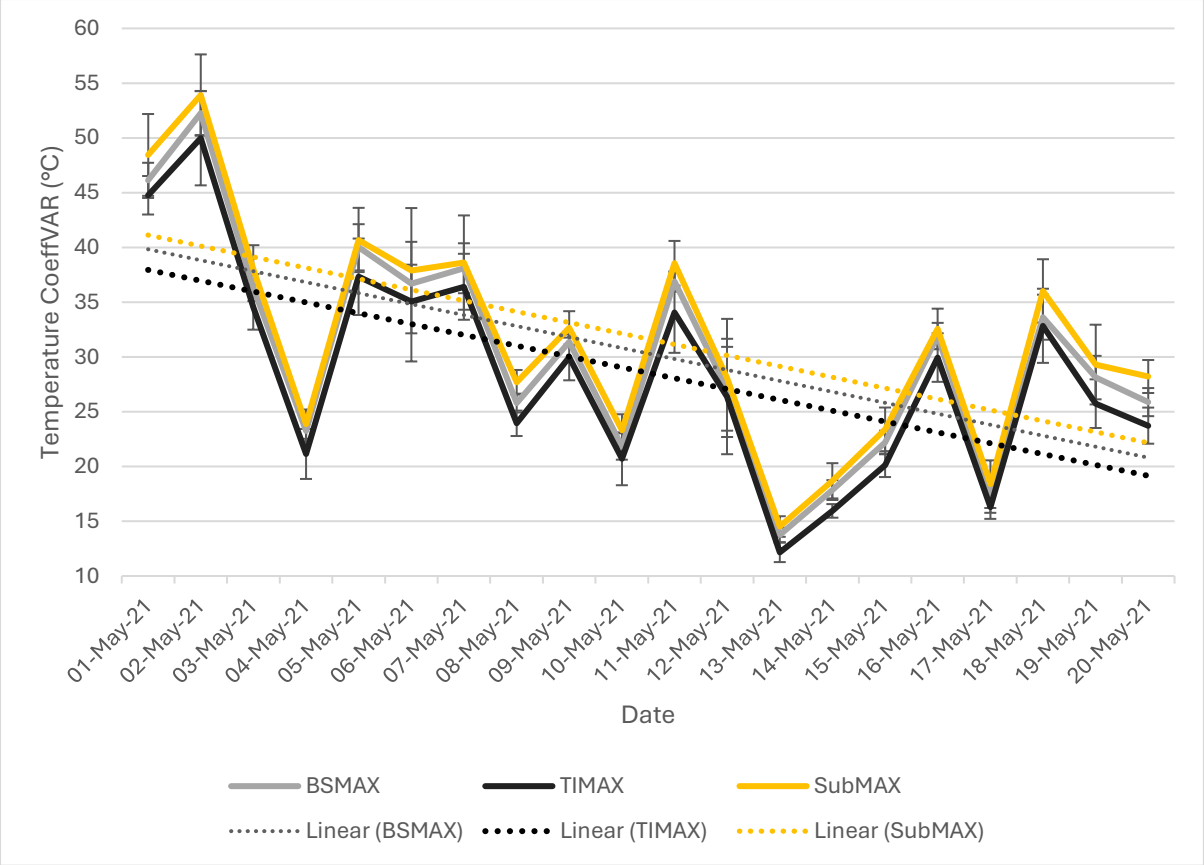


Figure 24 – Temperature Coefficient of variation (CoeffVAR) overtime for EXP2, where two soils were compared and multiple pant models. CoeffVAR was statistically greater for Sub compared to bare soil (BS; p=0.03) and soil with Trifollium incarnatum (TI; p=0.001). Error bars are confidence limits. Sub soil was on average 3% greater than BS (+/- 1.49%) and as much as 5% greater than TI (+/_ 2.5%). Total N=60 over 20 days.

4.3.2 Field trial

Precipitation and moisture content (MC) followed a similar pattern (Figure 25). The difference in moisture content between Meadow and Disturbed was variable and on the final data point, MC was approx. 3%, with no statistical difference. In general, temperatures in Meadow were significantly ($p<0.05$) lower and more attenuated in both the soil and the surface (Figure 26 and Figure 27). Temperature at 10cm was up to 20°C less than surface, at solar maximum, in both Meadow and Disturbed. The difference between the soil and the surface was calculated for each of the scenarios and there was no significant difference ($p=0.302$, t test), meaning that the contrast between soil and surface was consistent across Meadow and Disturbed. Furthermore, Disturbed soil showed a highly significant difference ($p=5.2377 \times 10^{-84}$, n=2693) in

STDEV (between samples), indicating greater spatial heterogeneity, compared to Meadow.

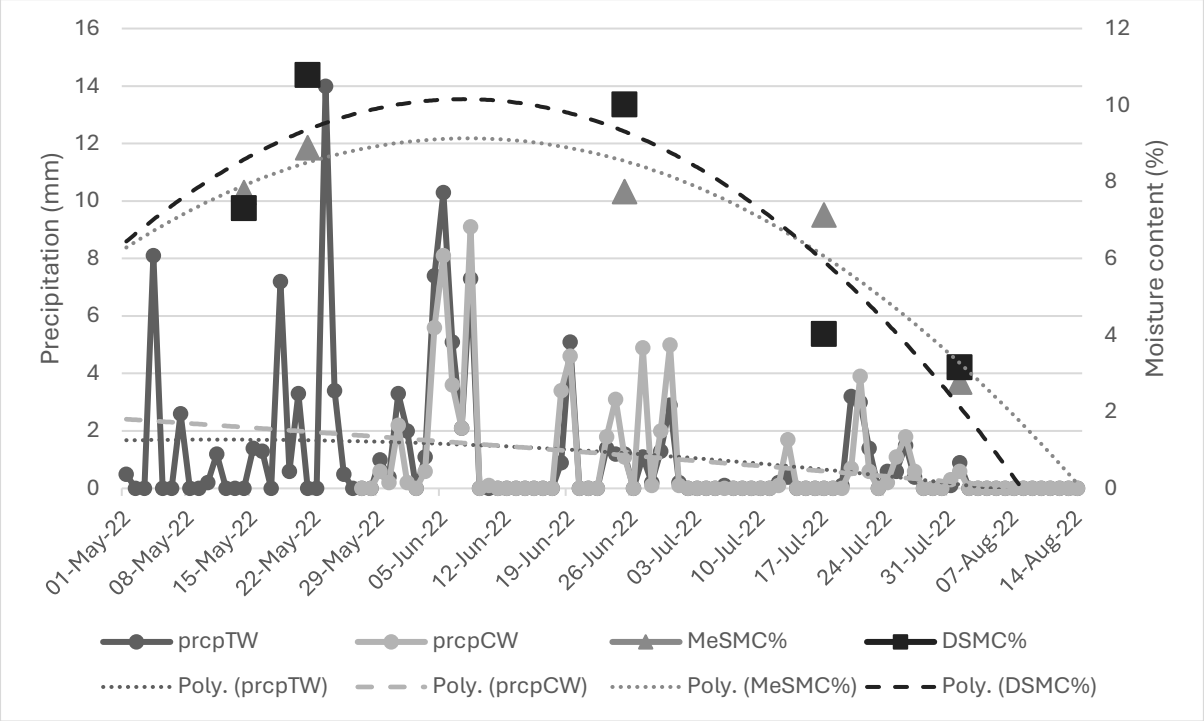


Figure 25 - Relationship between precipitation and moisture content for Meadow (MeSMC%) and Disturbed soil (DSMC%). Greater rainfall (average of 2mm per day) early on (1st May to 6th June), followed by a period of lower rainfall (average 0.8mm per day) up to 31st August, contributed to the declining soil moisture. Precipitation data available at (MET Office, n.d.) from two nearby weather stations, Tunbridge wells, 15.3 miles away (prcpTW) and Charlwood, 28 miles away (prcpCW). Left axis corresponds to precipitation data (prcpTW and prcpCW), right axis is moistureN=80 (for moisture data) across 5 data collection points.

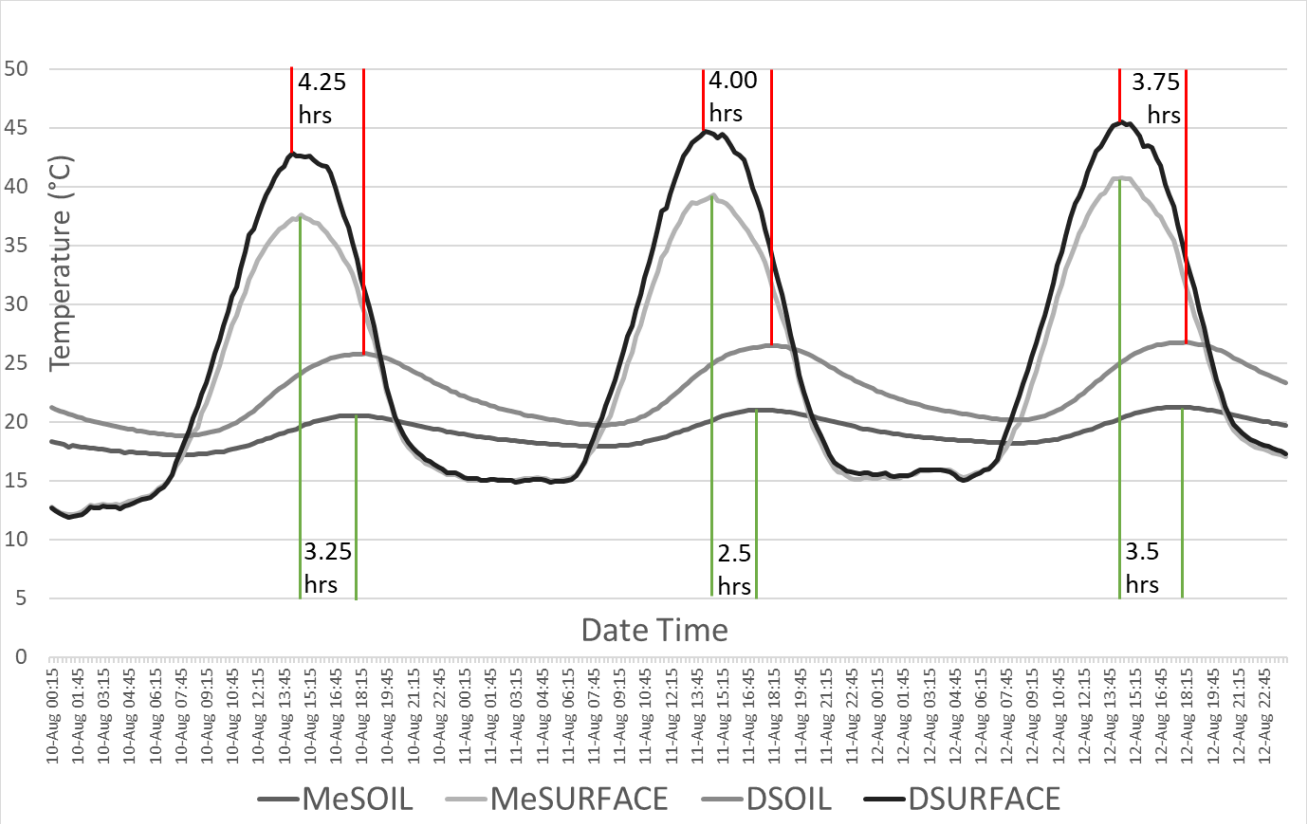


Figure 26 - Soil at 10cm and surface temperature across 3 of the hottest days during the experiment. Temperatures in the Disturbed soil at the surface (DSURFACE and DSOIL) peaked statistically higher ($p<0.05$) than the Meadow (MeSOIL and MeSURFACE). The time difference between peaks of surface and soil was evident and the average time difference between peaks of surface and soil was 2.75hrs – 3.5hours for Meadow and 3.11hrs – 4.06hrs for Disturbed soil, however they did not differ significantly.

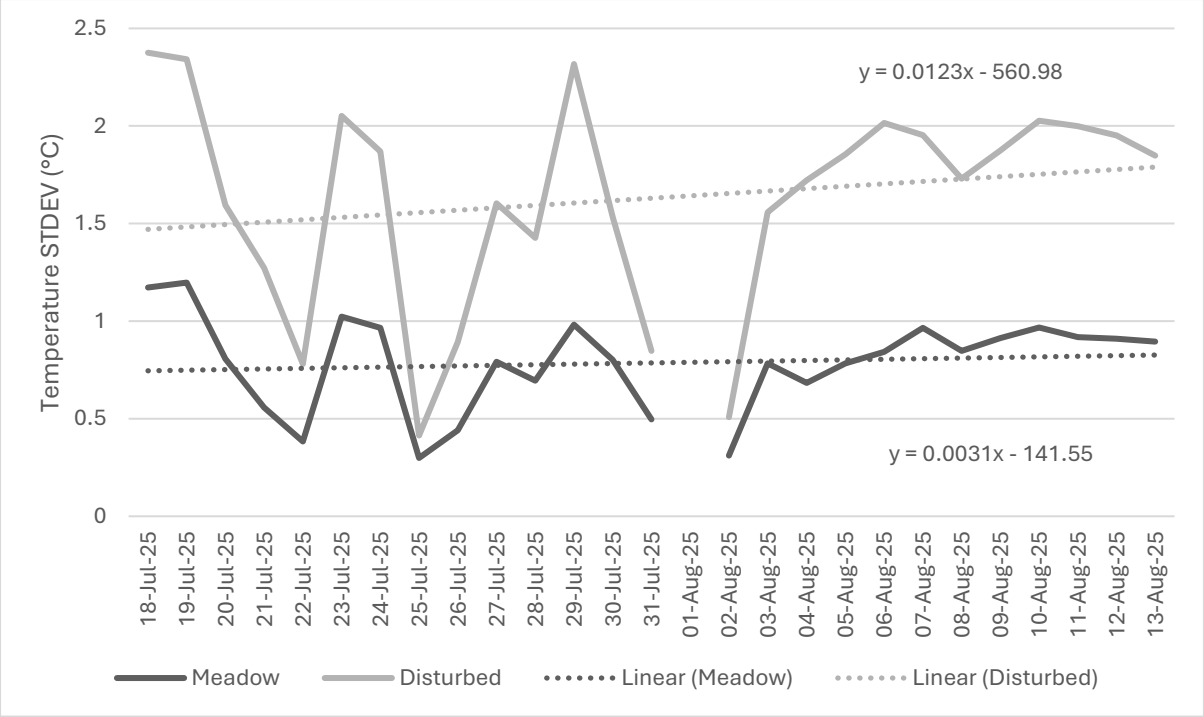


Figure 27 – Soil temperature STDEV across 26 days of the experimental period. Data between 31st July and the 2nd August is missing due to a technological failure in the sensors following data collection.

4.3.3 Correlations between variability indices

Temperature measures such as MIN, MAX and MEAN were compared with variability indices such as DTR, Coeff VAR and STDEV, to asses goodness of fit to the model in Figure 13. Summary data and statistics are given in Appendix B. MIN temperature indices tended to correlate negatively with variability metrics, whereas MEAN and MAX tended to correlate positively (Table 5). Table 5 displays rank values for ordinal correlation. Figure 28 shows how STDEV correlates with MAX across all experiments. When grouped as glasshouse trials and field trial, the correlation shows good linear fit for both groups (Figure 28) and although experiments were carried out at different times all glasshouse experiments fit the slope well (R^2=0.94).

Table 5 – Correlations between MEAN temperature, variability indices (STDEV, DTR and CoeffVAR) and other temperature measures (LoMIN, MEANMIN, HIMAX, MEAN MAX and MEANMEAN, see methods). Figures are correlations of Spearmans rank, where negative values show negative correlation and positive values show positive correlation. MIN temperatures tended to correlate negatively with variability indices

(first 2 rows) and MEAN and MAX tended to correlate positively (Last 3 rows). All correlations shown are significant (Spearmans Rank, p<0.05).

	MENSTD	MEANDTR	MEANCoeffVAR
LoMIN	-0.50803 to -0.44548	-0.59111 to -0.44538	-0.62662 to -0.39493
MEANMIN	-0.50803 to -0.46459	-0.38731 to -0.36801	-0.81338 to -0.62662
HiMAX	0.77934 to 0.80632	0.82378 to 0.87955	0.68939 to 0.71669
MEANMAX	0.90159 to 0.9386	0.94382 to 0.97734	0.75699 to 0.86081
MEANMEAN	0.51526 to 0.65391	0.4171 to 0.72907	0.2967 to 0.46889

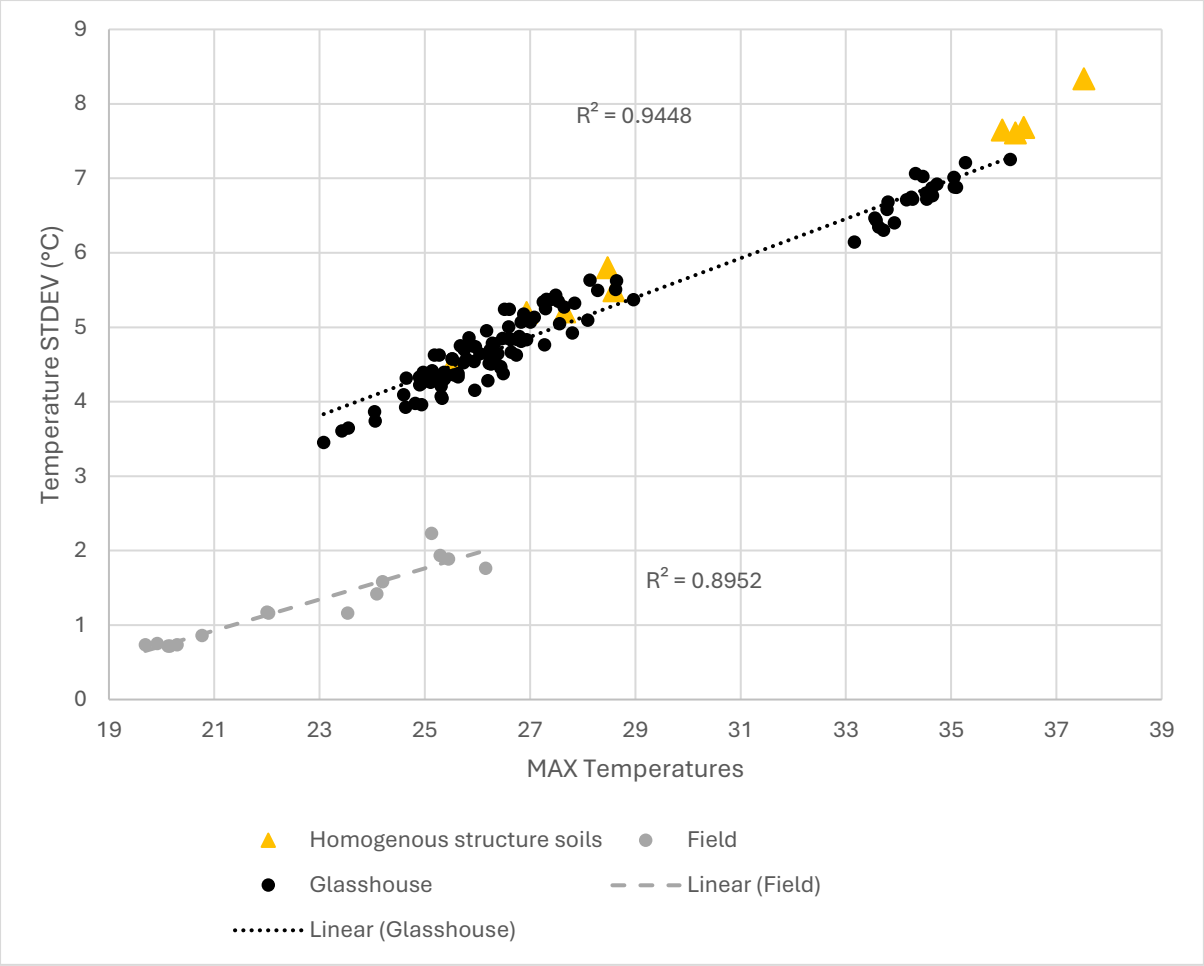


Figure 28 - Correlation between STDEV and MAX. Field trial (EXP4) was analysed separately from the glasshouse trials and occupied a comparatively lower MAX and STDEV domain. Both data sets showed good linear fit (R^2>0.89), however, the linear trendline in glasshouse trials was slightly steeper. Poor soil (Sand and Sub), tended to be in the upper quartile of each experiment and the coefficient (Stdev/MAX) was significantly higher (p=0.001) than other plant-soil combinations. .

4.3.4 Temperature rate of change

The change in temperature between data collection points (15 mins) was calculated and compared with the average temperature at that time (Figure *29*), see Appendix C for data used to generate Figure *29*. The rise and fall of the diurnal temperature flux was separated in to three episodes; the lower third of temperatures that surround the MIN, the middle that represents the rising and falling of temperatures between the MAX and MIN, then the upper third of temperatures that surround the MAX. Sand in EXP1 was significantly faster in the upper (>24°C; $p<0.0001$) and middle (>17<24; $p<0.0001$) thirds of the data but not the lower third (>17°C). With increasing temperature, the rate of temperature change in lower complexity plant-soil systems is faster than at lower temperatures (HB&S Temp rate 3). The distribution of the data and the shape creates, implies that at peaks and troughs the sample comes in to thermal equilibrium with its surroundings as there is no difference in temperature change. Rate increases in between the peaks when temperature is either rising or falling.

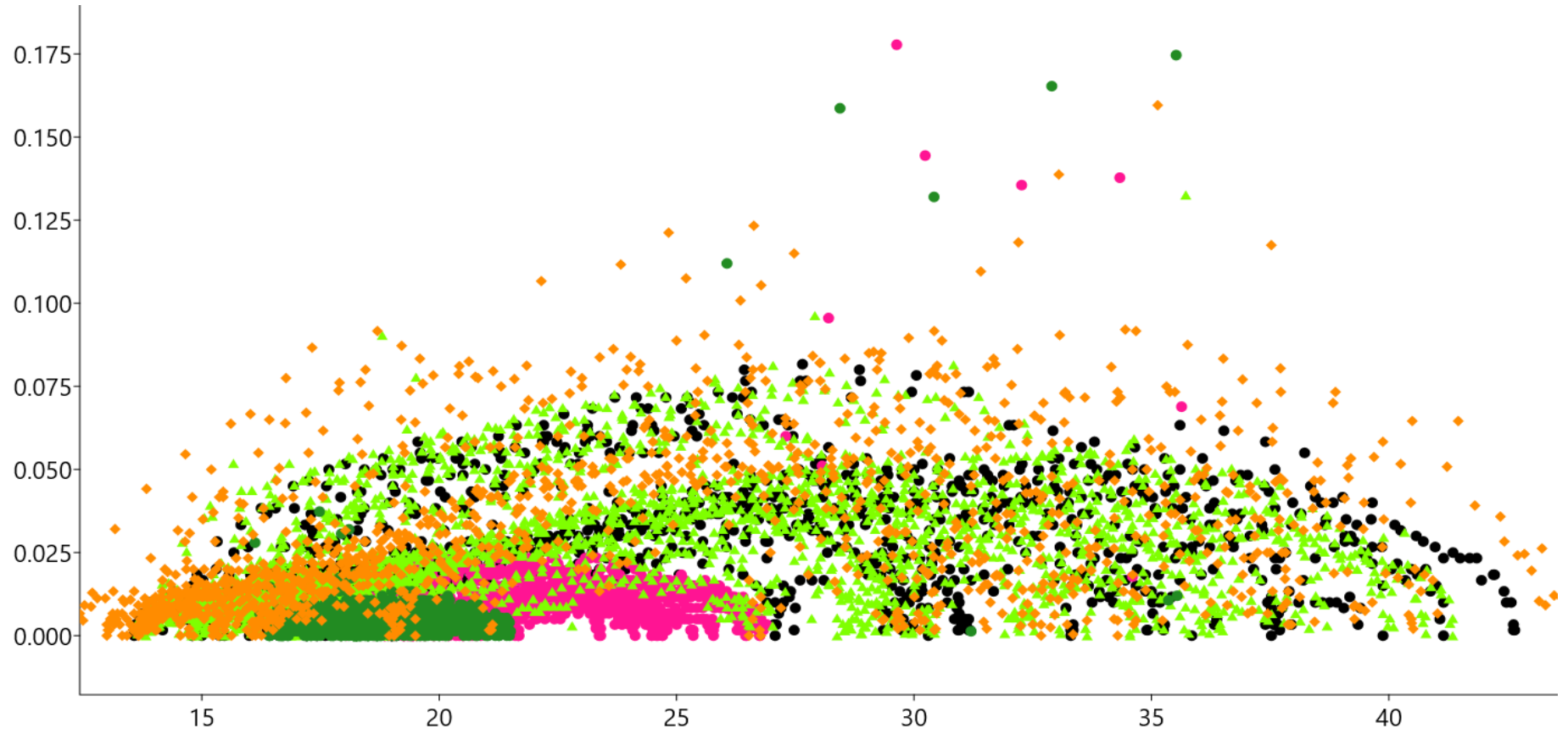


Figure 29 - Rate of temperature change every 15 minutes (y axis) and average temperature every 15 minutes (x axis), from EXP1 and EXP4. A bell curve is evident where very little differences are observable in the extremes (maximum and minimum of y axis). The extreme environment caused by the pots in glasshouse, extends the curve to over 40°C. Sub soil (orange points) seems to extend the furthest for both temperature rate and averages. Bares soil (black points) and samples with plants (green points), are reduced but still extend over 40°C. The field trial on the other hand, seems to occupy a completely different temperature:rate space entirely and the distinctions between Meadow (green data points) and Disturbed (pink data points) soil is very clear.

4.3.5 Difference between bare soil and treatment

The MEANSTDEV of samples containing plants (TI, TI+, BJ), with shading (Sh) or with different soils (Sand, Sub) was subtracted from the bare soil (BS) across all experiments (Figure 30). Appendix D shows the calculations and data analysis. The more homogenous soils (Sand and Sub soil), tended to result in a significant ($p<0.05$) negative change (MEANSTDEV was greater), whereas samples containing plants were generally a significant ($p<0.05$) positive change (MEANSTDEV was lesser). The greatest positive change was exhibited by the Meadow when compared to the Disturbed site (Figure 30). When organised as plants and non-plants there is a highly significant difference between them ($p<0.006$, t test).

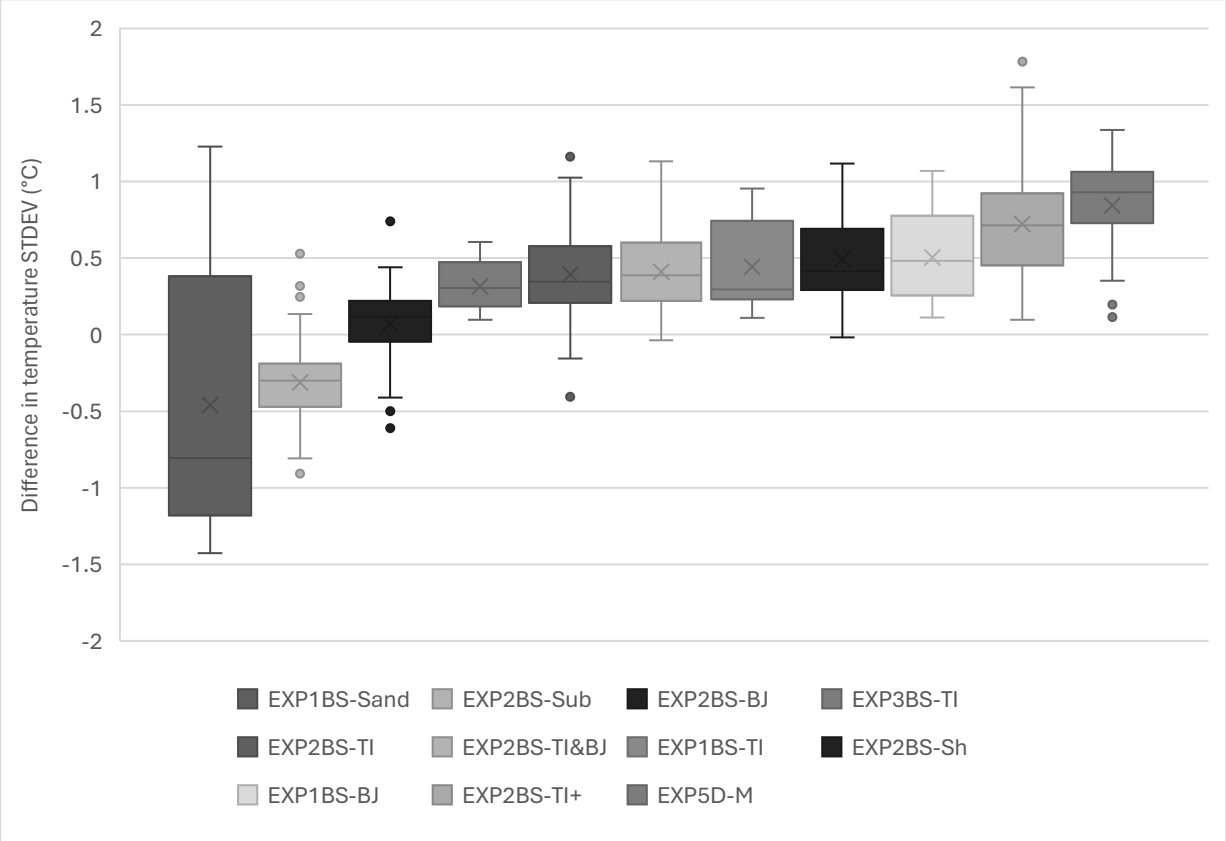


Figure 30 – Box plot of the difference in MEANSTDEV between bare soil (BS) and other samples containing plants or different soils, across all trials. All samples with plants showed positive difference to BS and all samples with more homogenous soil showed a negative difference, on average. Total N=226. Boxes are standard deviation and whiskers a ranges.

When compared against the Black soil, pure sands are both hotter at peak temperatures and cooler at minimums (**Error! Reference source not found.**), whereas the samples with plants in are the opposite, warmer in low temperatures and

cooler in high temperatures. The average difference in temperature (**Error! Reference source not found.**), between bare soil and the Sand at the solar maximum was 8.9˚C (+/- 0.26°C), whereas the BJ and TI were -0.324 (+/- 0.03°C) and -0.499 (+/- 0.03°C) respectively.

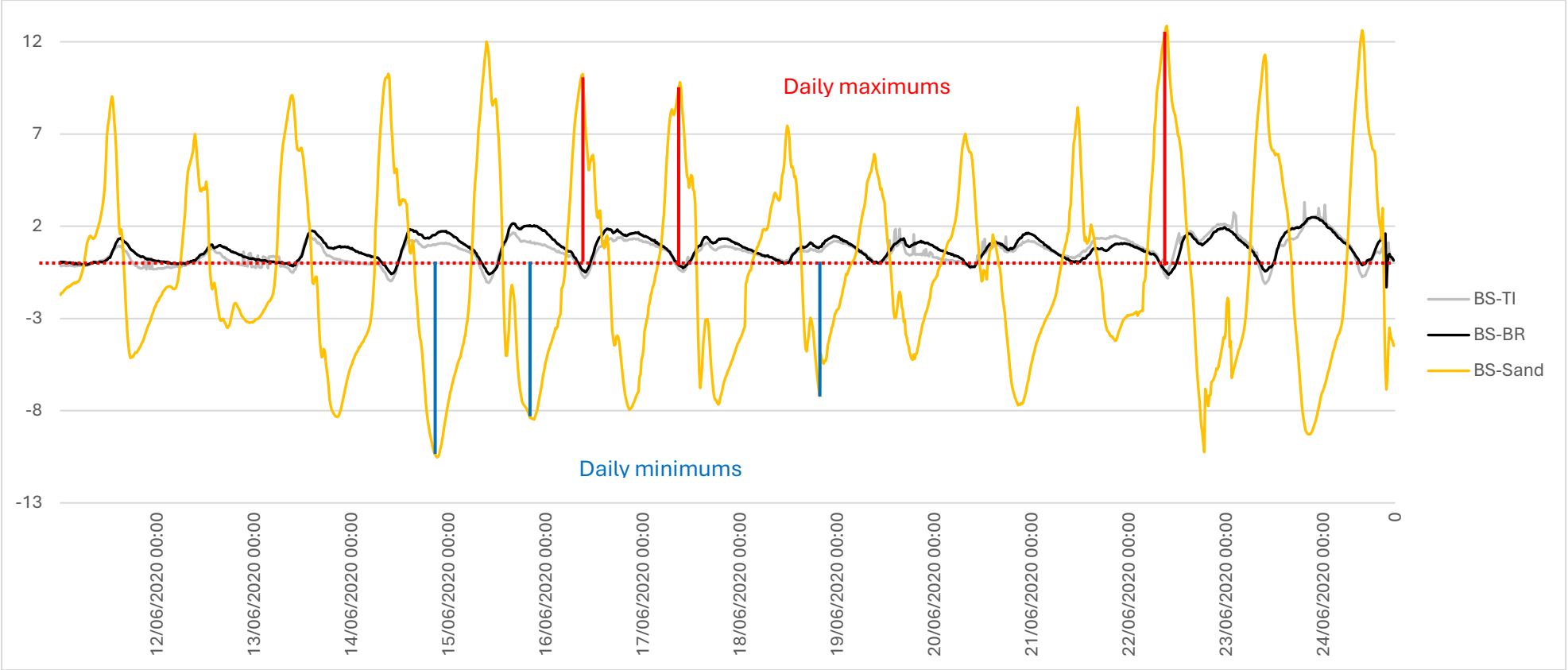


Figure 31 - The difference between plant-soil combinations and bare soil, calculated by subtracting Sand (yellow), TI (dark grey) and BJ (light grey) from the bare soil control over a period of 14 days in EXP1, where a pure sand was compared with bare black sols and Trifolium incarnatum (TI) and Brassica juncea (BJ), both in black soil. Data is continuous with data points every 15minutes. The Sand (orange line) oscillates dramatically and the difference is significantly higher ($p<0.0001$) compared to the samples with plants. Peaks and troughs from the daily average bare soil baseline (red dotted line) are steeper and opposite for Sand compared to both TI (dark grey line) and BJ black line), in that, at daily minimum temperatures (vertical blue lines), TI and BJ are higher and at daily maximums (vertical red lines) they are lower, whereas Sand is much higher at maximums and much lower at minimums.

4.3.6 Dry weight for EXP1 and EXP2

In EXP 1 there was no statistical difference for dry mass per plant between *Brassica Juncea* and *Trifolium incarnatum*. However, in EXP 2, both sample sets containing *Brasssica juncea,* were close to twice that of sample sets with just *Trifolium incarnatum* ($p<0.001$; Figure 32). Although, this did not show any correlation with temperature variables.

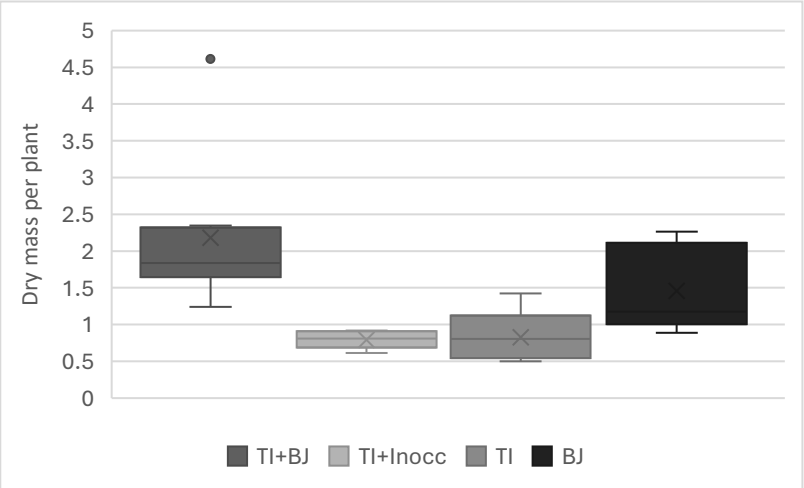


Figure 32 - Dry mass per plant of all plants in EXP 2, where two soils were compared and multiple pant models. Samples containing Brassica Juncea (BJ) contained on average ~1g more dry mass per plant (+/- 0.4g) of those containing Trifolium incarnatum (TI). Boxes are standard deviation and whiskers a ranges.

4.3.7 Changes in STDEV at different temperature bands

STDEV of the 8 hours leading up to MAX temperature was calculated for days when MAX temperatures were within certain temperature bands, see Appendix E for calculations and data analysis. For the most part STDEV increased with MAX temperatures, similarly observed in the correlation table (Table 5). In addition, samples containing plants were distinguished from bare soil and the more homogenous soils primarily between temperature bands 25-35˚C. For example, in EXP1 samples containing plants were significantly different ($p<0.03$) from both Sub and BS for 25-30 and 30-35 (Figure 33), but not for 35-40. Similarly, in EXP2, differences were not significant until band 25-30 (Figure 34). However, looking at the field trial (EXP4), differences were visible at the 20-25 band (Figure 35).

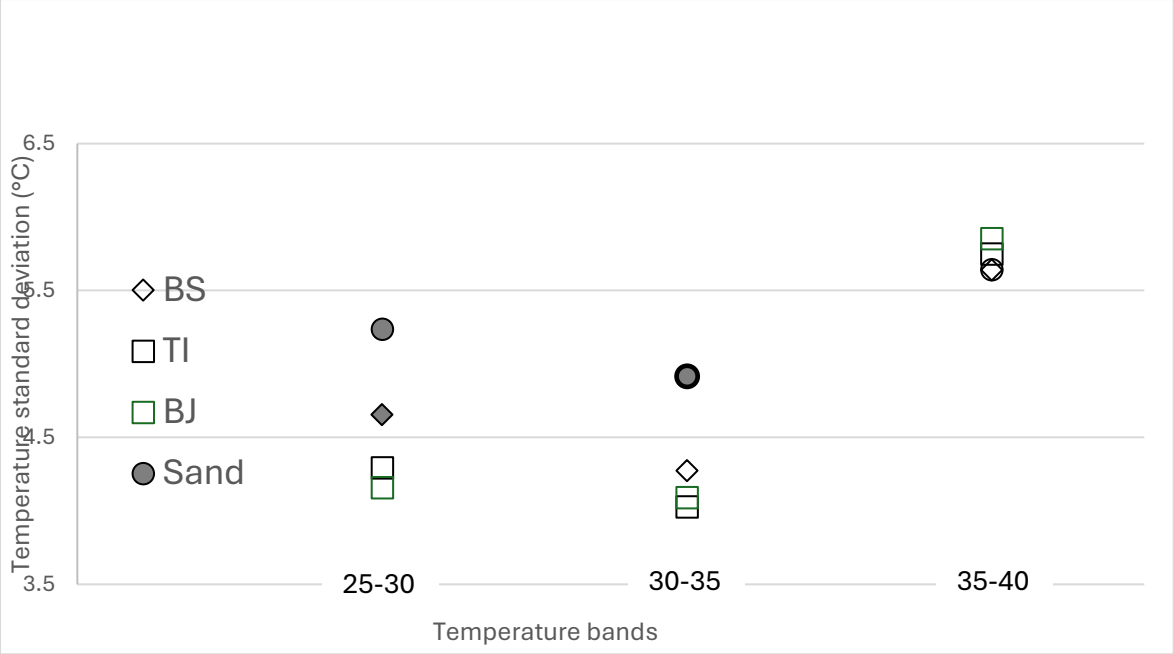


Figure 33 – MEANSTDEV for temperature bands, in EXP1, when maximum temperatures are within certain temperature bands. Plant treatments have lower STDEV in lower temperature bands but not in higher temperature bands. Samples containing plants (squares) were significantly different (p<0.03) from both Sub and BS for 25-30 and 30-35, but not for 35-40. Greyed out points are significant.

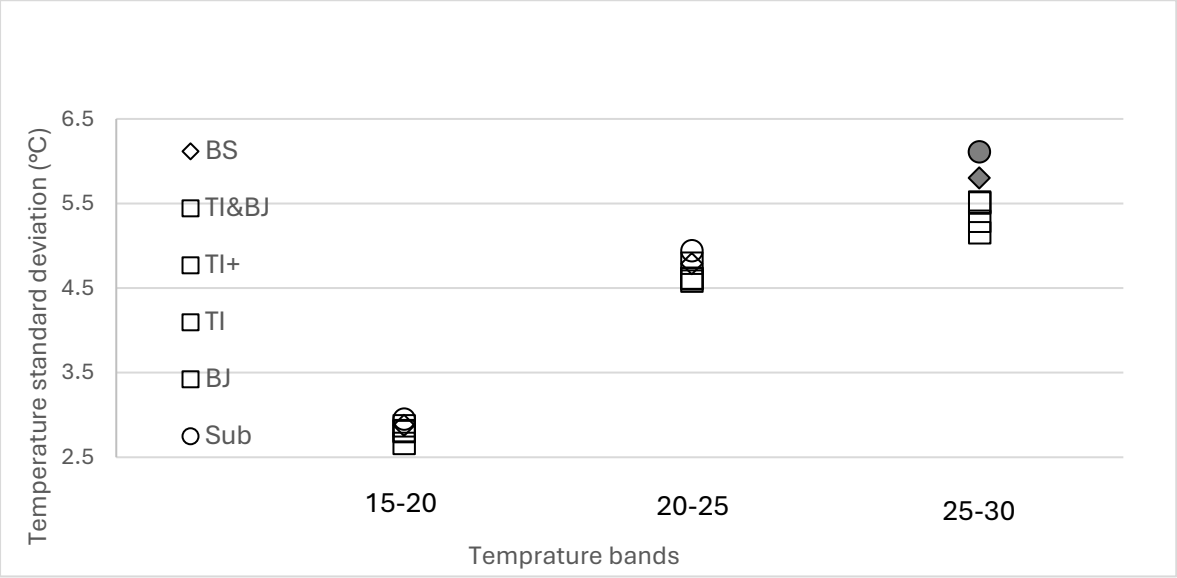


Figure 34 – MEANSTDEV for temperature bands in EXP2, when maximum temperatures are within certain temperature bands. Treatments more distinguished in temp band 25-30. Differences were not significant until band 25-30 and the clustering is evident in the 15-20 and 20-25 band. In the 25-30 band, the BS (circle) and Sub (diamond) are significantly different (greyed out).

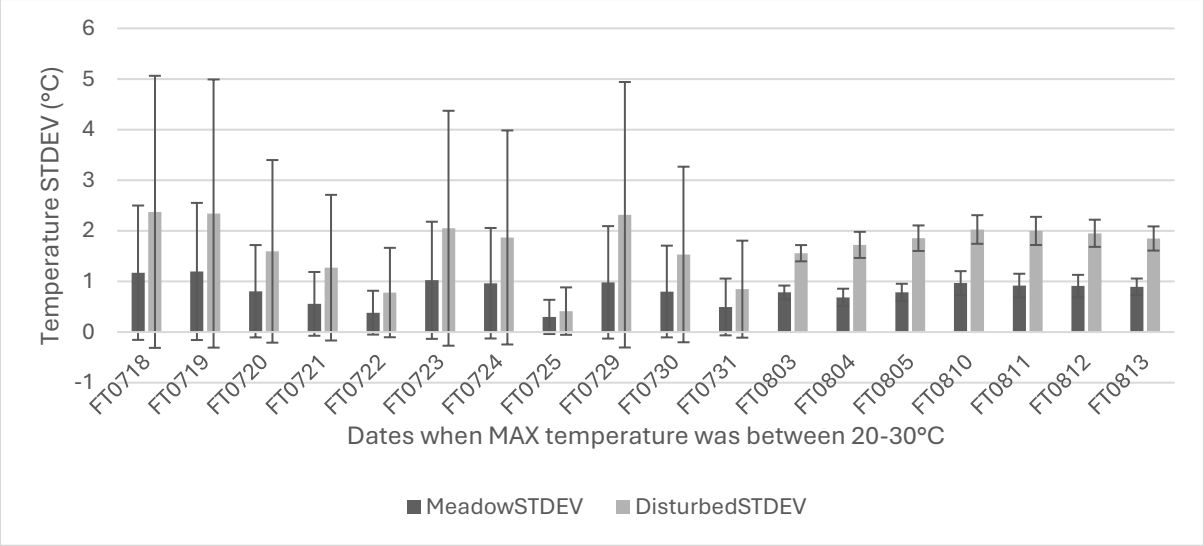


Figure 35 - STDEV of soil temperatures in EXP4 during the 8 hours leading up to daily MAX, for 17 days during the trial period, when MAX temperatures were as low as 19˚C. Disturbed site consistently greater STDEV p<0.001) except a few days (5, 8, 9 and 12). Confidence limits (error bars) were quite dramatic for the Disturbed soil (grey columns), this is likely due to logger malfunction on those days resulting in lower n. Total N = 129

4.3.8 Desiccation period

Over the desiccation period in both drought simulation experiments (Drought1 and Drought2), soil moisture content declined more in the first 2 days and was lower in the final day, but the difference was much less (Figure 36). Samples with plants tended to show the most water loss (Figure 36). MC reflected temperature variables and on the final day both MAX and DTR were statistically higher for all samples, despite similar ambient temperatures (Figure 36) in Drought2 (Figure 37).

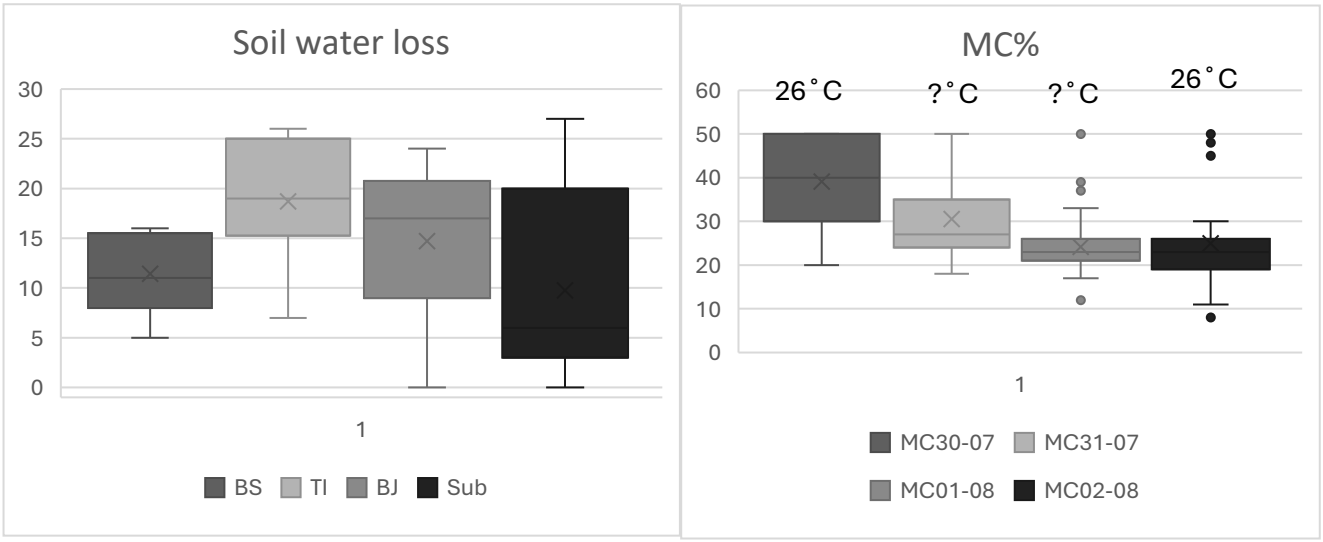
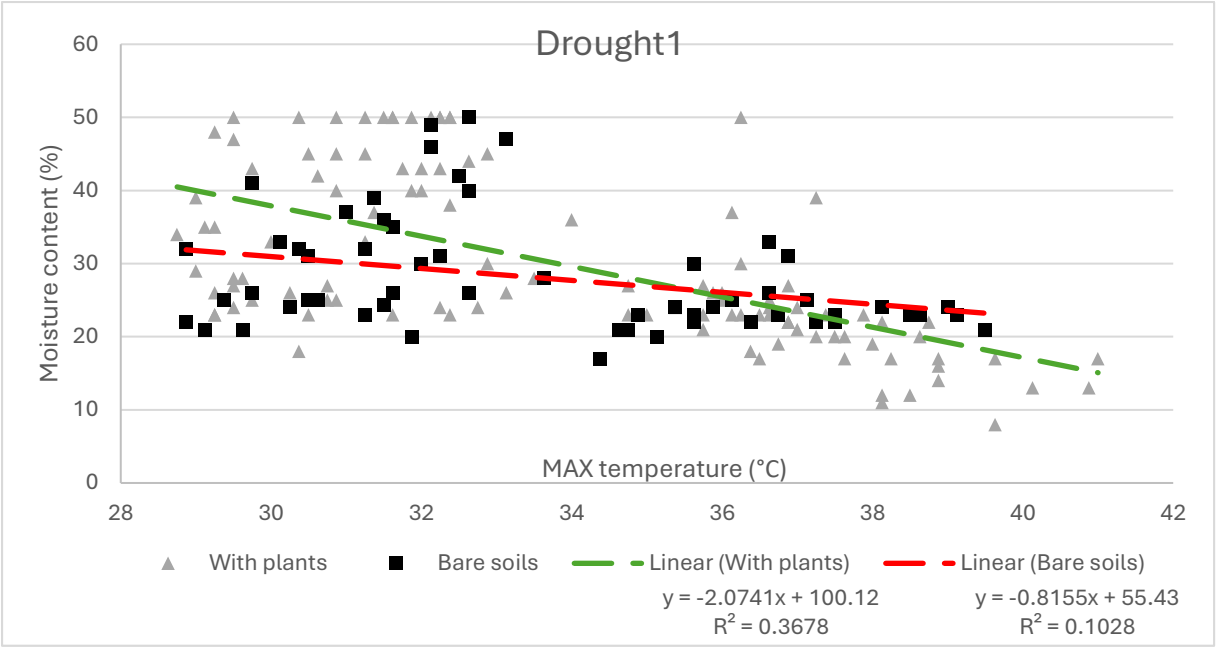


Figure 36 – Moisture content and soil water loss during Drought1 (24th-27th May) and Drought2 (30th July – 2nd August). Left, total water loss for each sample group in Drought1, where water loss was greater in sample groups with plants; Brassica Juncea (BJ) and Trifolium incarnatum (TI) Right, Moisture content (MC%) for all samples across the period of desiccation. Water reduced more rapidly in the first two days compared to the last two days. Ambient temperatures on the final day (above boxes) were on average the same as the first day n=192..Boxes are standard deviation and whiskers a ranges.

4.3.9 Temperature, moisture correlations

Across both desiccation periods, there was a clear highly significant negative correlation between moisture and temperature metrics such as DTR and MAX temperatures. Interestingly bare soil treatments showed lesser linear fit (lower r^2), than with plants (Figure 37). Most temperature metrics correlated negatively with MC% (MAX p= $6.7361X10^{-13}$, MIN p= $7.4902X10^{-12}$, MEAN p= $1.806X10^{-15}$, STDEV p=0.022376, DTR p=8.0919E-12, CoeffVAR p=0.065376, Spearmans rank).



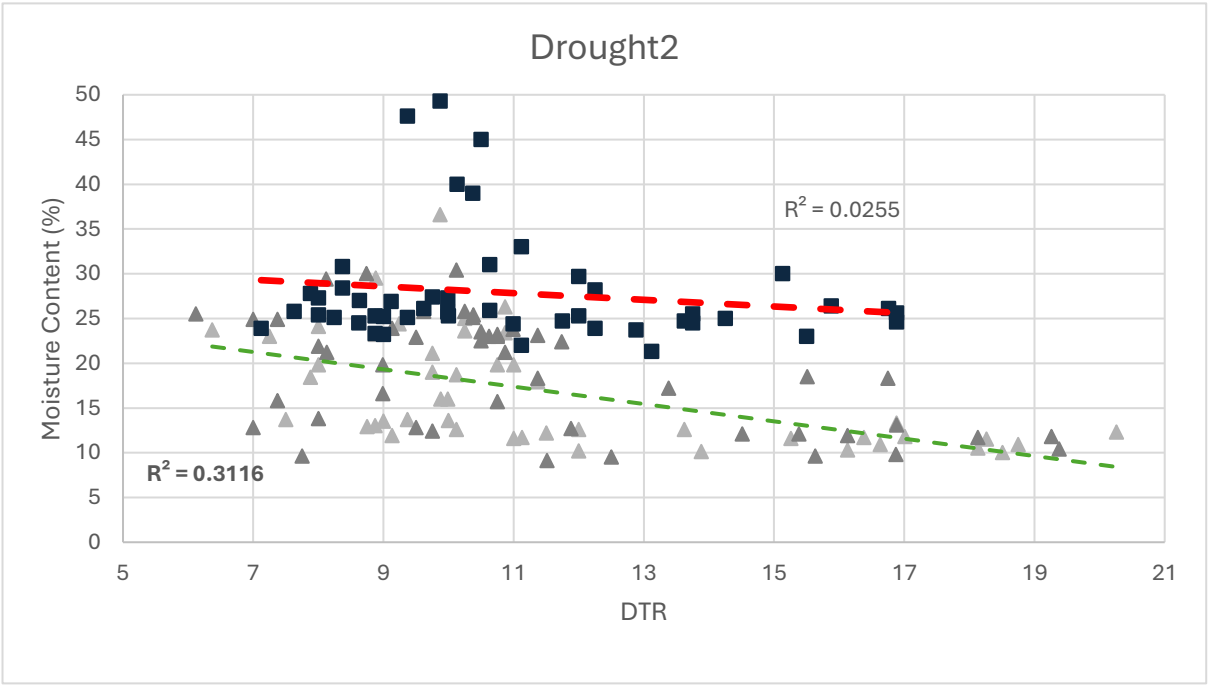


Figure 37 - Temperature and soil moisture correlations of two drought experiments (Drought 1 and Drought 2). . In both occasions samples with plants (triangle; green linear dashed trendline) showed better linear fit (R^2=0.36) compared to bare soils (R^2=0.1; square; red linear dashed trendline).

4.4 Discussion

4.4.1 Temperature variability as a soil health indicator

The utilization of temperature as an indicator of soil health is little discussed and complicated by a number of environmental factors, such as changes in weather, landscape formation, vegetation differences, soil management practices, etc (Al-Kaisi *et al*., 2017). The experiments here have attempted to minimize these interferences and work in a controlled environment to better understand it's implications in soil health monitoring. In many ways this has made the analysis more complicated, because ecosystems are emphatically open (Boltzmann, 1905; Schneider and Kay, 1995; Vihervaara *et al*., 2019) and by closing them off, the trends that were expected have become a little obscure. However, some expectations were realised.

Soils with less structural heterogeneity (Sand and sub soil) in EXP1 and EXP2 were less attenuated (greater STDEV, DTR and CoeffVAR) than those with more distributed textural properties. Sand being the most variable overall (Figure 20, Figure 30 and Figure 31), followed by Subsoil (Figure 22, Figure 24 and Figure 30). In the first instance higher thermal conductivity of clay particles (Abu-Hamdeh, 2003) found in the loam soils compared to sand, has shown in previous literature to impact how fast the soils change in temperature (Sauer and Horton, 2005). That said, both the sub soil and the Loam soil contained the same amount of clay particles (Figure 15), indicating further contributing factors of the Subsoil's thermodynamic response. With its higher content of sand particles, the Subsoil had a lower density per surface area, which is known to increase the radiation of heat to the surroundings (Farouki, 1981). Furthermore, the reduced moisture holding capacity of the free draining sand soils would have undoubtedly had an impact. Water acts as a thermal mass, with high values of latent heat (Koorevaar *et al*., 1983) and through the evaporation process, contributes to free energy dissipation (Abu-Hamdeh, 2003; see chapter 5).

Although both temperature variability indices (STDEV, DTR, CoeffVAR) and temperature metrics (MAX, MEAN and MIN), provided adequate distinction between the expected plant-soil models, MAX, MEAN and MIN, by far showed the greatest confidence (Figure 16, Figure 17, Figure 18 and Figure 19). Deviation from average trend lines in Figures 16 through 24, is indicative of the high variability as a result of a myriad of different interacting abiotic and biotic factors that drive energy flux (Lotka,

1922; Odum, 1969; Pokorný *et al*., 2010; Michaelian, 2015; Vihervaara *et al*., 2019; Suman *et al*., 2020). Note that in most circumstances (Figure 16, Figure 17, Figure 18 and Figure 19), with the increase in soil structural heterogeneity or inclusion of plants (increasing complexity), deviation from the average trend line shallows, evidenced by the decrease from MAX and the increase from MIN, with similar decrease in variability indices. This demonstrates the buffering capacity of the plant-soil system (E. D. Schneider and Kay, 1994; Schneider and Kay, 1995; Jørgensen, 2006b, 2008b; Ferri and Arnés García, 2023) and fits the model presented in Figure 13, supporting the utilization of temperature as a thermodynamic indicator of ecological structure and function (Norris *et al*., 2012; Michaelian, 2015; Avelar *et al*., 2020).

The behaviour of soil temperature variability at extremes is different from the behaviour at mid-range temperatures. Overall there is a strong corelation between STDEV and MAX temperatures, a result of the relationship that STDEV has with the MEAN. However, Figure 28 highlights the influence that increasing temperatures has on temperature variability and how a loss of structure and function can negatively impact the systems ability to regulate itself (Santos *et al*., 2019; Howe and Smith, 2021), The rate of temperature change is also affected (Figure *29*) and diminishes toward the extremes, likely a result of the soil coming in to equilibrium with its surroundings at minimum and maximum events. At both extreme ends of the temperature scale (very low and very high), the rate of temperature change tends to be slower due to the physics of heat transfer and the limited capacity for molecules to absorb or release energy at those extremes; essentially, it takes more energy to significantly change the temperature when already very hot or very cold. The higher rates experienced are also reflected in the temperature bands (Figure 33 and Figure 34), where STDEV levels out between samples in lower temperature bands (15-25) and upper temperature bands (35-40), with significant differences experienced in mid-range temperature bands (25-35). That said, the fact that in EXP4 (field trial) showed differences between Disturbed and Meadow between 20-25, indicates that variation at relative to the specific conditions of the experiment. These novel findings warrant further research into the evolution of temperature variability at different temperature bands.

Drought scenarios were tested by desiccation, to explore the relationship with moisture content and thermal properties in water limiting conditions. MC was mostly negatively correlated with temperature measures and variability. As moisture decreases the system becomes increasingly more unable to dissipate the solar energy. The role of moisture and evapotranspiration is discussed in more detail in the following chapter 5, however it can be noted that the correlations drawn here support just how important moisture is in the dissipation of energy (Norris *et al*., 2012; Michaelian, 2015; Avelar *et al*., 2020). Interestingly, the results in Figure 19 and Figure 22 show that MIN temperature is a good indicator of the soils structural properties rather than soil moisture, whereby Sub soil in EXP2 and Sand in EXP1 were statistically lower MIN temperatures to other samples, but in EXP 3 there was no statistical difference between the 2 water regimes. Exploration into the relationship between soil temperature metrics and soil properties like moisture content and soil structure in this context could perhaps identify more specific uses of the individual temperature metrics, for example MIN temperatures indicative of soil structure and MAX temperatures indicative of soil function.

Complications of the simplified experimental design are more noticeable when examining the moisture content, in relation to the temperature. In some circumstances such as EXP3, the relationship to temperature is clear.Over the desiccation period in both drought simulation experiments (Drought1 and Drought2), soil moisture content declined more in the first 2 days and was lower in the final day, but the difference was much less (Figure 36). Samples with plants tended to show the most water loss (Figure 36). MC reflected temperature variables and on the final day both MAX and DTR were statistically higher for all samples, despite similar ambient temperatures (Figure 36) in Drought2 (Figure 37). However, with a lack of a true control group, careful analysis is required to distinguish the thermal regime as a result of the treatment (soil texture or with and without plants), or that influenced by the ambient temperatures. The ambient temperature of the final day of desiccation, when moisture levels were at a minimum (wilting point), was on both occasions, the highest. This challenges the ability to validate the results, due to the external influence of the ambient temperature. However, day 1 (30-07) of EXP3, was the same MAX ambient temperature (26˚C) as day 4, despite a significantly lower MAX temperature experienced by the samples – day 1, 32.63 and day 4, 37.97 (Figure 36 and Figure 18). This shows disparity between

the ambient temperatures and the temperatures experienced within the soil samples, supporting the case for moisture influence. For the most part, correlation between moisture content and temperature metrics in is as expected and this experiment supports the consensus that soil thermal properties are somewhat driven by moisture content (Abu-Hamdeh, 2003), its variability with porosity and the volume fractions of solids (Farouki, 1981), however, needs further investigation, i.e. a more effective way to control the moisture content of the samples (explored in chapter 5).

The correlations drawn between temperature measures (MAX, MIN and MEAN) and variability indices (STDEV, DTR and Coeff VAR) validate the data with Figure 13 in support of temperature as a proxy of energy dissipation (Ulanowicz, 1997; Jørgensen and Fath, 2004; Ulanowicz, 2009c; Norris *et al*., 2012; Molozzi *et al*., 2013; Michaelian, 2015; Avelar *et al*., 2020). Maximum temperatures, including the HiMAX and the LoMAX tend to correlate with measures of variability (Table 5 and Figure 28). As pressure from solar radiation increases so does variability. Increasing solar radiation inputs more energy in to the system and without the necessary structures and functioning to effectively dissipate the energy, a greater fraction is lost as heat, essentially due to a breakdown in entropy production and exergy storage (E. D. Schneider and Kay, 1994; Schneider and Kay, 1995; Jørgensen, 2006b, 2008b). Interestingly MIN temperatures, especially the LoMIN mostly corelated negatively with measures of temperature variation (Table 5). This fits the model in Figure 13 and the more homogenous soils were at the upper end of variability (Figure 28), corroborating previous research exploring temperature as an indicator of complexity and exergy storage (Norris *et al*., 2012; Michaelian, 2015; Avelar *et al*., 2020). Through the relationship with structure and function. This demonstrates that temperature can effectively determine the ability of a system to dissipate incoming solar radiation by examining the variability of temperature during the period leading up to the MAX.

Where this research is most open to refute is the impact of shading on the results in EXP2. Shading blocks the solar radiation and the energy of which is either absorbed by the object or reflected into the surroundings, which is of course true for the plant as well, but the mechanisms are different, one being where the energy is degraded or dissipated through biological processes and the other being a purely physical one. These figures were not gathered, however, shading (Sh) performed high in the ranking

of cross comparison (Figure 30), more similarly behaving like samples with plants, rather than bare soil. Indicating that the shading has a similar effect on thermal performance as biomass. On one hand this shows just how effective plants are at dissipating solar radiation, on the other hand it questions whether temperature is more a result of the plants simply acting as a shading object. In EXP 2, perhaps measurements of surface temperatures would facilitate the ability to discern the contributions of both the biological processes and the physical ones. However, despite there being a significant difference in temperatures overall between Disturbed and Meadow in the field trial, the difference between the surface and soil in each of the treatments was not found to be significant (p=0.30252), indicating that vegetation cover impacted both systems with strong biological influence. As such, none of the results here clarify whether shading is an influential factor and future research needs to understand this factor, before progressing with the concept.

4.4.2 In support of a thermodynamic approach to soil assessment and management

In the various experiments within this study the scientific enquiry compared samples/ plots differing in their structural and functional properties, representing degrees of exergy. From pure sands and more homogenous soils to heterogenous textures, with and without plants, and diverse meadows. Temperature variability overall tended to decrease with more complex scenarios (Figure 30. This was expected, especially in the field trial, where previous research showed similar trends in forest eco-systems (Norris *et al*., 2012; Michaelian, 2015; Avelar *et al*., 2020). Heterogeneity within the physical and ecological structures, formed through plant-soil interactions (Ehrenfeld *et al*., 2005) create gradients as the system distances from equilibrium (Chapter 3; Boltzmann, 1905; Schneider and Kay, 1995; Vihervaara *et al*., 2019). High disturbance and/or in scenarios of highly eroded soils, where texture and structure is poor (Peipoch *et al*., 2015; Parrish *et al*., 2003); gradients diminish and thermodynamic growth factors such as entropy production, specific dissipation and specific exergy all decrease (Jørgensen *et al*., 2000). Internal entropy builds (Lotka, 1922; Prigogine, 1955; E. D. Schneider and Kay, 1994; Aoki, 2012) and poor dissipation degrades energy in to heat.

As complexity builds (in scenarios containing plants or in the meadow), systems reduce their structural entropy, exporting it to the surroundings (Prigogine, 1967) and this is expressed in the individual temperature regimes (micro climate) of the samples.

Alter the mass of the system and the data indicates that it changes both the rate of temperature change (Figure *29*) and the extreme values of temperature, both in terms of extreme highs (Figure 17 Figure 18 and lows Figure 19). An ecological succession, as in Figure 12 can be visualized from the results here (Figure 31). Thermodynamic performance is related to structure and function (Boltzmann, 1905; Schneider and Kay, 1995; Vihervaara *et al*., 2019). Interestingly the meadow overall displayed the greatest significant difference from bare soil. Complex structures and greater levels of biomass and functional diversity, act to enhance the degradation of solar energy and regulate microclimate (Norris *et al*., 2012). Despite soil moisture content converging between the disturbed and meadow sites (Figure 25), in the field trial, temperature variability is consistently significantly greater in the disturbed site. This provides exceptional evidence of how complexity builds more efficient structures to dissipate energy. A number of species cohabit the meadow habitat (Figure 14) and their interactions whether through promoting soil structure or promoting functionality appear to have a positive impact on the thermal properties and so the thermodynamic behaviour. Furthermore, soil texture (the heterogeneity of particle distribution) can also modulate the effects of climate change with its influence on carbon cycling in forests, including tree growth response and OM retention (Gómez-Guerrero and Doane, 2018).

During desiccation, samples containing plants for the most showed an increase in moisture loss, this is due to enhanced evapotranspiration and did not always reflect in temperatures. In this circumstance the expected trends became less obvious, but in many ways highlights the openness of natural systems (Chapter 3;(Boltzmann, 1905; Schneider and Kay, 1995; Nielsen *et al*., 2019; Vihervaara *et al*., 2019). Evapotranspiration is a combined effect of evaporation from the soil and transpiration from plants and the latter moves water at a significantly higher rate, drying out the soil faster (chapter 5). This is evidenced by the greater moisture loss on average for the pots containing plants (Figure 36). It is worth noting at this point that previous literature suggests that vegetation and organic residues play a role in moisture retention (Howe and Smith, 2021), contrary to the perceived results here. However, as mentioned previously, this is a result of the isolation of the samples in this experiment. When the enquiry looks at the field trial where higher diversity samples yield significantly lower temperature variability despite similarly low moisture levels (at 10cm that is), it's clear how openness contributes to thermodynamic performance (Chapter 3; (Boltzmann,

1905; Schneider and Kay, 1995; Nielsen *et al*., 2019; Vihervaara *et al*., 2019). With a consistent supply of moisture in the soil, free energy dissipation and the associated entropy production (Lotka, 1922; Prigogine, 1955; E. D. Schneider and Kay, 1994; Aoki, 2012), constituted by photon dissipation and transpiration, is reflected in the micro-climate of the meadow (Norris *et al*., 2012; Michaelian, 2015; Avelar *et al*., 2020).

This study provides evidence for the important role that structure and function play in energy dissipation (Jørgensen *et al*., 2000). Supporting previous studies that examined complexity in the form of biomass, information and networks and its relation to ambient thermal properties (Eric D. Schneider and Kay, 1994; Norris *et al*., 2012; Avelar *et al*., 2020). To expand the knowledge base and explore belowground. The soil is often considered separate from the above ground structures, however they are in fact subsystems nested in larger interconnected systems (Gunderson and Holling, 2001). With cross scale interaction (chapter 2). Defined by an exchange of matter and energy across their individual boundaries. Overtime and with the advancement of complexity, these structures and autocatalytic loops refine, favouring loops with the least resistance (Ulanowicz, 1999, 2006, 2016). The resultant network is a more efficient version of itself based on the current constraints, reducing its structural entropy and therefore exporting entropy to its surroundings (Lotka, 1922; Epstein *et al*., 2006; Henry and Schwartz, 2019). These changes can be measured in the form of microclimate and this research corroborates previous papers with similar objectives (Eric D. Schneider and Kay, 1994; Norris *et al*., 2012; Avelar *et al*., 2020).

To a certain degree, this study evidences the impact of plant-soil interactions and the uniqueness of individual species. First let it be stated that by no means does the author feel it is scientifically appropriate to directly compare two different species as ‘treatments’, as there are too many factors and variables that are not accounted for in the simplified experimental design here. It is merely to represent the potential investigation into the role of functional traits in the context of this thesis. An improved experimental design would perhaps follow a traditional approach and breed model organisms to have functional deficiencies of certain traits, in which to compare.

If then, the different species are in fact considered as functional representatives, from the results here, it is possible to speculate that the traits associated with *Trifolium*

incarnatum tend to result in a greater improvement in temperature variability compared to bare soil (Figure 30). This could of course be explained by a reduced transpiration from the smaller leaf area compared to BJ (Tribouillois *et al*., 2015), that was leaving moisture in the soil, but this was not always consistent based on the data. Instead, it is also important to consider additional structures on this species that may enable more efficient energy dissipation. For instance, its rosette formation compared to the upright structure of the BJ. In EXP 2 dry weight as an indicator of biomass in both of the sample groups containing BJ, was twice that of TI (Figure 32), likely a result of the much greater leaf area (Tribouillois *et al*., 2015). Again referring to the openness of ecological systems, here the greater biomass production is resulting in a poorer attenuation of temperature, indicative of limiting energy dissipation (Eric D. Schneider and Kay, 1994; Norris *et al*., 2012; Avelar *et al*., 2020). TI is operating within the boundaries of the species' resource utilization, whereas the competitive trait of BJ requires more resources that exceed the limit of the semi-isolated system. Further supporting the case for openness in agricultural systems. Moreover, the combined effects of enhanced biomass production and greater evapotranspiration that is perhaps using more water, exasperates the BJ's thermal performance and explains the hotter and more variable temperatures experienced in the *Brassica juncea* samples. Functional traits related to leaves (Tribouillois *et al*., 2015b), may be a key variable in the difference between *Brassica Juncea* and *Trifolium incarnatum.* Although it was not measured, it fits well that leaf traits would influence energy dissipation, as they are closely related to both accumulation through photosynthesis and to control evapotranspiration, through stomata.

Although nodulation was not estimated due to the need for destructive sampling. Nodulation contributes to the uniqueness of the species. Legumes form refined autocatalytic loops that abate energy dissipation. Nodulation of Leguminous plants is a well-known structure that supports nutrient uptake and so structure formation. Although nodulation was not recorded here, it's fair to include in the assessment of the TI performance. An inoculant was added to one group of TI (TI+), but showed no statistical difference between the two. It is however difficult to make an assumption without data that confirms the extent of nodulation and could be an interesting avenue to take.

When the soil is viewed through the lens of different temperature bands, it shows that a goldilocks zone of thermodynamic function may be evident. In lower temperature bands, energy dissipation throughout all levels of complexity is similar and likewise in very high temperatures. Differences are primarily observed between 25˚ and 35˚ peak temperatures (Figure 33 and Figure 34). That said, the probes were not tested above 25˚C which may mean that above this temperature they are not as accurate. Also, a stress response could be evident as low as 20˚C as seen in the field trial (Figure 35). Understanding temperature thresholds better would further support the application of thermodynamics to soil health and further knowledge on the implications of ecological simplification on climate change.

Finally, In the field trial, surface temperatures mirrored soil temperatures. It highlights the relationship between soil and surface and how the soils ability to dissipate energy, influences microclimate at the surface (Sauer and Horton, 2005). Still maintaining their own temperature regime but intrinsically linked (Figure 26). Above all this along with many other results here bring to the attention of the scientific community, the necessity for openness that agricultural systems must adhere, to be truly sustainable.

4.4.3 Conclusions

Concepts of ecosystem health are rooted in systems-based perspectives, associated with theories on biodiversity and resilience (Michaelian, 2015). As such health indicators often look to species-based metrics and vulnerability to biotic and abiotic stressors, as well as quantitative measures of components, such as nutrient content (chapter 3). At present there is a lack of sufficient monitoring approaches to soil health (Lausch *et al*., 2018a), which are simple and cost effective that practitioners can easily adopt (Michaelian, 2015; Avelar *et al*., 2020).

Recently, enquiry into thermodynamics has shown potential for holistic indicators of soil health. This study corroborates research into thermodynamic indicators in mixed landscapes, taking the enquiry below ground and considering a holistic interpretation of plant-soil systems. The reason that temperature is a firm indicator of ecosystem function is due to the inherently thermodynamic character of living things. Ecosystem function can be extended to climate and temperature regulation through the development of structures that abet effective energy dissipation. Although it is important to maintain caution due to the simplified experimental design, the results

exemplify the intrinsically open character of eco-systems and the role this plays, in the structuring and functioning of the natural world.

The impact of shading on the soils thermal response needs to be properly understood in any future research into temperature as a thermodynamic indicator. What the results here show is that shading can give rise to a similar temperature response as vegetation. On one hand this does display the significance of above ground biomass on thermodynamic behaviour, however on the other hand it points out that temperature response may be a result of shading from vegetation rather than energy and matter flows, if they are in fact different.

One can surmise many structural and functional properties of eco-system's, yet none are more important and equally less investigated than the function of cycling energy and matter, that is driven by the interactions between above and below ground structures (Chapin *et al*., 1998; Hooper *et al*., 2000; Bardgett and van der Putten, 2014). This research has shown that feedback mechanisms between above ground biomass and the soil are tightly coupled and changes in the above ground thermodynamics (addition of living biomass) has an influence on the soils thermodynamic response. Temperature and micro-climate regulation is hypothesized to be a function of these processes and research in to temperature, with relation to structure and function, is only now emerging (Hobson and Ibisch, 2010; Norris *et al*., 2012; Stoutjesdijk and Barkman, 2014; Zhang *et al*., 2016; Greiser *et al*., 2018). As far as the author is concerned; in agronomy, the transition to cropping systems that consider thermodynamics, is a number one pre-requisite to a sustainable future.

Temperature has shown its usefulness in determining energetics, through its relationship to exergy and complexity. The measures derived from temperature data here do effectively capture the variability and temperature attenuation has shown a formidable relationship to structure and function. However, many other metrics can be derived from the temperature data that may be of interest in future research, for example, considering the temperature data as a wave and examining metrics such as frequency, wavelength, and amplitude.

Finally, this study has highlighted the importance of soil moisture in energy dissipation. Without inflow of this precious resource, the thermodynamics break down and the

system heats up. The following chapter explores soil water and temperature in a controlled environment with the use of a novel methodology.

5 Investigating the relationship between temperature, water and energy dissipation.

5.1 Introduction

The experiment detailed here attempts to overcome some of the limitations in experimental design from the previous chapter, utilizing a novel method for drought simulation (Marchin *et al*., 2020), to reveal the extent of moisture/temperature correlations. Exploring further their relationship with energy dissipation, their potential in soil bioindication and even identifying thresholds.

5.1.1 Soil moisture decline and the impact on ecological function

Evidence suggests that soil moisture is declining on a global scale. Between 2009 and 2019 in a study by the European Environment agency, soil moisture in the growing seasons of multiple years, was several times below the long term average (EEA, 2021). The increased frequency and intensity of drought pressure supports the investigation into drought tolerant and resilient agricultural practices. Global warming will undoubtedly accelerate water cycles, impacting soil moisture content (MC) in unknown ways. In a comprehensive study of the last 70 years Qin *et al*., (2023) found that MC in the top 200cm of the soil is decreasing on average by a rate of 1.284 kg/m2, increasing to 2.251 kg/m2 from 2010-2020 specifically. This is attributed to global warming and precipitation reduction, and will continue to decay in the future; further aggravating the global water cycle and the variability of extreme meteorological disasters (Qin *et al*., 2023).

Future climate models within already arid regions like the mediterranean, predict soil moisture deficits 5x over the standard deviation and up to 7x in extreme models (Soares and Lima, 2022). The frequency and severity of both precipitation and drought events are predicted to increase globally, impacting on critical soil processes such as microbial mediated decomposition of soil organic Carbon (Soares and Lima, 2022). In future scenario based simulations, Liang *et al*., (2021) discovered that soil organic carbon decomposition rates were more sensitive to drying than wetting, emphasising a nonlinear response, where decreased decomposition by microbes during drying is not compensated by wetting. What more the decline in soil moisture is accompanied by an increase in temperature and vapor pressure deficit (Meng *et al*., 2022). A fairly recent drought map developed by Pinke *et al*., (2022), provides

alarming evidence of the extent of soil moisture decline across the entire continent, between 1981 and 2017. With half of European countries experiencing a deficit, the most severe in Southeastern countries and around the Mediterranean, soil moisture is predicted to continue declining, with deep connotations for soil processes (Qin *et al*., 2023). In fact, in extreme arid areas of the world such as Portugal, this has even been predicted as much as a 20% decrease (Soares and Lima, 2022). Furthermore, without addressing climate related soil drying, up to 29% of global land could experience significant soil moisture depletion (Joo *et al*., 2020).

In corroboration with Huang and van den Dool (1993) and Illston *et al*., (2004), Agboma and Itenfisu, (2020) demonstrated that precipitation anomalies of less than the average long term rainfall amounts, decrease the upper soil moisture and lead to above average summer temperatures. This has been evidenced in many studies related to climate, or the predictability of soil moisture and temperature. The amazon basin, for example, where anomalies on air temperature correlate with anomalies in soil moisture (Tang and Chen, 2017). In Artic-alpine environments, soil moisture and temperature can be extremely variable (Aalto *et al*., 2013). Temperature can vary by 5 degrees and moisture by 50% over 1m distance (Aalto *et al*., 2013). This is strongly effected by local vegetation (Aalto *et al*., 2013). Different vegetation covers can lead to differences in water retention and there is a strong correlation between average MC and soil OM content (Wang *et al*., 2013). Soil organic carbon in particular, influences soil hydrology due to its structural properties and its impact on soil wettability (Védère *et al*., 2022). On the other hand, water availability influences biological activity itself across all scales, from precipitation levels shaping plant communities at the landscape scale, to the facilitation of OM decomposition at the micro scale (Védère *et al*., 2022).

The relationship between temperature and moisture in the soil has been studied for some time (Al-Kayssi *et al*., 1990; Z. Zhang *et al*., 2020), largely considered a product of the increased solar energy absorption resulting in greater heat storage capacity at higher MC (Al-Kayssi *et al*., 1990), which was also found to positively impact plant growth rate (Al-Kayssi *et al*., 1990). As such, soil moisture and temperature are significant factors affecting crop growth and development in agriculture, as well as being extremely influential factors for regional climate change, making their relationship increasingly more important to understand. Z. Zhang *et al*., (2020) reported an inverse proportional relationship with soil moisture and temperature in a

farmland setting and being that temperature is a strong determinate of crop growth, this exemplifies the need to address soil drying in agricultural landscapes. Furthermore, recent investigation in the field of ecosystem thermodynamics has started to draw comparisons between soil moisture, temperature and ecosystem function, exploring their utilization in health monitoring (Ulanowicz and Hannon, 1987; E. D. Schneider and Kay, 1994; Ibisch *et al*., 2010; Norris *et al*., 2012; Michaelian, 2015; Lin *et al*., 2018a, 2020; Avelar *et al*., 2020). As drought severity increases alongside the prospect of concurrent drought scenarios (Hoover *et al*., 2021), understanding thresholds of soil drying and how it may impact on key ecological processes, such as energy dissipation, is a necessity.

5.1.2 Evapotranspiration as a key process in energy dissipation

Thermo-hydrological processes are critical processes in the Earth system. The Earth is emphatically thermodynamic and the thermal and hydrological regimes are intrinsically linked. Work that began a century ago with Lotka (1922), concerning energy flows (see chapters 2 and 3), shifted early reductionism to systemic approaches rooted in physical laws, discussed extensively in chapter 3.

The second law is reflected in soil water movement as it depletes gradients in soil water potential (Hildebrandt *et al*., 2016). Energy is dissipated as the molecules in water spread out (Hildebrandt *et al*., 2016). Water along with every other substance in the universe, exists in one of three phases, dependent upon the temperature and the pressure, and (unless at triple point) distinct boundaries of phase change exist, manipulated by thermodynamics. Water vapour has a higher entropy than liquid and for every infinitesimal amount of vaporized water, a quanta of entropy is exported to the surroundings. In fact nearly half of the entropy production by atmospheric circulation is through the hydrological cycle (Pauluis, 2005). The evapotranspiration process dissipates the energy in the water inside the plant/soil, by dumping high entropy water vapour into the surroundings. This acts to cool the system primarily due to the phase shift as particles at the surface of the water gain energy from the medium. At a fundamental level, evaporation defines a phase change of energetic molecules, lowering the average energy of the molecules that remain, which are then open to absorb energy from the surroundings. Temperature is not a limiting factor as some of the molecules always have enough energy to enter the gas phase. Soil evaporation drives water availability and the portioning of sensible and latent heat (Koorevaar *et*

al., 1983; Abu-Hamdeh, 2003; Hesslerová *et al*., 2019). Evaporation occurs primarily at the soil surface, dependant on atmospheric demand (Or and Lehmann, 2019), dropping below the surface in low moisture levels due to the formation of a dry soil crust, which significantly slows evaporation (Lehmann, 2023).

Networks of plant-soil interactions that characterize ecological systems can be considered as part of a water column and are primarily active in the top 60cm of the soil horizon, which is the main water consumption area. Soil moisture is affected by evapotranspiration and as such, it moves upwards through the soil matrix (Y. Wang *et al*., 2021). Soil moisture fluctuation signals reflect evapotranspiration and when evapotranspiration is large water transport increases (Y. Wang *et al*., 2021). Below 60 cm is the main water storage area. Surface layers respond much quicker to precipitation whereas it can take over 260 hours for deeper layers to respond and movement of water can occur over 7 hours after the upper layers (Y. Wang *et al*., 2021). Deeper layers respond a lot slower to temperature and/or precipitation anomalies (Yuan *et al*., 2015; Yin *et al*., 2018) and soil moisture persists longer in deep layers rather than shallow (Wang and Shi, 2019). Moisture anomalies in the deep soil exhibit the longest hydrological memory compared to shallow and intermediate soil levels (Agboma and Itenfisu, 2020), as such, MC at surface soil layers are better at predicting short term drought and MC at deeper soil layers are better at predicting long term drought (Xu *et al*., 2021).

Evapotranspiration accounts for much of the energy dissipation within plant-soil systems and can be measured in the form of microclimate regulation (Norris *et al*., 2012; Michaelian, 2015; Avelar *et al*., 2020). As demonstrated by Pokorný *et al*., (2010), through the process of evapotranspiration, solar energy utilized by eco-systems for self-organization (chapter 2) acts to cool the system by exporting entropy to its surroundings, in the form of heat. Forests and wetlands are often discussed in terms of their mitigation potential to climate change through their function as a sink or source of greenhouse gases. However, the permanent vegetation has a direct impact on climate change through the process of evapotranspiration (Hesslerová *et al*., 2019). The water held in wet vegetation transforms solar energy into a greater proportion of latent heat within water vapor. This phase change of water that occurs through evapotranspiration has a significant cooling effect, mitigating thermal extremes and closing water cycles. For example, a dessert oasis forms a stable cool microclimate

which is not only helpful for vegetation growth, it creates a thermal circulation between the oasis and the adjacent desert that conserves water vapour over the oasis (Gao *et al*., 2004). These processes slowdown in simplified and degraded eco-systems, increasing the proportion of sensible heat, creating a warming effect (Norris *et al*., 2012; Michaelian, 2015; Avelar *et al*., 2020). Although transpiration is largely considered to be light limiting, in soil water abundant tropical forests, however, Meng *et al*., (2022) provided some interesting evidence to support a switch to water limiting under drought conditions, during the 2015-2016 El Nino drought.

Evapotranspiration rate seems to hold significance to structure and even function, a body of water for instance will evaporate water at a slower rate than a saturated bare soil, related to the difference in thermal properties between soil and water, driven by their structural properties (Li *et al*., 2020). The additional structure of plants further increases the rate (Chapter 4) and vegetation restoration even at landscape scales can cumulatively increase evapotranspiration rate (Qingming *et al*., 2022). Interestingly, increasing vegetation cover can lead to soil water deficits and a decrease in rainfall infiltration (He *et al*., 2024). In fact He *et al*., (2024) found that bare patches facilitated the recharge of and retention of soil water. Similarly, C. Zhang *et al*., (2020) found that introduced shrubs decreased soil water resources which led to degradation and lower species richness, concluding that in water limiting areas, grassland establishment may be a more suitable restoration goal. As such, restoration efforts must pay particular attention to soil moisture dynamics.

Hydrological cycles are linked to the surface energy balance and water emissions from soil through evaporation is a key process, limited by soil surface characteristics (albedo, roughness, residues) and hydraulic properties, as well as precipitation and solar energy (Lehmann, 2023). Evapotranspiration is an important ecological process, substantiated by comprehensive information on transpiration, in both natural settings ((Meng *et al*., 2022) and agroforestry systems (Zhao *et al*., 2022) on open-water evaporation (Shaw, 2005; Harwell, 2012) and well-watered crop lands (Allen *et al*., 1998; Jensen and Allen, 2016). However little is discussed from bare soil (Quinn *et al*., 2018), especially in reference to temperature and ecological function. It is the hysteresis between drying and wetting that is thought to dominate energetic dissipation, where significant heating is caused (McNamara, 2014).

5.1.3 Hypothesis

“During limited moisture conditions, the energy dissipation associated with evaporation and the ability of the soil to store energy are impeded, leading to hotter and less attenuated temperatures” (Norris *et al*., 2012; Michaelian, 2015; Avelar *et al*., 2020).

5.2 Methods

5.2.1 Experimental design

The design of the experiment followed a revisitation to a novel method for maintaining constant MC in potted soil from Marchin *et al*., (2020). The method utilizes the capillary action of floral foam in combination with a water reservoir to achieve fairly precise soil moisture constants. Four tanks, each containing a slab of floral foam, were fed by two reservoirs on stop cocks, one of which was height adjustable to simulate the slowly reducing water table. The four tanks (two for each treatment) were connected using low-density polyethylene piping and were arranged to achieve the best variation in positioning as possible, given the constraints of the experiment (see diagram below). Following leak testing of the tanks the floral foam was placed inside them and water level brought up to the highest in all four to begin the experiment.

3L pots were used that were slender enough to fit 6 on each floral foam slab (Plate 6). Large holes were made in the base of the pots that was then lined with a tightly woven, thin fleece material to allow moisture to pass but contain the soil above. This was so that when the pots were placed on to the foam, there would be sufficient contact with the soil to ensure water transport. The pots were then filled to equal volumes and weighed before being placed on the saturated floral foam slabs.

Plate 6 - Photograph of experiments setup. The wet and dry treatments were separated in to 2 sets of 6 pots and were positioned diagonally from each other to minimize to a certain degree the location influence on temperature.

The soil used was purchased from a nearby top soil quarry and was sterilised and sieved at 4-6mm, for ease of filling the pots, whilst preserving the integrity of macro-aggregates (Kravchenko *et al*., 2015; Zhou *et al*., 2020). Analysis of the particle size distribution measured as a pure loam (refer to Loam soil in chapter 4) . pH was 6.5 on average. Field capacity is approximated at 30% for good loams and less than 10% for permananet wilting point (Romano and Santini, 2002).

5.2.2 Data collection

Two data sets were collected, continuous temperature and regular MC estimates. Temperature data was measured by way of bespoke built temperature array and data logger. The system utilized Arduino prototyping boards alongside Dallas precision temperature sensors, that stored data on to an SD card at 15 minute intervals. Time was kept by a regularly synced real time clock and the system logged following an external clock source that switched the system on and off at the desired intervals. The temperature sensors were positioned at a 10cm depth from the top of the soil surface,

through a hole made in the side of the pots, that was moisture sealed using IP65 rated glands, to minimize moisture exchange with the atmosphere in the sides of the pots. Ambient temperature data was available but limited and the daily highs of some days are included in Appendix F (Summary data for Figure 38).

MC was measured by weight of the samples and in the control group was maintained at approx. 30% to follow field capacity (Romano and Santini, 2002). The initial dry weight was used as a reference and the subsequent increase in weight was taken as water in the sample, calculated as a mass percentage of the total weight of the whole sample. This was taken weekly and sometimes twice a week. Plants were not included in this trial, firstly to remove the influence of plants on the weight of the samples. Secondly, to remove any interreference of transpiration and create a baseline to work from of a worst-case scenario for an agricultural system.

5.2.3 Statistics and data analysis

Continuous temperature data recording at intervals of 15 minutes generates vast data sets of thousands of data points and can be extremely time consuming to analyse. As such a bespoke basic analytical programme was written using Pythons data analytics toolkits. This was primarily to speed up the analysis process, but also to rectify some occasional faults in the temperature array. The Python script took the raw data and firstly identified any missing data points that were due to power issues, or other glitches in the operations, it did this by comparing the date column to a complete date series. With these infrequent gaps identified the code interpolated the data as it needed complete data sets to run the next step. The code looked 8 hours back from the maximum (MAX) temperature of each day and calculated the average (MEAN) and standard deviation (STDEV), these three parameters (MAX, MEAN and STDEV) were then used in statistical analysis. A further step to save time was employed on Excel to automatically extract and transpose the data into workable columns and rows.

Looking back 8 hours from the MAX temperature, gave the rise in solar radiation up to the peak incidence. The STDEV of this shows the variability of this solar flux in the system. These two parameters were compared between treatments on a daily basis and correlations between moisture and temperature were analysed. MC was also interpolated between analysis dates to give an estimate for each and every day of the

experiment, that could be correlated with temperature data. Correlations were examined in terms of the difference between the control and the treatment.

5.3 Results

5.3.1 Soil moisture and temperature over time

Both the STDEV and the MAX temperatures deviated in conjunction with soil moisture content Figure 38. Significant at juncture from the 31st May ($p=0.0164$; Mann-whitney). Occurring on a day where MAX temperatures were 34.80°C-37.27°C and a difference of 10.6% SMC was recorded between drought and control group corresponding to a temperature difference of 2.46 degrees. Preceding this a consistent difference in STDEV ($p>0.00117<0.05$) followed and on average there was an increase in MAX temperature of 1°C for every 4. 33% drop in moisture, during this period (+/- 0.87%).

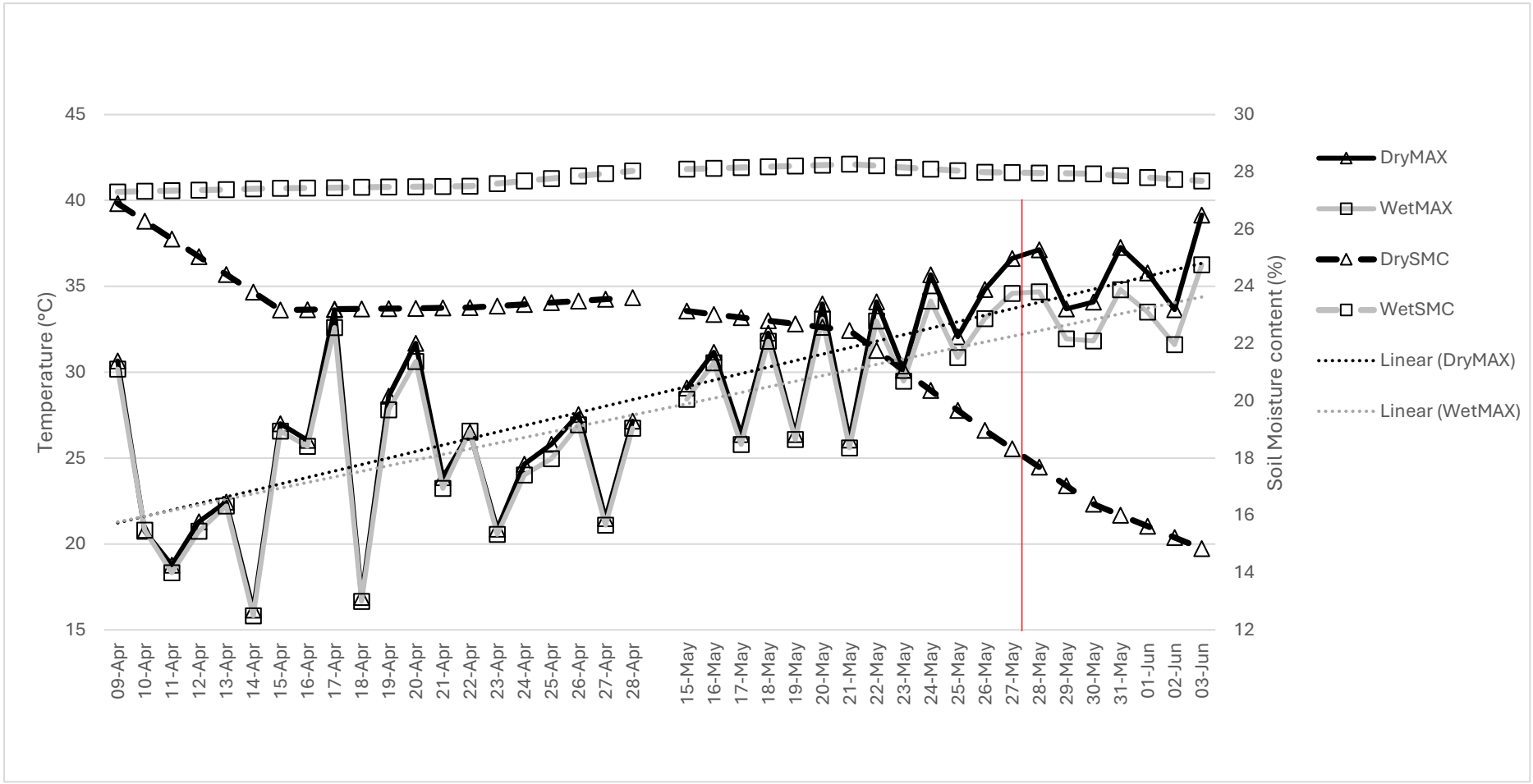


Figure 38 – Combined graph of maximum temperature (MAX; solid lines) measured as temperature (°C) on the left axis; with soil moisture content as a percentage (SMC; dashed lines), on the right axis. SMC was steady in the control group (WetSMC; grey) and the slow reduction of soil moisture in the treatment is evident (DrySMC; red) Temperature indices of treatments (MAX and STDEV) mirror each other and the drought treatment begins to separate around the 24th May, to a significant difference on 31st May ($p>0.00117<0.05$; red vertical line). Total N=120.

5.3.2 Soil moisture and temperature correlations

The difference in MAX and the difference in MC were calculated and compared to create a model of soil water and temperature with soil drying (Figure 39). The graph shows an exponential curve with high regression fit (0.841) and that a 12% (+/- 0.7%) decrease in soil moisture can increase MAX by nearly 3 degrees (+/-0.22°C). Refer to Appendix F for summary statistics.

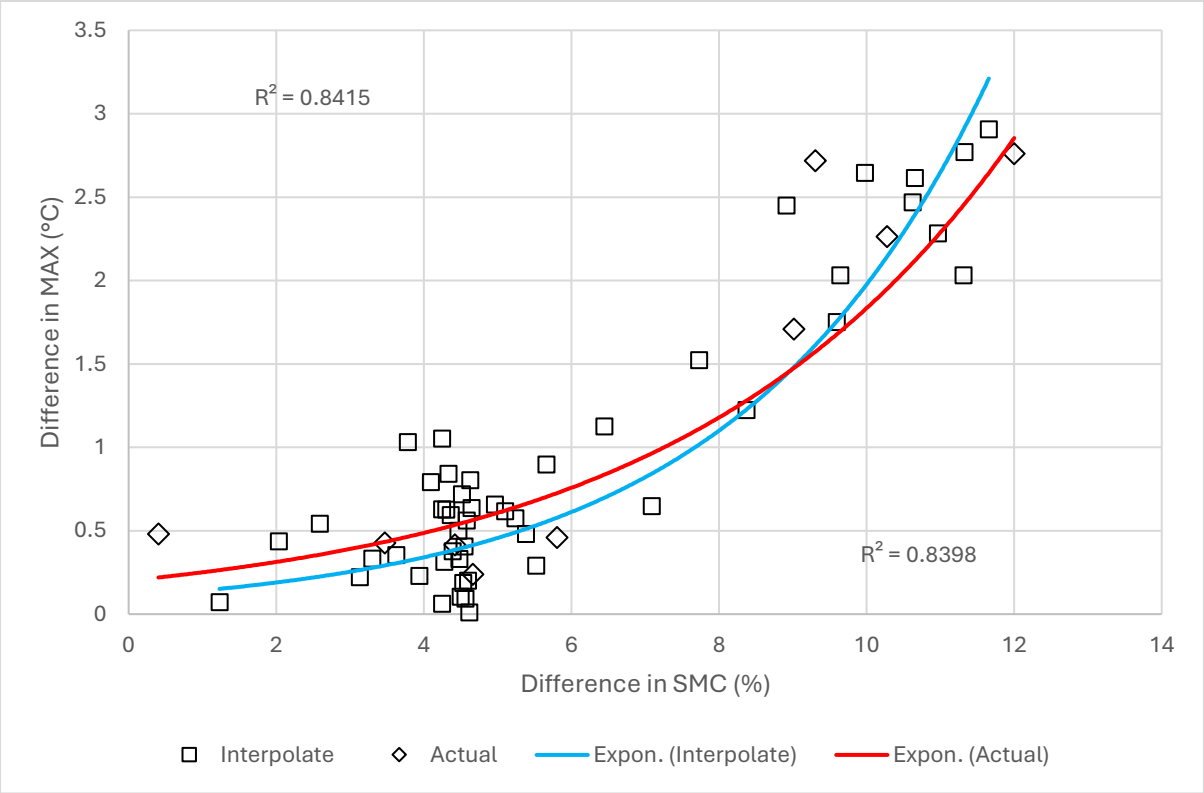


Figure 39 – The difference in MAX temperatures between Wet and Dry soil as compared to the difference in MC. At similar moisture contents MAX difference between Wet and Dry show little deviation and don't begin to separate until around 6% becoming significant at 10% difference, occurring around the 31st May ($p<0.0001$, Mann-Whitney). Each data point is the average difference between wet and dry for one day of the trial period. The trend shows good regression fit to exponential curve and the interpolated moisture data (square) fits well to the actual moisture data (diamond). n=24, over 54 days).

5.3.3 Thermodynamic recovery

Following re-wetting, a recovery of the temperature regime was evident, indicating that soil thermodynamics have an inherent resilience to drought, following soil water recovery (Figure 40). Appendix F gives summary data for the figure.

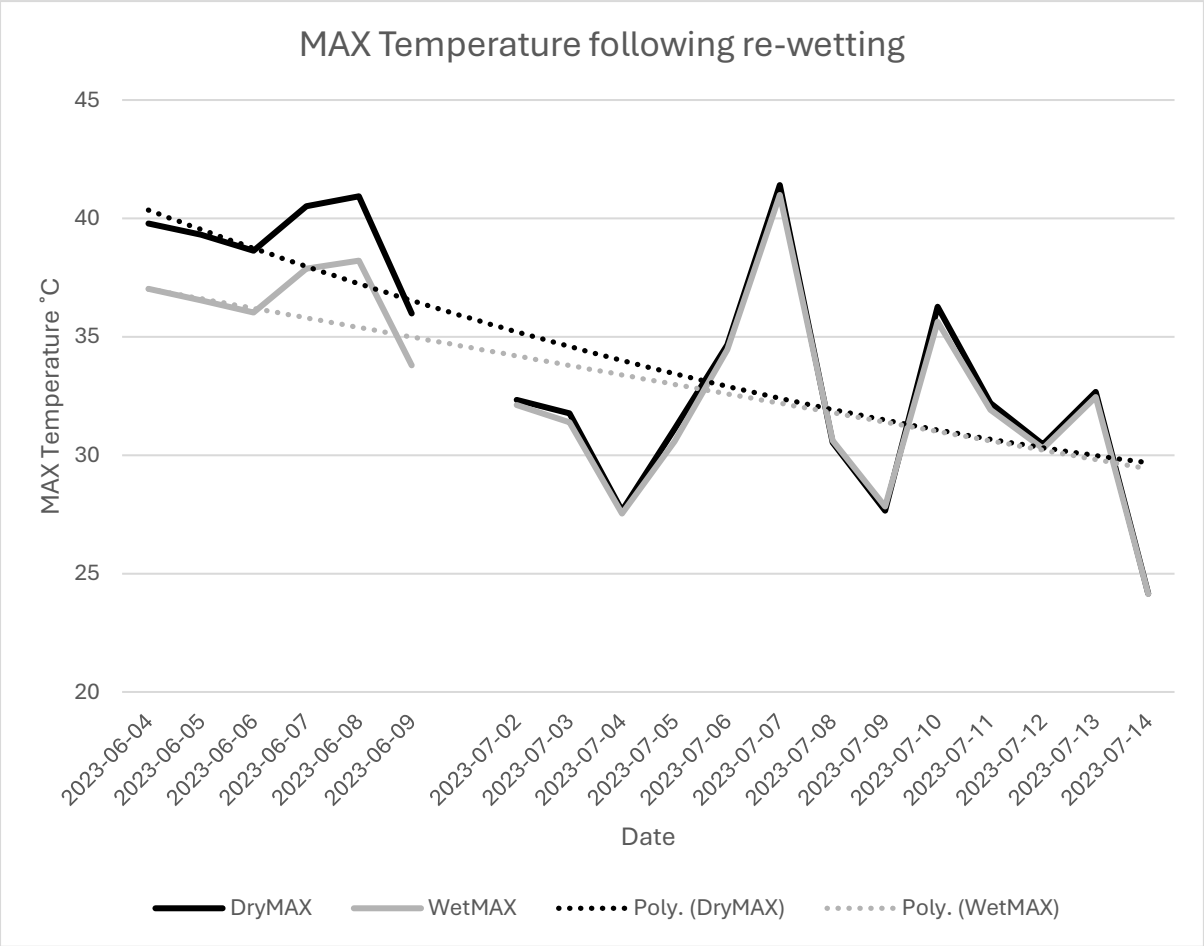


Figure 40 – MAX temperatures averaged across both treatments overtime, whilst the soil moisture was equalised between wet and dry. Dry samples re converged with the wet samples sometime in between 9th June and 2nd July, the exact date is unknown due to data loss from sensor malfunction. Total N=102

5.4 Discussion

5.4.1 Temperature and moisture as functional indicators.

Above all, this data confirms temperature's intrinsic relationship with soil moisture and the two as potential functional indicators. As indicators of function within managed landscapes such as agricultural systems, continuous measuring of temperature and moisture offer an accessible and simplistic way of monitoring the soil. Continuous measurements allow the inspection of temporal variation, capturing the systems state of flux. MAX indicates the peak solar incidence and STDEV (of the 8 hours before MAX) the variability as solar radiation increases to that point. The results here support the findings of similar studies investigating the relationship with soil temperature and moisture (Al-Kayssi *et al*., 1990; McNamara, 2014; Z. Zhang *et al*., 2020). In particular, Figure 39 shows an exponential relationship between the two and although this correlation is fairly well documented (Al-Kayssi *et al*., 1990), it is poorly understood (Z. Zhang *et al*., 2020) and reference to ecosystem functioning is very little discussed. It does however have some meaningful relevance to field studies in to thermodynamic indicators above ground (Ulanowicz and Hannon, 1987; Eric D. Schneider and Kay, 1994; Ibisch *et al*., 2010; Norris *et al*., 2012; Michaelian, 2015; Lin *et al*., 2018a; Avelar *et al*., 2020).

As evapotranspiration is the main form of energy dissipation (Michaelian, 2015) and it is intrinsically linked to ecosystem function (Pokorný *et al*., 2010; Hesslerová *et al*., 2019), it follows that MC has an influence on thermodynamic stability. As moisture evaporates from the soil and disperses, entropy is exported with it (Pauluis, 2005; Hesslerová *et al*., 2019). In optimum soil water conditions (likely close to field capacity), the system responds with a greater ability to dissipate incoming solar radiation and an increase in entropy export (Jørgensen, 2002; Fath *et al*., 2004; Aoki, 2012). In water limiting conditions, energy dissipation and entropy export diminish (Hildebrandt *et al*., 2016; Pauluis, 2005) and the resulting build-up of high entropy wastes, yields erratic temperature readings (Norris *et al*., 2012; Michaelian, 2015; Avelar *et al*., 2020). The results support the case for temperature as an effective indicator of function, hinting at a fundamental role of soil moisture in maintaining thermodynamic stability and ecosystem function in bare soil.

The correlation between moisture loss and difference in temperature (Figure 39) has a high R^2 for the exponential curve, indicating that nearly 90% of the variability in the results can be explained by this curve. This provides evidence of the profound influence moisture has on the thermodynamic stability of the soil and so the eco-system function (Jørgensen, 2006b). Moisture enhances the ability of the soil to store and dissipate incoming energy through supporting the formation of biomass, information and networks (Jørgensen, 2006b), see chapter 3. Moisture lubricates the growth and development of biological activity which in turn supports ecosystem function.

The movement of water through the soil and in to the atmosphere creates the necessary gradient in soil water potential to enable effective energy dissipation (Hildebrandt *et al*., 2016). A statistical difference between wet and dry occurred on the 31st May (Figure 38) and corresponded to a difference in MC of 10%. Could this represent a threshold?

5.4.2 Understanding thresholds and mechanisms of water retention

Historical predictions from arid environments carried out by Soares and Lima, (2022), revealed a potential 5x over the standard deviation and current soil moisture deficits of between 5 and 20%. The data here shows that although 5% deficits do not impact ecological function, 20% certainly will. The 5% decrease in MC remained thermodynamically stable for the period of the analysis (Figure 38). The first significant difference occurred on the 30th May 2023 (Mann Whitney, p=0.00060352), when the Drought samples averaged at 34.085 and the Control group at 31.8225, a difference of 2.2625℃. This represented a MC difference of 10.2%. Precipitation anomalies that may cause soil moisture deficit are shown to increase temperatures in accordance with Agboma and Itenfisu, (2020). This is proposed to have a detrimental affect on fundamental processes such as soil organic carbon decomposition (Liang *et al*., 2021). What is more interesting is that the thermodynamic destabilization appears exponential, in that a mere 3% further decrease in MC takes the MAX temperatures up to 3 degrees on average. This is a significant increase in MAX temperature!

Understanding thresholds more clearly can support the more sustainable use of water in agriculture. For example, if the temperature response becomes significant at 10% below field capacity, which can be interpreted as a threshold for MC, it suggests that

eco-system function can still perform to the same level, in MC as low as 10% below field capacity. If soil moisture and temperature was recorded regularly in the soil this threshold could inform when to irrigate more sustainably. With recommendations based on thermodynamic performance rather than solely crop growth factors. These are of course an important consideration, however a trade-off must be met between this and ecological integrity. Of course, this threshold is only representative of the physical constraints of the experimental design here and no way reflects natural conditions (likely more exaggerated). However, it still provides some insight and prompts further investigation, giving a starting point for future study.

The difference in temperature indices increased exponentially with the difference in MC between the wet and dry samples. Indicating that at high moisture levels, when MC is low, the slower evaporation (Han and Zhou, 2013) is not as effective at dissipating solar energy (Pokorný *et al*., 2010). Without a steady supply of moisture in the soil, solar radiation is converted in to a higher proportion of sensible heat (Koorevaar *et al*., 1983; Abu-Hamdeh, 2003; Hesslerová *et al*., 2019) which creates a warming effect, especially at solar maximum (MAX). This corroborates previous studies that have investigated above ground mico-climate (Norris *et al*., 2012; Michaelian, 2015; Avelar *et al*., 2020).

The evaporative process of moisture from the soil is known to follow three distinct stages. Going from a relatively high rate in stage 1, followed by a lower rate in stage two and a very low rate in stage 3 (Han and Zhou, 2013), a saturated bare soil will evaporate water faster than a dry bare soil (Li *et al*., 2020). Although evaporation rate was not estimated, it can be assumed that in the latter stages of moisture loss the evaporation rate was slowed significantly, impacting the ability of the samples to dissipate solar energy, resulting in the exponential curve of temperature indices and MC correlation (Figure 39). Re-wetting and the short-term recovery from drought (Figure 40), appeared to return the dry soils back to baseline (mirroring the wet samples). This confirms that the MAX temperatures relate to soil moisture and the soil here may show some level of resilience to short term drought.

This experiment only looked at bare soil, so it is not possible to confirm the influence of plant addition. However, crop growth consumes a lot of soil water, especially when vigorously growing, and will likely exasperate the situation (Z. Zhang *et al*., 2020). This

begs the question, how do natural systems regulate themselves and what are the mechanisms of soil moisture retention and acquisition present in the natural world, to inform agricultural practice. The development of effective mitigation strategies for the emerging climatic threats is compromised by a lack of understanding of how natural and managed eco/biological systems respond to shifting hydrological and climatological regimes. Evapotranspiration is the key variable linking eco-system functioning, climate feedbacks, agricultural management and resource (water) use (Fisher *et al*., 2017).

5.5 Conclusions

The research here confirms to some degree that moisture and temperature are effective together as indicators of soil function. This is related to the role of moisture in evapotranspiration, which is a fundamental process that promotes effective energy dissipation. Although MC measurements were not continuous, interpolation was carried out and assumes a linear decline of MC following drying which may not be the case. However, due to the stability of MC given by the equipment in the experimental design (i.e. the floral foam), it is satisfactory for the results of this experiment. In addition the actual data showed good linear fit to the interpolated data.

The experiment promotes utilization of a novel experimental design for drought simulation, that has been revisited by Marchin *et al*., (2020). Compared to digital mechanisms for controlling MC, this method is very cost effective, although the floral foam in that volume is not cheap and it is also not reusable once dried, not to mention the adverse environmental impact. There is perhaps a need to explore other materials with similar properties, to make this type of experimental design more cost effective with lower environmental impact.

Evidence is presented that conforms to expectations, of the correlation between soil moisture and temperature. However, the role of evapotranspiration was only speculated and measurements of evapotranspiration itself would have supported the argument further. Long term monitoring of evapotranspiration and temperature in the field would enable a deeper understanding of the concepts here. Eddy covariance method is considered a reasonable method for estimating evapotranspiration and linking to temperature variables, however this is extremely costly. Temperature alone

is a fraction of the cost and if temperature can be utilized just as effectively, this would make the monitoring of energy dissipation much more accessible to farmers and agronomists.

The recovery of temperature regime with rewetting, both confirms the relationship and is quite reassuring. Indicating that short term drought situations are recoverable. However, the research here makes no effort to explore longer term drought scenarios, or perhaps the hysterical drying and wetting regimes. Future research would benefit from the exploration in to how drought legacies may effect long term ecological function (Hoover *et al*., 2021).

Above all, the study shows how moisture is an important factor in energy dissipation and that the ability of a system to sustain evapotranspiration, is fundamental to its effective thermodynamic functioning. This experiment was carried out under laboratory conditions and may not reflect real life situations. It was also carried out with bare soil and no inclusion of plants, however this process is expected to exacerbate the results here, due to the openness of ecological systems. The experiment only looked at bare soil and significantly underrepresents the effects that plants have in the system. Future research would benefit from exploring relationship with plant biomass and temperature in drought scenarios, to further understanding of the role of soil moisture in energy dissipation. However, estimations of mass would need a robust method to ensure accuracy.

Moisture has revealed itself as a key variable in energy dissipation. Agricultural practice would benefit from research in to mechanisms of soils moisture acquisition and retention to support sustainable and resilient agro-ecological systems. Resilient soil is dependant on the ability of soil to dissipate energy, mediated by microorganisms. The following chapter explores holistic management in the context of resilience whilst introducing a novel indicator related to energy and matter interchange.

6 Novel analysis of REDOX potential, as a resilience indicator, in the transition to holistic agricultural practice.

6.1 A shift in soil management

The ability to predict the evolution of the planet, as mankind faces unpredictable climatic changes, is high on the agenda of politicians; as is measurables of key descriptors of eco-system health, such as resilience (Nielsen *et al*., 2020). Resilience is defined by the systems ability to bounce back to its stable state . Perturbations caused by stressors (heat, flooding, etc), destabilize systems and depending upon severity, can cause a collapse and reorganisation, shifting the soil in to a new regime (Gunderson and Holling, 2003). Resilience is the flexibility inherent in complex systems, and is not to be confused with resistance which is far more a result of constraint (Ulanowicz, 2020). In the case for species compositions, Resilience and resistance form thresholds that relate to both response diversity and functional diversity, respectively (Ludwig *et al*., 2018). The former being the range of reactions to environmental change among species, contributing to the same function; the latter being a community of functionally dissimilar, but complementary species (Elmqvist *et al*., 2003). A focus on resilience over resistance would help to increase effectiveness of agro-ecological management (Elmqvist *et al*., 2003).

Land use change from agricultural development impairs soils physical, chemical and biological processes (Kv *et al*., 2019). Proper planning and management is crucial and healthy soils can only be achieved by conserving key traits that involve biomass, structure, water storage, nutrient cycling, biological activity and biodiversity (Lal, 2004; Khormali *et al*., 2009; Ayoubi *et al*., 2014; Azizsoltani *et al*., 2019). Holistic management is slowly being regarded as an important feature to developing sustainable agro-ecosystems. Low tillage systems for example have been found to improve soil structure, aggregate stability, biological diversity, OM and nutrients, water and water use efficiency; reducing degradation, erosion and greenhouse gas emissions (Hassan *et al*., 2022). Organic farming has been shown to offer greater protection and resilience to environmental changes (Jouzi *et al*., 2017). Furthermore, it is slowly becoming apparent that OM is a key variable in soil resilience and in a comprehensive assessment of soil degradation through novel analysis of satellite imagery, Nascimento *et al*., (2022) found that locations with less OM presented a higher degradation level, supporting the case for exploration in to management

regimes that promote OM retention in the soil (Alexander, 1978; Afshar *et al*., 2010; Sanderman and Berhe, 2017).

Soil resilience is the "Capacity of the soil to recover its **functional and structural** integrity after a disturbance; where this integrity can be considered as soils capacity to perform essential soil functions" (Karlen *et al*., 1997). As discussed in previous chapters structure and function is seen to be closely related to the thermodynamic character of a system. Natural systems abide to thermodynamic laws, in that, living things utilize energy from photons to drive mass flows, that contribute to maintenance and growth and in line with second law, export entropy to their surroundings (chapter 3). From a thermodynamic perspective, holistic management seeks to preserve the natural processes evolved over millions of years, that maintain eco-system function (see chapter 2 and 3). In the thermodynamic model of a farm in chapter 3, by Jordan (2016), the system relies on energy subsidies to maintain order. Jordan (2016) argued that holistic management is favourable, as endosmotically derived feedback mechanisms promote natural organisation and thus less reliance on energy subsidies. For example, under heat and drought stress conditions Yuan *et al*., (2024) found a dynamic interplay between plant and soil, whereby plants leverage on microbes to improve resilience.

A thermodynamic characterisation of agricultural soils would help to study and understand the complex interactions between organisms, substrate and atmosphere and better inform transition to sustainable practices. A challenging goal considering the difficulties in direct measurement of thermodynamic variables, such as exergy (Chapter 3; Nielsen *et al*., 2020). The previous chapters have explored temperature metrics as viable proxies of thermodynamic variables, showing their ability to distinguish between levels of complexity and their intrinsic relationship to soil water. This chapter explores another soil metric with huge potential. Recent studies have emphasized the application of REDOX potential in health monitoring, due to its intrinsic link to microbial activity and OM (biomass) (Husson *et al*., 2015; Mattila, 2023). What more, these studies have shown Eh response to holistic management, indicating that carbon farming practices result in lower oxidation due to the build-up of OM (Husson *et al*., 2015; Mattila, 2023) and conservation agriculture tends to restore favourable EhpH conditions for plant growth (Husson *et al*., 2018).

6.2 Soil REDOX as a biochemical proxy of matter interchange.

Application of REDOX as a thermodynamic metric involves the consideration of soil microbial functions as key pathways for matter and energy flow, between the soil and the environment (Barros, 2021). Interchange of matter essentially drives nutrient cycling and is for the most part a microbial mediated process, emerging from the cyclical interactions of species (chapter 2). Nutrient cycling in this sense has been investigated since the turn of the century (Fallou, 1857). Many studies focus on elemental compositions, in particular the mass balance of Carbon () and Carbon Dioxide) CO_2 that defines the soil as both a carbon sink and source (Conant, 2010). Differing abiotic and biotic reactions constitute the interchange of matter and the biotic part involves the interactions of multiple different organisms, through metabolic reactions (Barros, 2021). Without these organisms, the soil is incapable of maintaining function and sustaining other life forms.

Eh, especially when standardized with pH (EhpH) is an emerging dynamic of the soil, that shows potential as an indicator of soil health and has received a lot of attention over the last decade for this purpose, particularly in agriculture (Husson, 2013; Husson *et al*., 2015). However, authors have not yet emphasised the relationship with ecological thermodynamics. The soil is a surface catalyst and through electron transfer, organisms build their biomass and perform work that contributes to the ecosystems functioning as a whole. Soil microbiomes metabolically require a multitude of substrates, acting as suppliers of chemical elements, in complex molecules that constitute OM (Barros, 2021). A chemical characterization of OM is challenging due to its high chemical and physical complexity, coupled with a lack of knowledge and poor synergies across disciplines(Hedges *et al*., 2000; Šimon, 2007; Tfaily *et al*., 2015).

In electrochemistry, Eh has a direct relationship to Gibbs Free Energy, where the standard cell potential (E^o) calculates the difference in potential between an anode and a cathode. In nonstandard conditions, E^o can be substituted in the Nernst equation with Eh. In this circumstance Eh measures the tendency of a reaction to lose or gain electrons and in the soil constitutes to a more reductive (lower Eh), or oxidising (higher Eh) conditions. Standard cell potentials are measured at 298k and 1

atmosphere, in 1M solutions. Internal energy can be calculated from E⁰ through an inverse relationship to ΔG:

$$\Delta G = -nFE^0$$

Where ΔG is the change in Gibbs free energy, n is the number of electrons transferred in the reaction, F is the Faraday constant

Due to Eh basically dictating the energy available for metabolism and the form that nutrients take (later discussed). It is becoming recognized as a key environmental factor shaping microbial community structure and function (DeAngelis *et al*., 2010) (Vincent *et al*., 2021). Gibbs free energy, denoted G, combines enthalpy and entropy into a single value. The change in free energy, ΔG, is equal to the sum of the enthalpy plus the product of the temperature and entropy of the system:

$$\Delta G = \Delta H - T\Delta S$$

Where ΔH is the change in Enthalpy, T is the temperature and ΔS is the change in entropy.

Eh is the energy of the products minus the energy of the reactants. Given that both can be used to forecast whether processes are spontaneous, it is not unexpected that variations in the quantities of ΔG and Eh are related to one another. A negative ΔG corresponds to a spontaneous reaction, therefore as soon as Eh becomes negative reactions are no longer spontaneous and require energy. An example of this is photosynthesis. Photosynthesis is a REDOX reaction where excitation of chlorophyll provides energy needed to transfer electrons from oxygen in water and synthesise glucose. The oxygen in water is the most electronegative substance and the half-cell potential = +0.82V. Partially reduced carbon, like that found in glucose is equal to -0.42V. The synthesis of a molecule of glucose requires the transfer of 24 electrons from oxygen to carbon and the E° can be calculated as follows:

The redox potential of oxygen in water = +0.82 eV

E° = E (acceptor) - E (donor). Or, E° = -0.420 - (0.82) = -1.24V.

ΔG = - (1) x 96000 x (-1.14) = 109440 J mol-1 (=109.4 kJ mol-1)

ΔG is positive and indicates a non-spontaneous reaction (requires energy). This is because the complex and organised structure of phytomass is a negative entropy product (Epstein *et al*., 2006; Virgo and Harvey, 2007), evidenced by the positive ΔG. Considering that plants are primary producers in trophic chains, it's clear what Schrödinger (1944) meant by "feeding on negative entropy". Examples of how plant biotic activity can alter EhpH to more favorable conditions, are in rice paddy fields, where plants adjust the soil REDOX around the root rhizome, by as much as 300mV and up to 4mm away from the root tips (Flessa and Fischer, 1992). This hypothesized to be a result of elevated CO_2 promoting root radial oxygen loss (Li *et al*., 2024).

Exergy has been previously discussed as an important thermodynamic metric in soil health (chapter 3 and 4). ΔG is related to exergy, in that it is a measure of internal/ available energy. However, this is only fully accurate in an isothermal/ isobaric ensemble. ΔG, enthalpy and entropy are the three fundamental and connected elements that make up a thermodynamic system's internal energy state (Engel and Reid, 2006). They are state functions as opposed to exergy, which is a state variable according to (Jørgensen, 2007) since it depends on the system and environment (Wu *et al*., 2017). Exergy and ΔG are related concepts, but exergy is a general term for work extracted from a thermodynamic system, while Gibbs is for a specific process. Exergy is dependent on the system's surroundings, while ΔG is independent. Like Exergy, G, enthalpy and entropy have shown adequacy as indicators of ecological structure and function (Wu *et al*., 2017), they similarly require the establishment of proxies such as REDOX potential, as they cannot be measured directly.

EhpH drives mass flows of nutrients throughout the soil substrate. The chemical evolution of soils is mainly determined by proton and electron fluxes that define the predominant soil mineral fields (Schwertmann and Murad, 1983; Chesworth *et al*., 2006). The mobility of several nutrients in complicated chemical and biological milleu is substantially influenced by pH and Eh (Gambrell and Patrick Jr, 1978; Laanbroek, 1990). EhpH diagrams (Pourbaix diagrams) plot the stability zones of an element's several chemical forms in a solution as a composite function of pH and Eh, based on thermodynamic laws (Pourbaix, 1945;). In Figure 41 for example at pH 7 nitrogen (N) shifts from thermodynamic stability in NH^{+}_{4} to NO^{-}_{2} at approx. 350mV and as REDOX climbs over 400mV nitrogen shifts again to stabilize as NO^{-}_{3}. Eh an pH then predominantly influence in which form N is assimilated by plants, having a

considerable effect on cellular regulation (Marschner, 1991). As plants strictly use NH^{+}_{4} to synthesis proteins, assimilation of N from its NO^{-}_{3} form, induces an energy cost for the plant to reducing NO^{-}_{3} to NH^{+}_{4} (Marschner, 2012) According to Figure 41 this occurs above approx. 350mV at pH 7 (Husson 2013).

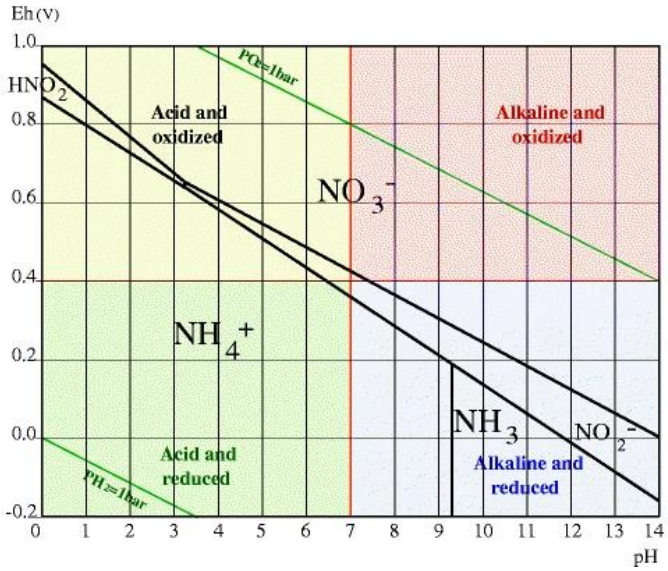


Figure 41 - Pourbaix diagram of nitrogen stability zones representing the various forms of N in a 100 µM solution at 25 °C as a function of Eh (in V) and pH. Diagram adapted from MEDUSA Software. Puigdomenech 2009–2011 as a function of Eh and pH. Soource: (Husson, 2013)

REDOX status in the soil has profound effects on the nutrient use efficiency. The oxidized conditions that a low OM content bring, reduces nitrogen use efficiency and may contribute to poor fertilizer efficiency (Tittonell *et al*., 2008). The drop in fertilizer efficiency is a result of plants needing to adjust the EhpH through root exudates that utilize a large share of their photosynthetic production (Husson, 2013). A role otherwise filled by micro-organisms in the presence of sufficient energy from OM.

Redox kinetics determine the dominant reactions among those that are thermodynamically available at any given moment (Chadwick and Chorover, 2001). As a result, it is important to carefully evaluate the complex kinetics of oxidation-reduction reactions in heterogeneous and changing soils (Sparks, 2001). Since microbial activity catalyzes these processes, Eh and pH also have an effect on their kinetics (Fenchel *et al*., 2012) (Husson, 2013). EhpH in many ways is a measure of the electrochemical environment for the exchange of energy and matter. Of course, microbial metabolism is the conduit for this exchange, within the communities of micro-

organisms. Metabolic types emergent in bacterial communities are largely determined by the Eh and pH of the milieu they reside within (Stumn, 1966; Billen, 1973). Research in to Eh and its relation to the development of microbial communities dates back to Heintze (1934), who proposed that Eh can characterize groups of microorganisms. More recently Dick and Tan (2021) provide genomic evidence for Eh chemical link to community composition.

Microorganisms are adapted to specific Eh conditions, characterized by the range in which they can develop, as is equally true with pH. EhpH fluctuations are likely to be a strong selective force on the composition of microbial communities and may promote metabolic plasticity or redox-tolerance mechanisms (Pett-Ridge and Firestone, 2005). On the other hand, micro-organisms have the ability to modify their surroundings, more so than other organisms (Rabotnova and Schwartz, 1962). Furthermore, bacterial growth correlates directly with changes in EhpH (Kimbrough *et al*., 2006) and in anaerobic soils, both microbial and enzymatic activity are negatively correlated with EhpH (Snakin and Dubinin, 1980; Kralova *et al*., 1992; Brzezińska, 2004; Husson, 2013; Dick and Tan, 2021; Mattila, 2023).

It is particularly important to consider the response from significant disturbance, such as flooding or perhaps extreme temperatures. Crossing a tolerance thresholds puts the microbial community at risk of collapse and it is the inherent resilience, in the way of response diversity (Elmqvist *et al*., 2003; Ludwig *et al*., 2018) , that enables the system to re-stabilize and recover from the perturbation, by either a return to base line conditions, or stabilization at a new steady state ((Prigogine, 1955; Prigogine and Nicolis, 1977; Müller, 1998; Ulanowicz *et al*., 2006; Nielsen *et al*., 2019). For example, in soils prone to flooding, the fluctuating Eh creates dynamical conditions and this can drive microbial diversity (Randle-Boggis *et al*., 2017). Resilience is engendered by the microorganisms ability to shift between active and quiescent states, to match REDOX shifts (Fierer and Jackson, 2006). In addition, it is the availability of nutrients that shapes community structure, far more than pH alone (Zhang *et al*., 2024), driven largely by REDOX conditions. Plants function within a specific internal EhpH and following a disturbance, the plant microbial network will act to alter the Eh and pH in the rhizosphere to reach cell homeostasis (Husson, 2013).

EhpH in the soil is highly variable, with daily and seasonal cycles (Snakin *et al*., 2001; Mansfeldt, 2003). Sabienė *et al*., (2010) also documented inter-annual variations in relation to climatic conditions and soil moisture. This is primarily a result of the oxygen status in the soil. Generally, microbes lower the Eh (Potter, 1911; Rabotnova and Schwartz, 1962) and in anaerobic soils this is due to the consumption of oxygen (Kralova *et al*., 1992; Bohrerova *et al*., 2004). Soil water has a similar effect (Savant and Ellis, 1964), with rapid decreases reported after flooding and restoration after drainage (Balakhnina *et al*., 2010). Pore space oxygen becomes quickly consumed in saturated soils and the significant depletion of oxygen as a terminal electron acceptor (TEA) may slow organic carbon decomposition (Sexstone *et al*., 1985; Keiluweit *et al*., 2017; Lacroix *et al*., 2021; Wilmoth, 2021). Perhaps the reason why lakes are such successful carbon sinks. Both microbial activity and flooding also tend to lead to acidification (Rabotnova and Schwartz, 1962) especially in organic soils (Kashem and Singh, 2001). In fact, pH is changed and regulated by the metabolism of the microorganisms in the acidification of a culture medium (Rabotnova and Schwartz, 1962). Fungi similarly influence soil chemical environment close to their hyphae (Garrett, 1963; Twining *et al*., 2004).

Rapidly fluctuating environmental conditions can significantly stress organisms, especially when thrown outside the thresholds of normal physiological tolerance (DeAngelis *et al*., 2010). To prevent significant oxidative damage, a network of buffering mechanisms exist in the soil (Noctor *et al*., 2000; Dietz, 2003; Kandlbinder *et al*., 2003; Hansen *et al*., 2006; Lambers *et al*., 2008; Hanke *et al*., 2009) and the simultaneous presence of highly reducing and highly oxidising compounds is the basis for regulation (Scheibe *et al*., 2005). The soils EhpH buffering capacity is an important factor pertaining to soil health. EhpH buffering mechanisms determine the evolution of oxidation-reduction conditions and the soils response to an injection of electrons (von der Kammer *et al*., 2000). OM is one of the biggest drivers of EhpH conditions, in the soil (Oglesby, 1997). It is the most reduced fraction of the soil and the most thermodynamically unstable (Macías and Camps Arbestain, 2010). OM is a prolific source of electrons (Chesworth, 2004) and constitutes the bulk of the soils reduction capacity (Lovley *et al*., 1998; Chadwick and Chorover, 2001). During decaying processes OM acts as a carrier of electrons (Lovley *et al*., 1998), supplying them to more oxidized species in the soil (Chesworth, 2004). In most circumstances, an

increase in OM lowers Eh, as oxygen consumption leads to the formation of compounds with reducing properties (Lovley *et al*., 1998: Husson, 2013).

Different fractions of the soil organic matter have varying impacts on the soil REDOX status, in terms of buffering mechanisms. Labile substances are typically in a reduced state and undergo rapid oxidation, in high redox conditions; high redox activity is promoted by their quick degradation (Baldock and Smernik, 2002). Recalcitrant substances are less prone to oxidation, persisting across varying redox conditions, decomposing slowly and utilized primarily under extreme conditions (Zabel and Morrell, 2020). Humic substances have the greatest buffering capacity, as they exhibit a mix of redox active groups, acting as electron shuttles, but can also alternate between oxidation and reduction depending on conditions (Kögel-Knabner *et al*., 2008). Dou *et al*., (2020) argued that the distinctiveness of humic substances is fundamental to the soil, and thus further studies should be focused on revealing this.

Changes in mass, such as textural differences, water content, fractions of OM and microbial biomass, seem are key rivers of EhpH conditions in the soil (Tano *et al*., 2020), promoting the applicability as a thermodynamic indicator of mass flows. This is likely a result of the changing oxygen status of the soil, with these mass properties. Oxidative processes involve electron extraction, electrons are passed through electron transport systems to a TEA , this generates energy and pumps protons. In an oxygen rich environment energy acquisition is high as O2 yeilds the most energy per unit, in low Eh decomposition is slow (think lake sediment) and can actually cost energy. Both circumstance exist on the planet, but neither are ideal. Buffering mechanisms act to keep soils within ranges where decomposition of OM is neither to fast (highly oxic) or too slow (highly anoxic) (Bayer and Mielniczuk, 1997). Soil microbes, such as ectomycorrhizal, saprophytic or pathogenic fungi, can modify the rhizosphere by producing organic acids (Chaignon *et al*., 2002; Hinsinger *et al*., 2009).

The literature demonstrates how the root system, the soil structure and microbes interact to produce Eh-pH conditions in the rhizosphere (Husson, 2013). Soil structure creates Eh-pH niches, home to various microorganisms, causing soil suppressiveness (Husson *et al*., 2021). The Eh-pH homeostasis paradigm is the foundation of soil and plant health. An Eh-pH perspective can be an effective tool for a "one health approach" that unifies various bio-physical processes (Husson *et al*., 2021). Eh in the soil dictates

the conditions for energy and matter flow by limiting certain nutrients (matter) and the yield from chemical reactions (energy). Hence why EhpH dynamics may be suitable candidates for resilience indicators, however, its application in soil health analysis lacks empirical evidence.

6.3 Hypothesis

“Changes in the soils Eh reflect its response to disturbance, with holistic management promoting favourable conditions”

6.4 Methods

6.4.1 Samples sites

The study here examines Eh in a range of different management regimes. The enquiry included soils collected from 3 locations in Essex (Figure 42):

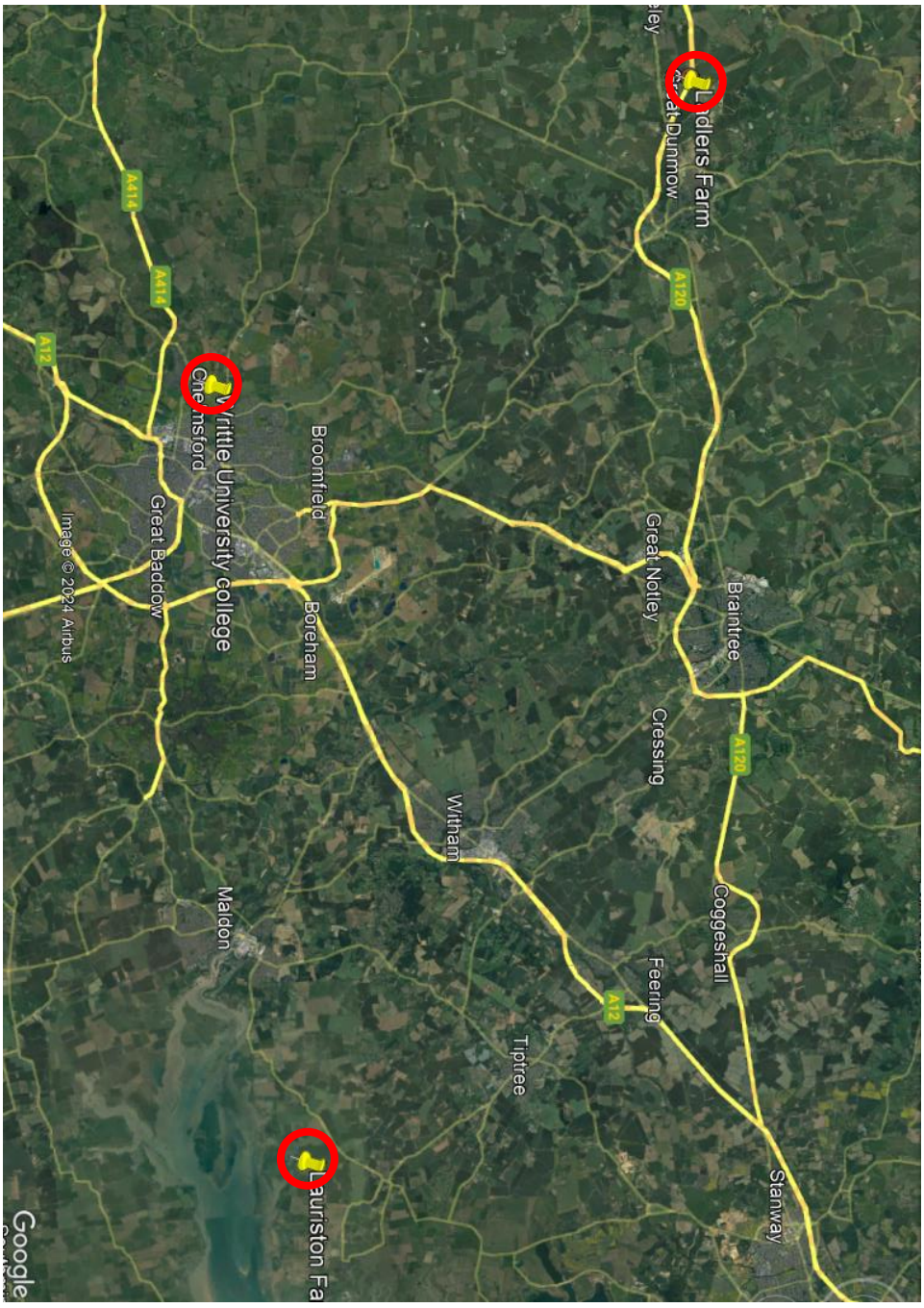


Figure 42 - Locations of study sites.

1. Writtle University College (Conventional):

Representative of an intensive agricultural farm, simple monocultures of crops are grown with the use of conventional fertilizers and herbicide applications. The soil is

characterized as a silt loam (Figure 43) and geographically located within the Landis Soilscape 6: Freely draining slightly acid loamy soils, bordering Soilscape 8: Slightly acid loamy and clayey soils with impeded drainage. Situated in an area surrounding the confluence of the rivers Wid and Can, that lead to the river Chelmer. Young woodland (YW) refers to a small copse within the grounds and adjacent to one of the agricultural fields (Figure 43).

Figure 43 – Map showing the fields where soil was collected at Writtle site. Two fields previously growing Rapeseed oil.

2. Ladlers Farm (Organic)

Located further North than WUC Ladlers farm is representative of organic management practices (Figure 44), non-reliant on chemical inputs, rather organic ones, with the utilization of cow manure from semi-naturally roaming Red Pole cattle in a rotation of crops. The location sits on and area of Landis Soilscape 9: Lime-rich loamy and clayey soils with impeded drainage.

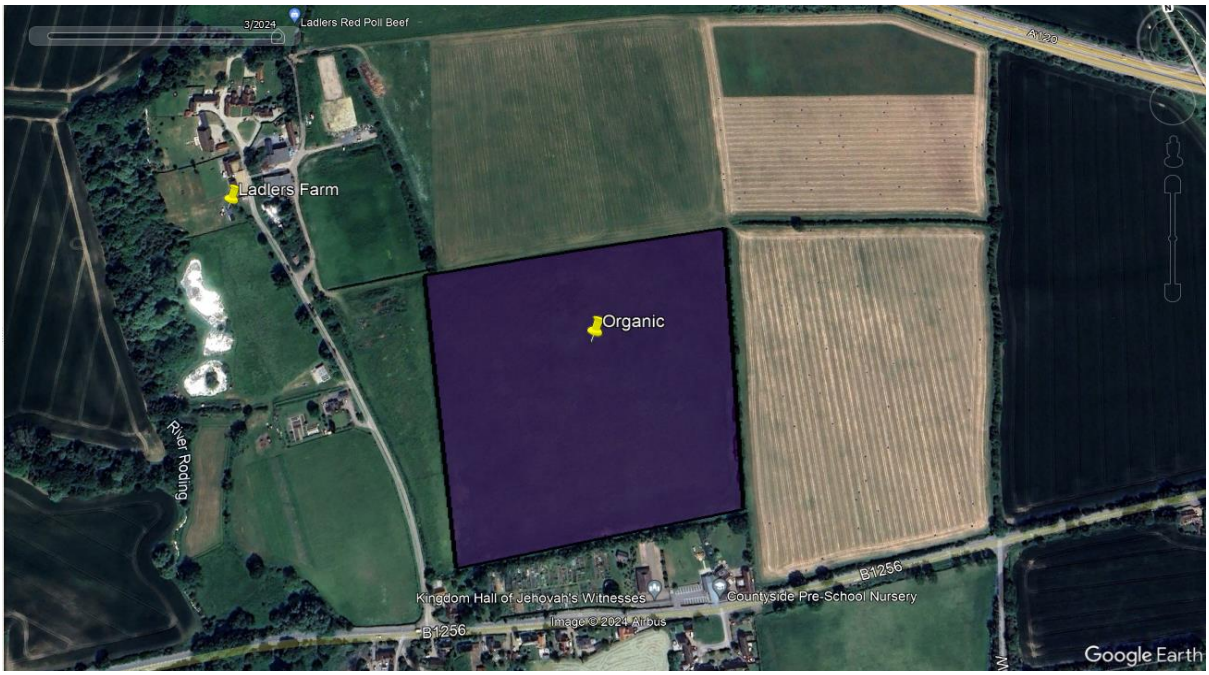


Figure 44 - Map showing the fields where soil was collected at Ladlers farm. An Organic farm North of Chelmsford.

3. Lauriston Farm (Biodynamic)

Situated almost on the banks of the River Blackwater, Lauriston represents a biodynamic farm, similarly reliant on organic inputs with a number of traditions that focus on soil health (Figure 45). The site is on the edge of an area of Soilscape 6: Freely draining slightly acid loamy soils. Bordering Landis Soilscape 18: Slowly permeable seasonally wet slightly acid but base-rich loamy and clayey soils.

Figure 45 - Map showing the fields where soil was collected at Lauriston farm. An Biodynamic farm North of Chelmsford

6.4.2 Experimental design

Data collection was carried out across 4 experiments with the intention to explore the efficacy of Eh as an indicator of soil health as well as the impact of holistic management. The first experiment (Baseline) was a one-off assessment of a number of soils that represented soil types and management principles (

Table 6). A further 3 experiments examined varying degrees of stress upon the soil; full heat sterilization, flooding and short-term heat stress. Summarized in table 6, the experiments were designed to explore the boundaries of EhpH under extreme conditions. The baseline assessment compared soils of different textural classes, as well as soils with similar soil texture, but different management regime (Figure 46).

Full heat sterilization was carried out by placing the dry samples (prepared using the method shown later for REDOX potential) in an oven at 65°C for 3 hours, while a

control group on the same soil mixes was left at room temperature. The following analysis continued as in the method. Flooding and recovery was simulated by measuring the EhpH at field capacity (see REDOX potential method), but in free draining containers, before saturating the soils in a shallow tray of water, bringing them over field capacity. The samples were weighed to estimate water content. Finally, Ehph was recorded alongside water content, over 3 hours of heat stress at 38°C. This time in open topped beakers containers that do not drain, 4 randomized samples per soil were individually measured every 15 minutes outside of the oven and again the samples were weighed before each measurement to estimate water content.

Table 6 – Summary of experiments with a brief description of the intention and key to treatments and samples, that indicates any important information about the soil like depth and texture.

Experiment	*Description*	*Samples and Treatments key*
Baseline	Direct comparison of soils taken from different locations representing differing holistic management.	WrS – Writtle (10cm) WrD – Writtle (30cm) OS – Organic surface (10cm) OD – Organic at 30cm LB – Biodynamic surface (10cm) REF – Reference soil, sterilized at 65°C for 48 hours (good loam) Sub – Sandy soil (equal clay content to REF, but higher sand and less silt)
Sterilization	Thermal sterilization of two soils at 65°C for 3 hours and compared to control group of unsterilized	WRC – Writtle soil control WRT – Writtle soil sterilized YWC – Young woodland control YWT – Young woodland sterilized
Flooding	Soils saturated in a tray of water). Followed by 24 hour recovery at room temperature	LB – Biodynamic surface (10cm) WrS – Writtle surface (10cm)

Heat stress	Heat stress after 1, 2 and 3 hours (38°C).	LB – Biodynamic surface (10cm) WrS – Writtle surface (10cm) REF – Reference soil (good loam) ROM – Reference with added organic matter. AMB – control groups at ambient room temperature.

6.4.3 Soil collection

Soil samples were collected in a W pattern across the fields. Approximately 24 samples were taken from each field and mixed together, before they were air dried. Textural analysis was carried out when possible, as in previous chapters (Figure 46), resource limitations during the analysis meant that it was not possible to analyse Ladlers farm.

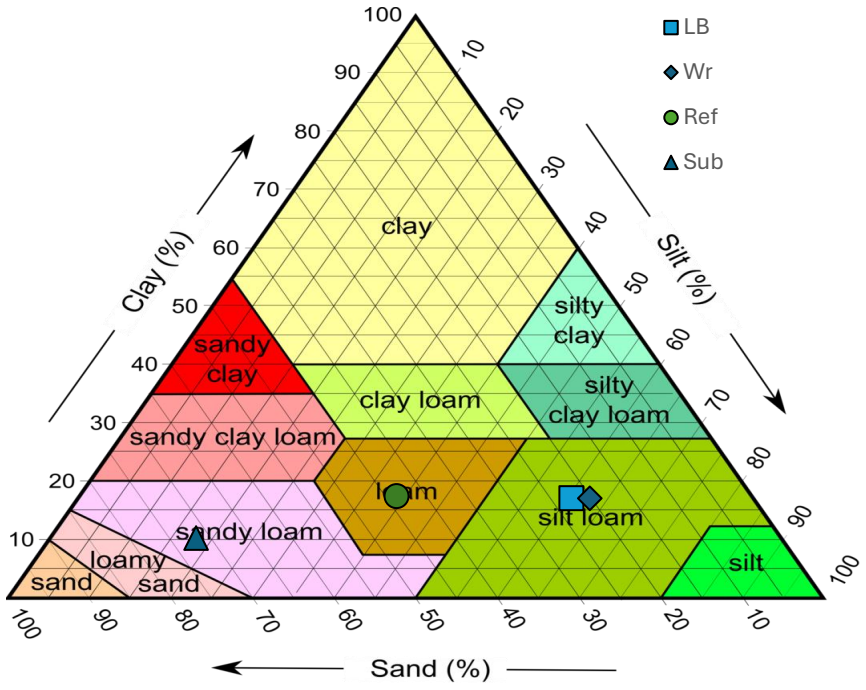


Figure 46 - Soil textural analysis of sampled soils. Lauriston farm (LB) occupied the silty loam quadrant and was most similar to Writtle soil (Wr). The reference soil (Ref) was chosen as it was the most even distribution of soil fractions (Loam) then the Sub Soil (Sub) was more of a Sandy Loam. All soils were considered to have similar clay contents (within 5%).

6.4.4 Loss on ignition

OM was estimated by using loss on ignition (LOI) method, taking in to consideration guidance from (Schulte and Hopkins, 1996; Combs and Nathan, 1998)

1. Place a 5 g scoop of soil into a tared 20-ml beaker.
2. Dry for 2 hours or longer at 105° C
3. Record weight to ± 0.001 g
4. Bring oven to 360° C. Samples must then remain at 360° C for two hours.
5. Cool to < 150° C
6. Weigh to ± 0.001 g, in a draft-free environment

Calculate percent weight loss-on- ignition (LOI):

6.4.5 Moisture content

Moisture content in the relevant experiments was calculated by weight. Losses were calculated as the difference between the starting wet weight and the finishing wet weight. For the water EhpH correlations, the % change in moisture content was taken from the weights of the samples through the heating process. A final dry weight was measured so that moisture losses could be corrected from the loss of material between each REDOX measurement. This gave the overall loss of water during the period as a percentage.

6.4.6 REDOX potential

Soil preparation and measurement for REDOX potential (Eh) meticulously followed the protocol extensively researched by (Husson *et al*., 2015). The samples of soil were air dried under an infrared light at 35°C for approx. 72 hours (up to 96h). It was ensured that the location was free from any electromagnetic interference, this included turning off florescent lights and any other electronic equipment in the vicinity of the recording. The probes used were dedicated for use directly in to soil. Prior to measurements the probes were calibrated, pH using pH 4 and 7 buffers and REDOX followed this protocol; the Eh probes were placed in a high poise REDOX buffer solution (Lights solution in this instance), before being placed in a low poise (poised solution diluted in 0.1 M KCl at 1:100) as in Husson *et al*., (2015b). Then the first measurement is discarded. For the soil preparation, 50 ml of the air-dried soil was measured out into a conical flask and brought to field capacity by adding a pre-determined volume of deionised water. Field capacity was determined prior to experimentation, by calculating the difference in weight between heavily wetted soil,

that no longer drains, and dried soil at 105°C for 48 hours. This was between 10ml for sandy soils and up to 30ml for clay soils. The samples were then shaken for 10s, with a parafilm over the top, before the probes are gently inserted in to the soil. An Eh reading is taken when there is no change in mV on the meter after 1 min, this often took 15-20 mins. After each sample the electrodes are washed with a squirt of deionised water, followed by an abrasive paper and a further squirt with the water. A maximum of 12 measurements were taken before the probes were calibrated again. Both temperature and pH are measured alongside Eh for further calculations.

6.4.7 Statistical analysis

In order to better define the redox conditions of a system, some authors (Glinski, 1985; Pidello, 2003; Husson *et al*., 2015) have proposed to correct the Eh to pH = 7 (EhpH7). Due to the great influence of pH on the Eh, this helps by standardizing the figures to pH 7 and can be achieved through the following equation:

$$EhpH = Eh - \frac{RT}{F} \times (7 - pH)$$

where Eh is measured in volts, R is the perfect gas constant (8.314471 JK−1 mol−1), F is the Faraday constant (96485.3383 C mol−1) and T is the temperature (in K).

This is necessary due to the relationship between pH and Eh. The upper and lower limits of nutrient stability in poubaix diagrams are linear slopes of 59mV per unit of pH at 25˚C. The above equation standardizes the results to the given pH and temperature in order to significantly reduce this influence.

The result of the above calculation was the final figure used for comparison within the experiments. Mean Ehph was used to inform the main differences between treatments and/or soils in each of the experiments,. In addition, variability measures were employed like coefficient of variation (EhpHCoeffVAR) and Standard deviation (EhpHSTDEV), as well as utilization of the Fligner Kileen test to compare variation between treatments.

6.5 Results

6.5.1 Baseline Assessment

6.5.1.1 REDOX

Soil from Lauriston Biodynamic farm (LB) and Ladlers Organic farm (OS and OD) were the statistically lowest EhpH averages. Writtle surface (WrS) and Writtle 30 cm (WrD) was also statistically higher in EhpH than OS and OD. The highest EhpH was the Sub soil (Sub) and despite it being deeper in the soil profile WrD was almost as high as Sub. Soils from holistic farms were significantly lower in EhpH compared to conventional soils and the reference soil (p=0.0001, Mann Whitney). Furthermore there was no significant difference between the reference soil and the reference soil ammended with compost (ROM). See poubaix diagram (Figure 47).

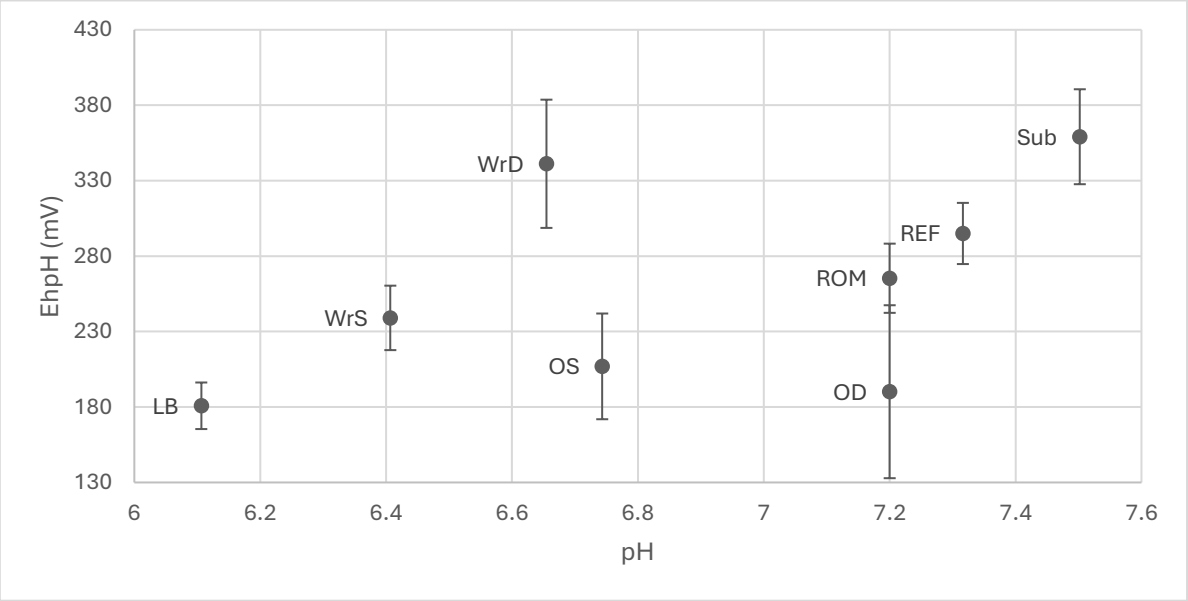


Figure 47 – Pourbaix diagram of the baseline survey, showing each of samples averaged in the Eh-pH space. Samples from organic soils under holistic management (LB, OS, OD) tended to have a lower EhpH (p<0.01, Kruskal-Wallis). The sub soil was statistically the highest (p<0.02, Mann-Whitney). Total N = 102.Error bars are confidence limits.

6.5.1.2 Organic Matter

From the OM estimates of soils, taken from loss on ignition (Figure 48), both the holistic sites were statistically higher than Writtle soils and the addition of compost to REF (ROM) increased LOI on average by 1% (an increase of approx. 25%). WrS was

on average 1.2% lower in LOI% (+/- 0.12%), compared to OS. Furthermore, there was a statistical corelation (p=0.049, Pearsons Linear r) between EhpH and OM.

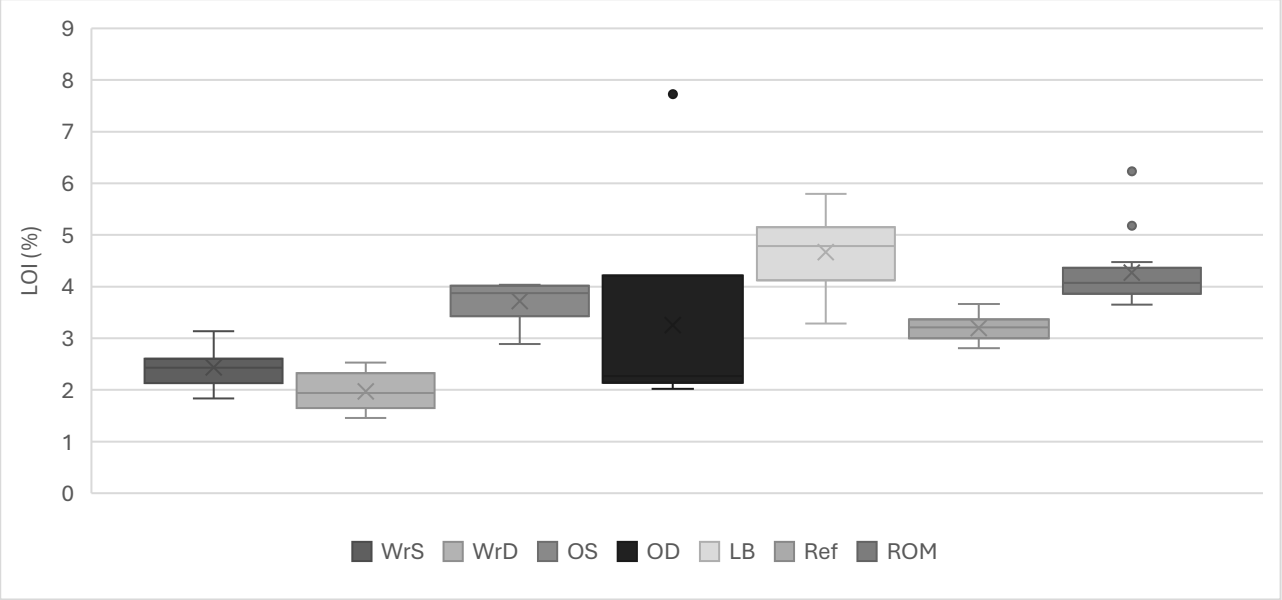


Figure 48 – Box plot of Loss on ignition at 360°C (LOI%) estimates for all soils recorded at baseline assessment. Total N = 95. Both Writtle soils (WrS at 10cm and WrD at 30cm) contained as much as half that of other soils (P<0.006). Holistic soils (OS and LB) had highest content (p<0.001, Mann-Whitney). Boxes are standard deviation and whiskers a ranges.

6.5.2 Sterilization

Sterile soil was statistically lower in EhpH compared to control of unsterilized soil (Figure 49), in soil taken from both WrS and YW. YW was also statistically lower than Wr in both sterilized (p=0.02) and control group (p=0.001, Mann Whitney). See Figure 49.

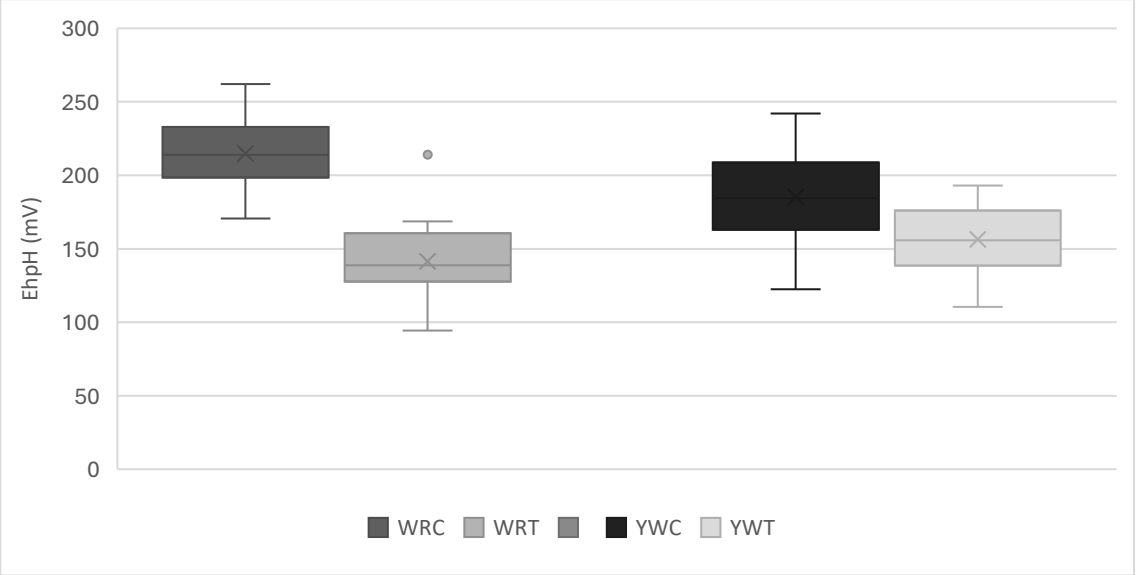


Figure 49 – EhpH comparison of sterilized (WrT and YWT) and control group from (WrC and YWC) Writtle 10cm (WrS) and Young woodland (YW). WrS was on average 73.22mV (+/- 10.28mV) lower once sterilized and YW was 28.65mV (+/- 9.16mV) lower once sterilized. N=96. Boxes are standard deviation and whiskers a ranges.

6.5.3 Heat stress

EhpH showed statistically greater variability (Fligner Kileen test for equal coefficient of variation, p=0.007 for one tailed test), over the course of the 3 hours, when exposed

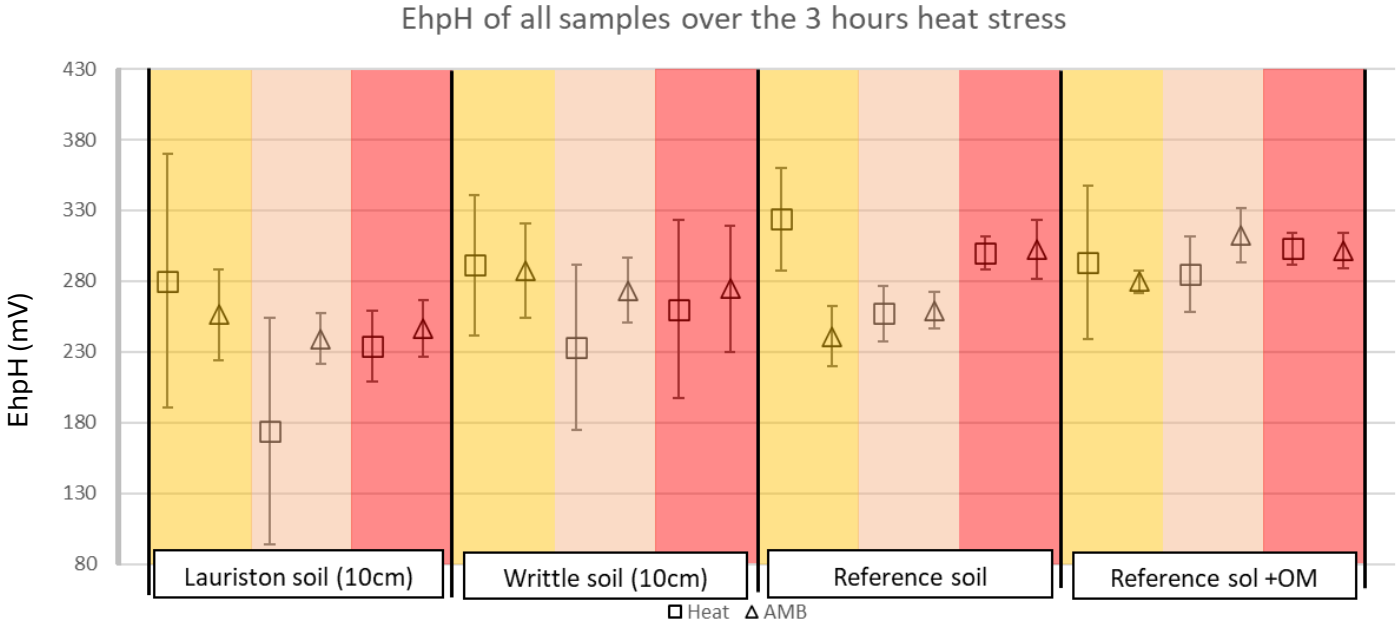


Figure 50 - EhpH of samples across the three hours of heat stress. Control groups (AMB) were statistically less variable than Heat stressed p=0.007, Fligner Kileen). The first and second hour (amber and light pink colour bands) showed the greatest deviation of 106mv (+/- 78mV) n=12 for each sample group. Error bars are standard deviation.

to high temperatures compared to ambient temperatures (Figure 50). This was for the most irrespective of management regime, however, was far more pronounced in the agricultural plots (LB and WrS) than the sterile Ref and ROM soils.

For samples under heat stress the variability (both STDEV and CoeffVAR) was statistically correlated (STDEV, p=0.023 and CoeffVAR, p=0.014, Spearmans rank) with the difference between initial water content and final water content (water loss %) and Heat samples resulting in higher variability compared to AMB samples (Figure 51). This is not statistically different between soils.

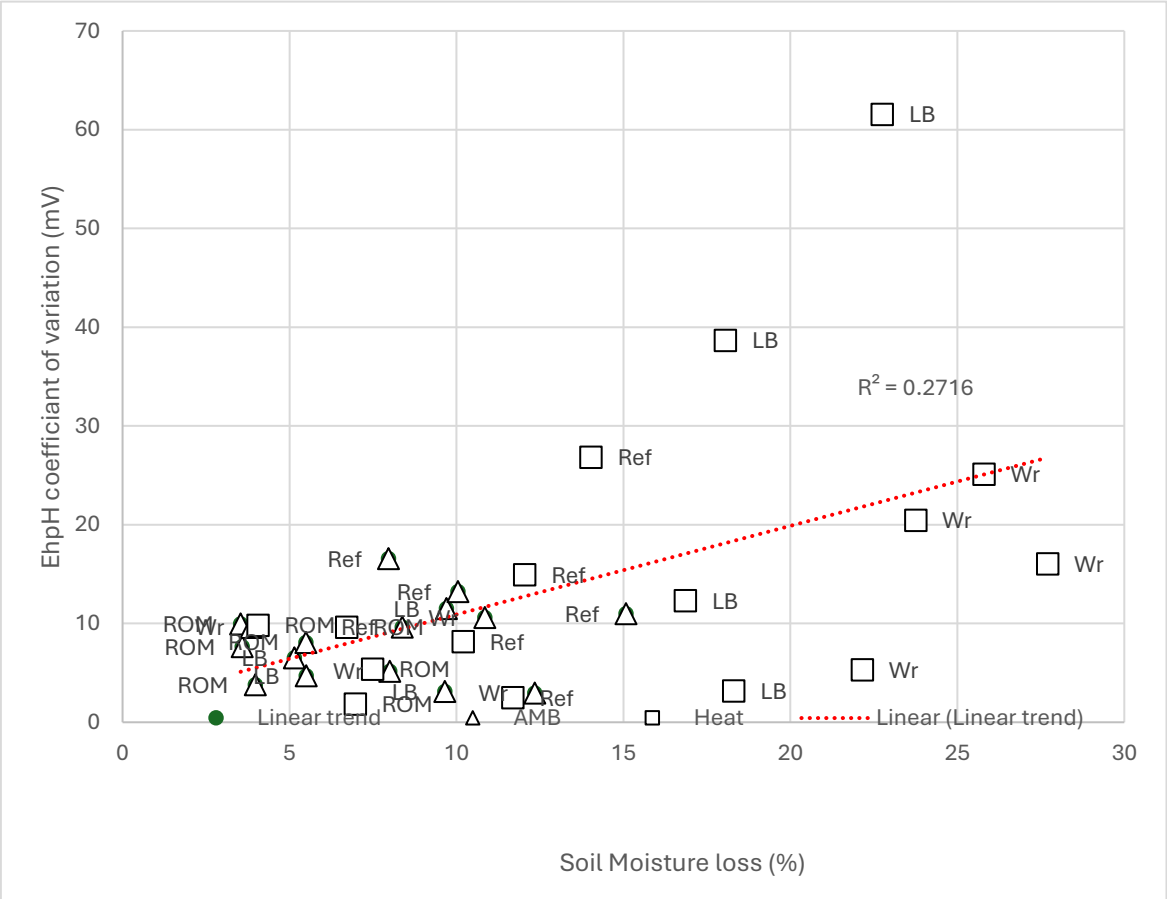


Figure 51 - Correlation between EhpH Coefficient of variation (CoeffVAR) and water loss over the period of heat stress, for 4 soils; Lauriston farm (LB), Writtle university farm (WrS), reference soil (Ref) and reference soil with added compost (ROM). Heat stressed samples (orange dots) tended to have higher variability than AMB (blue dots), ascociated with greater water loss over the heating period (y axis). Total N=32

6.5.4 Flood and recovery

Flooding resulted in a drop in EhpH for both the WrS and LB, although far more pronounced in LB (-671 compared to -395). Interestingly, WrS recovery EhpH was statistically higher ($p<0.05$, Mann Whitney) than the baseline, compared to LB which was not different (Figure 52).

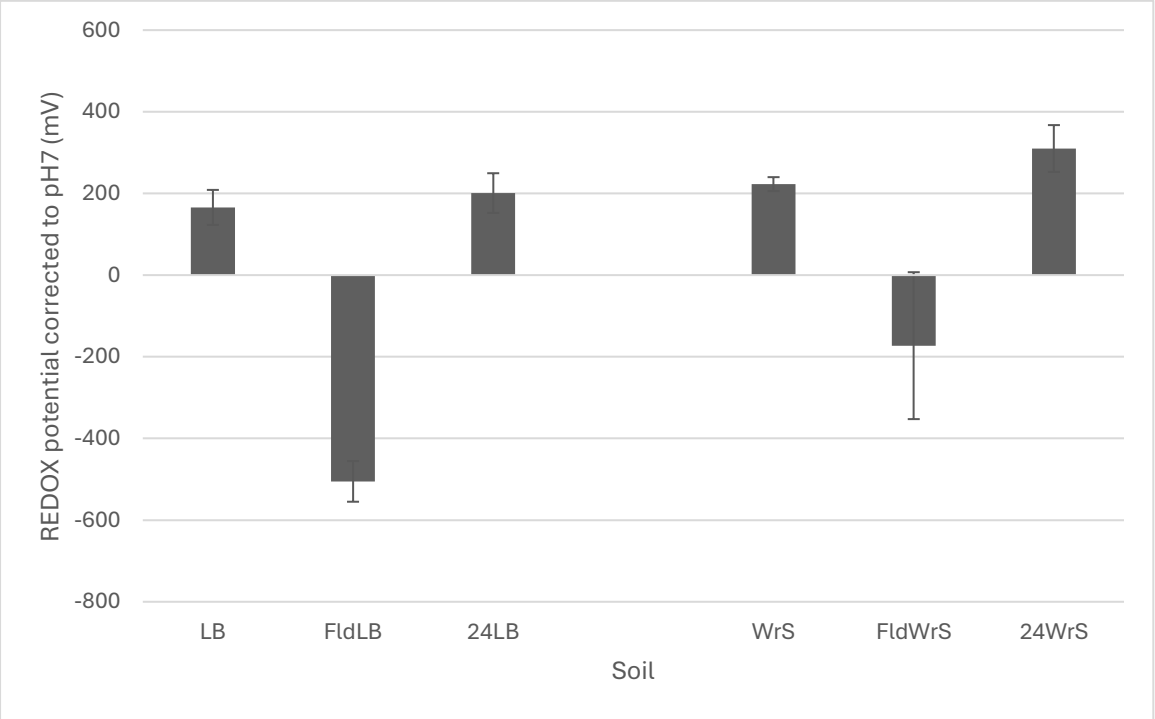


Figure 52 – The change in REDOX conditions following flooding and drainage for 24 hours. Flooding led to a significant decrease in EhpH that recovered after drainage. The recovery of Lauriston soil (24LB) was statistically closer to its original state (LB), compared to Writtle soil (24WrS and WrS). For Lauriston soil, flooding (FldLB) dropped the EhpH by far more than Writtle (FldWrS). Error bars are confidence limits. Total N=50.

6.6 Discussions

6.6.1 Supporting REDOX as a soil resilience indicator

EhpH has the potential to unify a large range of biophysical processes (Husson *et al*., 2021). It is however subject to immense variability (Snakin *et al*., 2001; Mansfeldt, 2003), through a myriad of biotic and abiotic processes (Pett-Ridge and Firestone 2005; Rabotnova and Schwartz 1962; Husson, 2013). This on one hand, gives great depth to its utilization in soil health assessment (Husson *et al*., 2021), but at the same time significantly challenges its interpretation. One of the greatest limitations of this

study is that one-off measures of parameters are never a true representation of the overall status of what one is measuring. Therefore, the following interpretation is open for further investigation and at the very least this chapter highlights avenues of enquiry.

It seems a lowering of the EhpH through OM favours a promotion in bacterial colonisation, whereas fungi would dominate in more oxidised conditions (Soares and Rousk, 2019; Barros, 2021). In this case it is difficult to assume the overall health of the soils microbiome from this measure, but perhaps predict microbial communities (Heintze 1934; Dick and Tan 2021), or more so the changes in bacterial to funghi diversity relations (Soares and Rousk, 2019; Barros, 2021). Although these measures were not taken, the results can be discussed in reference to microbial communities by way of their utilization of OM as an energy source. In many situations EhpH was able to detect small changes in the soil that may elude to its utilization in soil assessment. Common mass related variables that have been found to impact EhpH are OM, soil structure and moisture content. Expectations of the correlation to moisture and OM were satisfied, with further connotations related to holistic management. In corroboration with (Husson *et al*., 2015, 2018; Mattila, 2023) the results here demonstrate that REDOX can detect changes to soil structure and function related to holistic management through its relationship with OM. Likely a result of the build up of plant residues (Mattila, 2023). OM being a prolific energy source, clear relationships with thermodynamics can be drawn from the results and in this regard, EhpH presents as a highly effective soil proxy of thermodynamic variables, through its relation to ΔG. A lowering of EhpH indicates an increase in ΔG, i.e. the internal energy of the system increases. This results in an inflow of electrons and primes the metabolic activity of microbes. Based on relationship to ΔG and energy transformations in soil metabolism (Engel and Reid, 2006, DeAngelis *et al*., 2010, Wu *et al*., 2017), the results here show the average state of these factors within the soils; favouring holistic management toward enhanced energy dissipation (metabolic activity) and availability of resources (Veldhuis *et al*., 2018), leading to more favourable conditions for ecosystem function (Husson *et al*., 2015; Mattila, 2023).

The lowering of EhpH from flooding in this study (Figure 52), is a result of the depletion of oxygen in pore spaces (Balakhnina *et al*., 2010), either driven out by water infiltration or used up by microbes (Kralova *et al*., 1992; Bohrerova *et al*., 2004). Following this any metabolic activity will require energy at the value corresponding to Gibbs. In this

sense flooding limits the exchange of energy, due to oxygen as the terminal electron acceptor (Sexstone *et al*., 1985; Keiluweit *et al*., 2017; Lacroix *et al*., 2021; Wilmoth, 2021). Upon recovery, Figure 52 shows that EhpH detects differences in the return to baseline of the WrS soil compared to the LB, where LB returned close to baseline and WrS was significantly higher (more oxidized). This indicates that following flooding soils can shift to a state that may experience oxidative damage (Noctor *et al*., 2000; Dietz, 2003; Kandlbinder *et al*., 2003; Hansen *et al*., 2006; Lambers *et al*., 2008; Hanke *et al*., 2009) however, soils with higher OM, due to its buffering capacity could remain within a 'safe' level of REDOX conditions. This supports the concept of REDOX homeostasis in plant-soil health (Husson *et al*., 2021), as it shows that and organic rich soil likely able to support a diverse community of micro-organisms can better support homeostasis of REDOX conditions in the soil following perturbations.

For the most part, EhpH change was able to quite effectively show the impact of heat stress and is forthcoming in its use as a resilience indicator. Heat stress creates a recognizable disturbance that destabilizes the REDOX conditions. A correlation was drawn between percentage moisture loss and Change in EhpH (Figure 51), but only under heat stress, as AMB changed very little in both regards compared to Heat treatments. As moisture loss increases, the variability in EhpH increases, movement of water out of the soil seems to destabilizes the REDOX conditions. This corroborates the literature, as REDOX is known for its relationship to moisture (Rabotnova and Schwartz, 1962). However, in this context it shows its relationship to the flow of water out of a system. Water being the key mechanism for energy dissipation (Chapters 4 and 5), we can start do draw links with energy flow. Correlations drawn between Ehph and both water and OM, are likely a result of the connection to microbial activity, the functioning of which are key to energy and matter flows (Barros, 2021), that impact upon system resilience (Karlen *et al*., 1997). Interestingly, sterile OM as in the reference soil amended with compost (ROM), did not respond in the same way as the holistic soils did (Figure 47), perhaps indicative of endosomatic feedback mechanisms (Jordan, 2016; Ferri and Arnés García, 2023) and the role of microbial organisms in supporting soil resilience (Yuan *et al*., 2024). If OM is energy in the system and Eh does not respond to just simply adding compost, it shows that Eh is more measuring the changes in the availability of that energy – going from unavailable sterile biomass to live OM feeding the microbes in the soil.

What may contradict some literature and perhaps is product of the simplified design of the experiments, is how the oxidation status changed under heat stress. Instead of increasing the EhpH due to the driving of water out of the system and creating more oxic conditions (Noctor *et al*., 2000; Dietz, 2003; Kandlbinder *et al*., 2003; Hansen *et al*., 2006; Lambers *et al*., 2008; Hanke *et al*., 2009). EhpH decreased in some of the trials, in particular extreme heat stress (Sterilization), which may be explained by a release of mass in the system, whether through biomass loss from death of micro-organisms, or water loss embodied in the organisms. Never the less, it requires further exploration.

Although this study did not measure long term fluctuations in the soil in a natural setting, it does highlight just how variable the Eh. Eh fluctuations could perhaps be interpreted similarly to the above chapters utilizing temperature, however, field measurements are in no way as accurate and well researched (Husson, 2013; Husson *et al*., 2015, 2021) as temperature (see chapter 4 and 5), which is widely used across many industries. Challenges lie in the fluctuating soil moisture conditions, where facultative anaerobes may be active in one microsite and 1cm away inactive (Fiedler *et al*., 2007). The method developed by Husson (2015), can be used on fresh soil however careful assessment of moisture content should be followed and this method still does not capture the REDOX poising capacity (Pidello, 2003), or the stability of the chemical environment and this area is in need of more research.

6.6.2 Implications for agro-ecological management

The consideration of EhpH kinetics as fundamental determinants of energy and matter interchange, reveals the importance of supporting a biomass rich soil and should be a high priority in the development of agro-ecological principles. Transition to holistic management shifts soil EhpH, in corroboration with (Husson *et al*., 2015; Mattila, 2023), through mechanisms related primarily to OM, evidenced by Figure 47 and Figure 48. Conventional agriculture is subject to a more intensive management regime, where less attention is paid on preserving important natural processes (Jordan, 2016). This long term press disturbance, that keeps soils held in a poverty trap (Gunderson and Holling, 2003; Ludwig *et al*., 2018), significantly reduces OM in the soil, changing its structure and impacting on key energy pathways of microbial organisms. Sterilization is then behaving like a single pulse disturbance, dumping energy in the form of OM in to the soil system and lowering EhpH. Sub soil presented

the highest EhpH and was expected due to its podzolic character. These low fertility soils are free draining and are poor at retaining energy and matter (water, nutrients, etc), coupled with their low OM content, EhpH increases, sometimes outside of the optimum ranges for plant nutrient assimilation (Marschner, 1991, 2012; Husson, 2013).

This study provides evidence that holistic management regimes can create the necessary conditions for effective microbial mediated energy and matter exchange. OM content and soil textural properties maintained by biological activity help to keep the soil within the preferred range for ecosystem function and normal physiological tolerance (DeAngelis *et al*., 2010; Husson, 2013). Promoting the microfauna appears to be a sensible management objective in agro-ecological systems. The flood recovery in Figure 52 shows that modifications of the REDOX conditions by micro-organisms, can stabilize fluctuating soils back in to normal ranges and promote homeostasis (Husson, 2013; Husson *et al*., 2021). Plant homeostasis is thought to play a central role in plant defences to pathogens and is driven by multiple interactions between microorganisms and root systems (Husson *et al*., 2021). This study provides compelling evidence that holistic management overrides textural properties and creates variable Eh-pH conditions, necessary for a diversity of micro-organisms – The LB samples appear more responsive to change (greater fluctuations, perhaps indicating greater REDOX plasticity). The Highly significant drop with flooding compared to WrS, is perhaps indicative of greater microbial activity using up the oxygen faster (Kralova *et al*., 1992; Bohrerova *et al*., 2004). Both flooding and microbial activity acidifies soils especially in organic soils (Kashem and Singh, 2001). LB resulted in a highly significant drop compared to WrS, indicating that perhaps the increased microbial activity already present, utilized oxygen at a faster rate (Kralova *et al*., 1992; Bohrerova *et al*., 2004). Similarly, LB was far more variable in the heat stress experiment (Figure 50), compared to WrS, perhaps a result of the greater internal energy from increased OM. However, in the recovery from flooding (Figure 52), LB stabilized closer to its original conditions compared to WrS, which seem to push in to a more oxidised state.

With the natural processes of EhpH regulation, less energy is needed by plants to adjust the chemical environment, promoting fertilizer efficiency (Tittonell *et al*., 2008) (Husson, 2013) (Husson, 2013). EhpH drives the thermodynamic stability of certain nutrients (Pourbaix, 1945) and effective reactions promote efficient cycling, to support maintenance and growth. The fact that interactions between microbes and their milieu have such profound influences on the EhpH of the soil, demonstrates the role of living organisms in maintaining function. For example, following flooding, recovery of the WrS soil shifted to a new regime in which EhpH was moving dangerously close to destabilizing NH_4 and could lead to significant energy costs to the plants (Marschner, 1991, 2012; Husson, 2013). Eh is very limiting to plant growth and from this perspective any management or disturbance regime that has an impact on Eh will undoubtedly impact the ability of the system to harvest energy in the first place.

Redundancy is important due to the constant state of flux. In terms of REDOX the highly fluctuating environment is a strong selective force on the bacterial communities that are present (Pett-Ridge and Firestone, 2005; DeAngelis *et al*., 2010). Without the ability of microorganisms to turn on and off in response to optimum conditions and there being a functional analogue that is better equipped to the new conditions is switched on, then large fluxes will wipe out the community and perhaps this is what is seen in the results. Where the LB with its higher biomass and potentially more diverse community it was able to function more effectively following the perturbation. As systems accumulate exergy, they can stabilize and adapt to environmental changes by reconfiguring energy flows, which in turn allows them to maintain optimal functioning and resist perturbations (Michaelides, 2021). Exergy and entropy fluxes enable the system to maintain homeostasis (Yildiz *et al*., 2020).

Soil OM (OM) is highly regarded as one of the most crucial soil attributes for buffering soil degradation (Bayer and Mielniczuk, 1997). High levels of OM enhance fertility and improve soil structure and poor management may increase OM decomposition (Alexander, 1978; Afshar *et al*., 2010; Sanderman and Berhe, 2017; Nascimento *et al*., 2022), leading to a significant reduction in buffering capacity. This study confirms the buffering capacity of OM, in the recovery from flooding where LB was brought back to its original state and WrS ended up statistically higher than its baseline, indicating a shift to a new regime. Similarly, in the Baseline assessment, both the holistic soils (LB and Os), exhibited lower EhpH, despite LB being a similar soil texture to WrS, the

only measured difference here being the OM content. The expectation that OM content lowered EhpH (Oglesby, 1997; Lovley *et al*., 1998; Macías and Camps Arbestain, 2010; Husson *et al*., 2015), was for the most confirmed, however interestingly simply adding compost was not enough to have the same effect as holistic management. OM as source of electrons (Chesworth, 2004) requires metabolising to release the reducing properties (electrons). Supporting the case or holistic management that promotes OM storage in the soil.

6.7 Conclusions

Thermodynamics seems to drive soil properties and appears sensitive to biochemical processes, defining microbial community structure and function. Functions of which evolve through adaptations to thermodynamic constraints related to REDOX state of OM and the ΔG. As such, interpretation of these is essential in understanding resilience dynamics (Barros, 2021).

Embedded into thermodynamic theories of ecological systems, health is often discussed in terms of resilience and flexibility when confronted with perturbations. The study looked at two common stresses (heat and flooding) to examine the changes in EhpH with application to resilience. Both stress experiments provide compelling evidence of an EhpH response and confirm to some degree application to resilience monitoring.

EhpH responded to stress by an increase in variation, as disturbance factors develop, there are much more dramatic fluctuations – in keeping of a system reaching its boundaries and then restabilizing in a new regime, in the case of WrS. LB on the other hand although overall more variable in both the stress experiments, showed more elasticity, returning back to its stable state. Evidence of the buffering capacity of OM in holistic management regimes.

The more biomass (OM) the greater thermodynamic mass and redox potential is being regulated by mass and energy flows (the movement of water, the decomposition of OM). Interestingly LB was far more variable in the heat stress and the flooding compared to WrS, perhaps indicative of metabolic plasticity or redox-tolerance mechanisms (Pett-Ridge and Firestone, 2005) due to the increased energy in the system. However, it is not clear whether the response is a chemical or biological response and there is not a linear relationship. For soils to be an effective medium in

the pedosphere, they require finding the balance between reducing components (OM) that stop oxidation and oxidising components that ensure energy is maximized.

In agriculture, the trade-off between productivity and the negative environmental fall out from excessive use of fertilizer to boost productivity, is the greatest challenge in the development of agricultural sustainability. Thus, sustainable fertilizer use is an important factor to consider in resilience models.

Overall, redox heterogeneity at the level of minerals, microbial cells, OM, and the rhizosphere is a fundamental soil property. Further exploration may allow the more accurate prediction of soil and climate interactions and their sweeping impact on environmental sustainability.

Over the previous chapters this study has explored the application of thermodynamics to soil indicators. The following final chapter begins to speculate the connotations this has on agricultural management.

7 Reconciling thermodynamic theory with agricultural practice

7.1 The need for radical thinking

It is becoming increasingly more evident that a total reform of the agricultural sector is necessary to overcome the extent of environmental decline evident across the globe. Historically, agricultural production has risen to meet the demands of globalization, but at great cost to the environment (Rundgren, 2002; Altieri, 2009; Bazuin *et al*., 2011; Jouzi *et al*., 2017). Healthy soils are essential to sustainable development (Amundson *et al*., 2015; Wang *et al*., 2023), this is undoubted. However, achieving this requires a fundamental shift in socio-economic activities related to the land based sectors (Jouzi *et al*., 2017). With high spatial variability and an extremely complex interaction between land management and soil health, accounting for the legion of important factors is difficult (Löbmann *et al*., 2022).

The pedosphere is nested in the Earth system as an interface between the lithosphere, biosphere, hydrosphere and atmosphere (Weil and Brady, 2017). As such, soils embody the most critical natural resources, driving growth and innovation of life, and providing essential eco-system services (ITPS, 2015; Wang *et al*., 2023). Soils have critical relevance to global issues (Keesstra *et al*., 2016; Wang *et al*., 2023). They are the foundation of agricultural production (Nascimento *et al*., 2022) and maintaining their health is vital for sustainable development, as well as ecological stability. Without an effective framework, meeting the demands of anthropogenic growth and the intensified human use of land, will undoubtedly lead to the irreversible decline of ecosystem structure and function (Field *et al*., 2016; Wang *et al*., 2023).

Agriculture as a land use type, connects the soil as a resource to anthropogenic activities. To plausibly integrate new developments in ecological theory into a new agricultural paradigm depends on our ability to recognize the inherent cyclical and dissipative character of the natural world. This study promotes exploration in to new principles of agriculture, rooted in thermodynamics and recognizing the need to establish appropriate indicators that move away from the prescriptive biological, chemical and physical compartments of the soil (Huera-Lucero *et al*., 2020; Bathaei and Štreimikienė, 2023; Chapter 3), toward a more holistic interpretation. A thermodynamic approach based on flows of energy and matter.

7.2 Toward a thermodynamic approach

Introducing thermodynamic perspectives to ecological theory is often met with opposition from all fields in the scientific community, on account of the philosophical reductions needed to simplify the innate complexity of nature (Nielsen, 2019). At the lowest hierarchy of pre-biotic systems, energy terms like entropy, energy and exergy are well equipped to accurately determine the system state, more similarly operating like that of a Carnot engine. However, a slight imperceptible step up the evolutionary ladder and classical descriptions of energy terms completely break down. The asymmetry of higher organisms (Hoffmeyer, 1998), shift them to stabilize at dynamical states, away from equilibrium (Jørgensen *et al*., 2000). Classical and mechanistic laws are dependent upon the reversibility of equilibrium thermodynamics and this is straying in to the realms of irreversibility, as such, thermodynamic descriptors can still serve as metaphors, but it is necessary to redefine the concepts to make them suitable for non-equilibrium thermodynamic systems (Nielsen, 2019; Nielsen *et al*., 2020).

Despite this rather conspicuous challenge, non-equilibrium thermodynamics has still proven best use to describe natural systems. They are open to the exchange of energy and matter (Prigogine, 1955), as opposed to classical equilibrium-based thermodynamics, that by definition only applies to isolated systems. The fact that autotrophic organisms generate more than 200TW of energy in photochemistry, is a strong indicator that energy and matter exchange involved in biotic, activity operates far from equilibrium (Kleidon, 2012). The dissipation of solar energy that is accompanied by the emergence of entropy (chapter 3; (Zotin, 1990; Aoki, 2012) reveals the directional and irreversible tendency of ecological processes (Jørgensen *et al*., 2007). These cyclical and dissipative formations, (Lotka, 1922; Raymond L. Lindeman, 1942; Hutchinson, 1948; Odum *et al*., 1971; Bertness and Callaway, 1994; Ulanowicz, 1995; DeAngelis *et al*., 2012) are at the forefront of a new ecological metaphysic (chapter 2).

Recent advances in the field of evolutionary biology have revealed a hidden unexplored feature of evolution, that abets natural selection (self-organisation) and has been able to explain significant grey areas in theories of niche development and coexistence. New developments, posit that species evolve together, not consecutively as once presumed (chapter 2). Niches develop to occupy vacant domains in space-time (chapter 2), under the prescription that they advance the system further from

equilibrium (chapter 3). In addition, novel structures develop that may participate in the formation of autocatalytic loops with other species, catalysing their own and other species' evolution simultaneously (chapter 2). Substantiation of autocatalysis and the centripetal vortex it creates, has been pivotal to advancements in ecological theory (see chapter 2; Gatti *et al*., 2017, 2018; Veldhuis *et al*., 2018). Evolutionary processes combining the opposing forces of natural selection and self-organization (chapter 2; Veldhuis *et al*., 2018), give rise to biological structures that capture and dissipate solar energy to the maximum of the entropy productio (Lotka, 1922; Raymond L Lindeman, 1942; Odum, 1988; Aoki, 1991, 2012; Fath *et al*., 2004; Chapman *et al*., 2016; Vallino and Algar, 2016), in accordance with the second Law (Zotin, 1990; Aoki, 2012).

In order to maintain a complex organized structure, eco-systems maximize the flow of useable energy (Silow and Mokry, 2010) and invest in to eco-exergy (E. D. Schneider and Kay, 1994; Fath *et al*., 2004; Jørgensen and Fath, 2004; Jørgensen, 2006c, 2008b; Schick, Porembski, Peter R Hobson, *et al*., 2019), maintaining a steady state away from equilibrium ((Prigogine *et al*., 1972; Müller, 1998; Ulanowicz *et al*., 2006; Jørgensen *et al*., 2007; Nielsen *et al*., 2019). It is now widely acknowledged that the core mechanisms of this are in the cyclical and dissipative arrangements of autocatalytic structures. What more, these structures are successive and adaptive (Odum, 1969; Gunderson and Holling, 2001), behaving more like a propensity (*sensu* Karl Popper), that is in an open and nested system (in panarchy), enabling cross-scale interaction; a phenomena now used to explain new dimensions of heterogeneity – internal symbiosis at smaller scales and external competition at larger scales (chapter 2).

Agricultural production must rise to the challenges of closely mimicking natural processes, in order to minimize environmental impact whilst sustaining a growing population. Practitioners must come to terms with the duplexity between structurally maintaining processes and the decay and disorder that entropy evokes (Ulanowicz, 2009c, 2018). What follows, is the realization that agricultural systems, like natural systems are constrained by the boundaries of physical laws, but at the same time, require flexibility and responsiveness to change, with a successive (Fath *et al*., 2004), adaptive, and cyclical character (Gunderson and Holling, 2001). To install resilience, agricultural systems require networks of symbiotic associations, entangled in positive feedback loops in adaptive cycles (Gunderson and Holling, 2001) and strings of

redundant pathways, to create opportunities that respond to perturbation. This duality, supports eco-system functioning and widens the thresholds of ecological performance (resilience and resistance; (Gunderson, 2000; Chapin *et al*., 2011; Ludwig *et al*., 2018). Society now finds itself on the doorstep of a new paradigm in agriculture, one that recognizes the circular interaction of species and components that is abetted by a through flow of energy, in thermodynamically and ontologically open configurations. Herein proposed as ‘circular openness’.

7.3 Circular openness

Circularity in agriculture is certainly not a new concept and fundamentally is heading in the right direction by closing leaks in the system and recycling resources. However, could benefit from understanding the open character of the natural world, that promotes resilience. A system with greater capacity for energy capture and dissipation is considered more resilient to entropic collapse (Hobson & Ibisch 2010). Over time, enhanced rates of energy loss result in the build-up of high entropy wastes and reduced resilience (Odum, 1969). Combining the literature with the findings of this study, it is possible to put forth a revisitation of Jordan's (2016) thermodynamic farm model and concepts from Nature Positive (Ferri and Arnés García, 2023), to include this notion (Figure 53).

Figure 53 – A conceptual model for circular openness in an agricultural setting. Incorporating new developments in ecological theory and elaborating on the farm as a thermodynamic system. Source: Adapted from (Jordan, 2016; Ferri and Arnés García, 2023).

7.3.1 Focus on the dynamic.

A road map to sustainability in the agricultural sector, requires both an understanding of the true dynamics of ecosystem function, as well as the ability to transcribe these understandings into appropriate indicators. For without effective measurables, rooted to ecological processes, how does one intend to at least show what is working. Indicators often focus on serving as a surrogate for biological processes, which are fundamentally difficult to measure directly. The author argues that physical, biological and chemical compartmentalization, such as the utilization of single species or components, or even sets of species and components; is inadequate under the remit of modern understandings of the natural world. As described in previous chapters, ecosystem function is driven by thousands, if not millions of interactions across multiple temporal and spatial scales (Gunderson and Holling, 2001; Howison *et al*., 2017; Veldhuis *et al*., 2018).

Propositions of eco-exergy as a method for evaluating soil health and the complexity of ecosystems is well backed (Sciubba, 2004; Nielsen and Müller, 2009; Jørgensen, 2010; Vihervaara *et al*., 2019). Defined as the amount of work a system can perform when it is brought into equilibrium with its surroundings (Jørgensen, 1990), eco-exergy has been successfully applied to many studies to assess eco-system health, primarily in wetlands (Jørgensen, 2002; Lu *et al*., 2011; Romero and Linares, 2014; Lin *et al*., 2018b). However, it is not possible to measure Eco-exergy directly and it must be calculated (Nielsen *et al*., 2020). What follows is the need to identify appropriate proxies of exergy that are both effective at capturing the flow of energy and matter, as well as efficient in their acquisition.

Proxies of energy terms should focus on dynamics of the system, the interaction between the compartments and the flow of energy. Individual components like basic nutrient contents for example, are irrelevant in an inherently dynamic system, especially if the chemical environment makes the nutrient unavailable (Pourbaix, 1945). At the very least it is important to show the cycling of nutrients before an assessment can be made of the nutrient status; i.e. what proportion of nutrients are locked up in the system, or are mobilized within the fabric of the cycle itself, at the moment of analysis. That said, to be truly sustainable, practices should focus less on trying to artificially right the soil nutrient status, rather organically do so, through natural processes. What is perhaps far more appropriate instead of quantities or content of

nutrients, is the movement of elements as they are whisked about and act as a vessel for energy transformations.

This research explored temperature and REDOX as proxies of thermodynamic functions such as exergy and internal energy. It provides compelling evidence that thermodynamically derived soil proxies based on flows of energy and matter, are responsive to functional and structural changes in the soil (chapter 4), as well as an ability to distinguish between conventional and holistic soil management (chapter 6). An increase in solar radiation is compensated in a complex system, by the diversity of components and emergence of effective energy pathways, this is evident in the diverse meadow compared to disturbed site and the glasshouse trials in chapter 4, where more complex plant-soil systems yields to improved temperature attenuation (Norris *et al*., 2012; Michaelian, 2015; Avelar *et al*., 2020).

In chapter 6, REDOX was highly responsive to heat stress and flooding, showing a certain relationship with resilience. This was due to its relationship to the change in water content of the samples, indicating its ability to capture the flow of energy and matter (movement of water). Temperature by its definition measures the transfer of heat from system to surroundings and is well backed in above ground research (Norris *et al*., 2012; Avelar *et al*., 2020). This study confirms the same trends are evident in the soil. Furthermore, results from chapters 4 and 5 show that temperature is also closely linked to soil moisture, where the results go on to show that thermal attenuation is dependent on a consistent supply of water, only possible in thermodynamically open systems. Finally, the trials examined a range of biotic factors (plant biomass and soil organic matter) and abiotic factors (soil texture, soil water, and microclimate). The results illustrate how thermodynamic variables (e.g., EhpH and temperature) reflect the interdependence among these factors (Shu *et al*., 2022; Devi, 2024).

The research here is limited to controlled environments and is quite far removed from a natural setting. Although some evidence of field-based study is presented, the research community needs to move deeper into this *in-situ* analysis. Exploration of both temperature and REDOX as proxies of energy flow are in their infancy. Future research can start to explore these same principles in the field and practitioners can utilize the methodologies here to develop their own monitoring approach to soil management rooted in thermodynamics. For example, this study started to

differentiate between individual species and their thermodynamic character. A plant community is a sub ecosystem and due to variations in environmental conditions, different communities may have different energy states (Wu *et al*., 2017). Understanding the energetics of plant communities and establishing the relationship between individual communities energy states and the surrounding environment, would help to better predict environmental impact and to establish site specific thresholds.

7.3.2 Getting in to the flow of things

In an open system energy flow is maximised with complexity (Bullock *et al*., 2022 and Fath *et al*., 2004). Chapter 4 indicates that the presence of plants enhances water movement through evapotranspiration, this is increasing energy dissipation (Jørgensen *et al*., 2000) and is evident by the greater attenuation of temperature. Limit the inflow of water (as in drought scenario in chapter 4 and chapter 5) and the very mechanism that is increasing energy dissipation acts to drive the system to collapse (as seen when the plants thermal signature changed under drought). Similarly in chapter 6, heat stress pushes water out of the system and gives rise to highly variable conditions. Chapter 5 shows that in open systems, thresholds are evident that impede energy dissipation to a critical point. Finally in chapter 6 the presence of available energy in the form of OM gives rise to greater REDOX plasticity, indicating a responsive complex system.

Eh and pH are factors that strongly influence the stability of nutrients (Pourbaix, 1945; Gambrell and Patrick Jr, 1978; Laanbroek, 1990; Husson, 2013). If EhpH conditions strongly influence the stability of nutrients and so their availability to react, and organisms have the potential to modify their environment, then it's clear how much influence microbial activity has on nutrient cycles. Chapter 6 results suggest that holistic management can alter soil conditions and impact the availability of nutrients, keeping them within a more suitable range for metabolic efficiency. This corroborates what Veldhuis *et al*., (2018) postulate, that nutrient cycling and availability are emergent properties that arise from the fractal eco-space (Cazzolla Gatti *et al*., 2018), contrary to classical accepted views that they determine community structure (Veldhuis *et al*., 2018). In this sense REDOX relates well with theories of centripetality (Chapter 2 and 3), in that the adequate presence of biomass (OM) and an increase in endosomatic energy (E.D Schneider and Kay, 1994; Eric D. Schneider and Kay,

1994);; Jordan, 2016; Ferri and Arnés García, 2023), actively makes resources (nutrients) more available. Evidence here in Chapter, where holistic management, tends to place sol in favourable conditions. With this in mind, simple measures of nutrient content do not accurately quantify the nutrient status of the plant-soil system, for example, soil N fails to encompass nitrogen mobilized in living organisms, throughout the whole nitrogen cycle (Loreau, 1998; 2010; Lotka, 1925).

The farm is not independent from the surrounding environment, the parnarchy interconnects them (Gunderson and Holling, 2001; Gunderson and Pritchard, 2012) through a flow of energy and matter across the boundaries of many hierarchal sub systems (micro and macro-organisms), enables exergy storage . These can be crops that have associations with other organisms (nitrogen fixation for example), but they can also be wild, in fact as seen in chapter 4, a diverse assemblage of native species has profound influences on the thermal regime. Sharp physical boundaries set between farm and environment, fail to acknowledge the cross-boundary flow evident in the transient flow networks characteristic of natural systems (Gunderson and Holling, 2001; Post *et al*., 2007; Yarrow and Salthe, 2008; Gatti *et al*., 2018); such as, species migration across ecosystems or atmospheric dynamics. Energy and matter is imported and exported between local interactions at smaller scales (mammals or invertebrates foraging across the plot), to larger scales (such as migration corridors and climate influence). It is perhaps not simply a matter of strong interactions within components and weak interactions across boundaries (Nielsen *et al*., 2019), the extent of cross scale interaction, throughout the panarchy, suggests that boundaries are interwoven into the fabric of the landscape.

The farm is nested in its surrounding environment (Figure 53) and dependant upon the flow of energy and export of entropy, carried out by endosomatic processes to maintain its distance from TE (Prigogine and Nicolis, 1985; Jordan, 2016; Prigogine, 2017; Caviedes-Voullième and Hinz, 2020). By severing the connection between farm and environment, through fertilizer inputs (otherwise part of the wider network in autocatalytic interaction), pesticide and herbicide use (destroying important energy and matter carriers), this essentially isolates the system and as seen in Chapters 4 and 6, this can drive to collapse. There becomes a disconnect of energy and matter flow mechanisms. In the same way that (Lovelock and Margulis 1974; Lovelock 1995) and other authors hypothesised that the dissipation of Energy through the Earth

system is indicative of strong biotic activity, the endosomatic feedback (E. D. Schneider and Kay, 1994; Jordan, 2016; Ferri and Arnés García, 2023) coupled to open energy inflow (Chapter 3; Boltzmann, 1905; Schneider and Kay, 1995; Nielsen *et al*., 2019; Vihervaara *et al*., 2019) (circular openness), regulates the biosphere, with implications to climate change.

7.3.3 The role of biodiversity in mitigating climate change

Sustainable and resilient agronomic systems are needed to support the ever more demanding food-energy-water security nexus (Hatfield *et al*., 2017). Through simplification of the once heterogenous landscape, intensification has resulted in a loss of biodiversity and ecological function, heavily impacting critical eco-system services (Norris *et al*., 2012; Landis, 2017; Graaff *et al*., 2019). Climate regulation is one of the most important services that regulates atmospheric processes and above all, moderates temperature (Zari, 2017). The current climate crisis has been attributed to widespread land degradation and loss of biodiversity (García *et al*., 2018). Steps to increase production without addressing resilience and long-term provision of ecosystem services, can lead to highly undesirable environmental outcomes (Bennett *et al*., 2014). Biodiversity is often thought of as a carbon sink, this is true and Eco-exergy is stored in the biomass of carbon based lifeforms. However, climate change mitigation in the sense of circular openness recognizes biodiversity as a climate regulator, where structure and function promote effective energy dissipation and mediates local climate extremes (chapter 4).

In chapter 6, although certain stresses such as heat or flooding do destabilize the energy flow (evidenced by more variable EhpH in this instance) and this appears more exaggerated in a higher biomass regime (Lauriston compared to Writtle). The OM content (biomass) buffers recovery enabling a return to the baseline (as in the flooding recovery in chapter 6). Holistic management acts to increase OM in the soil, working to stabilize and lower EhpH. This has a direct impact on the flow of energy and more importantly, the availability of resources, such as nutrients.

One of the truly astounding features of biodiversity, is the sheer volume of species that can coexist in proximity. As discussed in chapter 2, new understandings in niche emergence predicts that species themselves exponentially create and manipulate available niches (Gatti *et al*., 2017), rather than being set in stone, which is where the

challenges of conventional biodiversity theories lie (Gatti *et al*., 2017). Biodiversity can be considered as a system of RAF sets and this can explain species coexistence (Gatti *et al*., 2017). As previously mentioned, biodiversity, is emphatically indeterminate (Peirce, 1892; Elsasser, 1981; Popper, 1990; Ulanowicz, 2009a; Fiscus and Fath, 2018; Kauffman, 2019). Laws constrain events, but they are incapable of determining outcomes, due to the deeply heterogenous features; biodiversity is unpredictable. This is often overlooked (Ulanowicz, 2009a, 2020), likely down to a lack of mathematical models of biodiversity, that quantify indeterminacy (Shannon, 1948; Grad, 1965; Ulanowicz, 2020).

The homeostatic effect (Lovelock and Margulis, 1974, 1974) of diverse assemblages, exhibiting feedback mechanisms (E.D Schneider and Kay, 1994; Jordan, 2016; Ferri and Arnés García, 2023) that efficiently utilize resources (Ulanowicz, 2006, 2016), coupled to redundant pathways that build resilience (Naeem, 1998; Petchey *et al*., 2007; Biggs *et al*., 2020; Ulanowicz, 2020), regulates ecosystems and even the biosphere. In the context of thermodynamics, the failings of conventional agro-ecosystems (largely monocultures), is the substitution of biological function with external, fossil fuel based, high energy inputs (Jordan, 2016). The self-regulating capacity inherent in natural systems is replaced by artificial resilience, in the form of fertilizers, machinery and soil amendments (Ludwig *et al*., 2018) (Romero and Linares, 2014). With biodiversity decline, agro-ecosystems capacity for energy dissipation is reduced and eco-system productivity is functionally dependant on biodiversity (Ferri and Arnés García, 2023). Agricultural practice must think more about maximizing energy storage and allowing a throughflow of energy toward a nature positive production (Ferri and Arnés García, 2023). This study provides evidence that this can be achieved by increasing system complexity. Chapter 4 explicitly details how complexity can directly impact energy dissipation and how soil temperature is an effective indicator of this. If energy output exceeds input then some degree of resource depletion is occurring at the likely expense of health. Fundamentally, agricultural systems spend too much focus on yield and not enough on eco-system function. The most important consideration is to ensure energy is naturally flowing through the development of a complex assemblage of species.

Results for the trials here indicate that with diverse assemblages of species and the advancement of complexity that brings in more energy and matter (biomass,

information and networks), mechanisms develop to buffer disturbances such as heat and drought, evidenced primarily by the attenuation for temperature in the Meadow compared to Disturbed (EXP4, chapter 4), despite a similarly low moisture content. In addition, the holistic sites in chapter 6 with their enhanced OM, did show a level of resilience in flood recovery. Within natural systems, multiple fail safes exist so the network may persist through disruptions (Woolley *et al*., 2017). Degradation of land means it can support fewer plants and implementation of appropriate regenerative practices, can mitigate the negative effects of anthropogenic development.

7.3.4 Life cannot exist without water

Perhaps the most obvious but with the furthest reaching connotations of the principles within circular openness. Water is well known to be a definitive indicator of life on planets and even in the most baron of deserts; where there is moisture, there is life. The limiting action of water was introduced early on in this narrative, with the Fairy Circles in Namibia. Water activates the soil, in the way that a professional baker would mix yeast with water first to activate it. Through hydrological feedback mechanisms, bio-physical formations create geometric, heterogenous patterns (Getzin *et al*., 2020), to combat the limited moisture conditions in arid landscapes. In semi flood plains, moisture levels in the soil control the route of matter degradation and so energy dissipation (Veldhuis *et al*., 2018). These water driven processes create landscape patterns both spatially and temporally. These phenomena, evidence how heterogenous features create stability in limiting conditions. With the fairy circles and other habitats found in limiting environments, the most stable solution is to develop a heterogenous patch dynamic, drawing resources to specific areas (islands of fertility).

The evidence toward moisture acquisition as a fundamental process in circular openness is quite compelling, a closed system cannot obtain the necessary energy/ matter (water in this instance) to sustain the system. The drought experiments in chapters 4 and 5 illustrate this rather well, when the system is open to an inflow of energy and matter (in this case water) thermodynamic function is as expected and the complexity yields to thermodynamic efficiency - evapotranspiration with a steady supply of moisture attenuates temperature. Isolate the system, by stopping the inflow of water and the thermodynamic function appears to almost reverse, the evapotranspirative action that once regulated the system, now drives it faster in to declining thermodynamic function (Figure 37). This begs the question then – how do

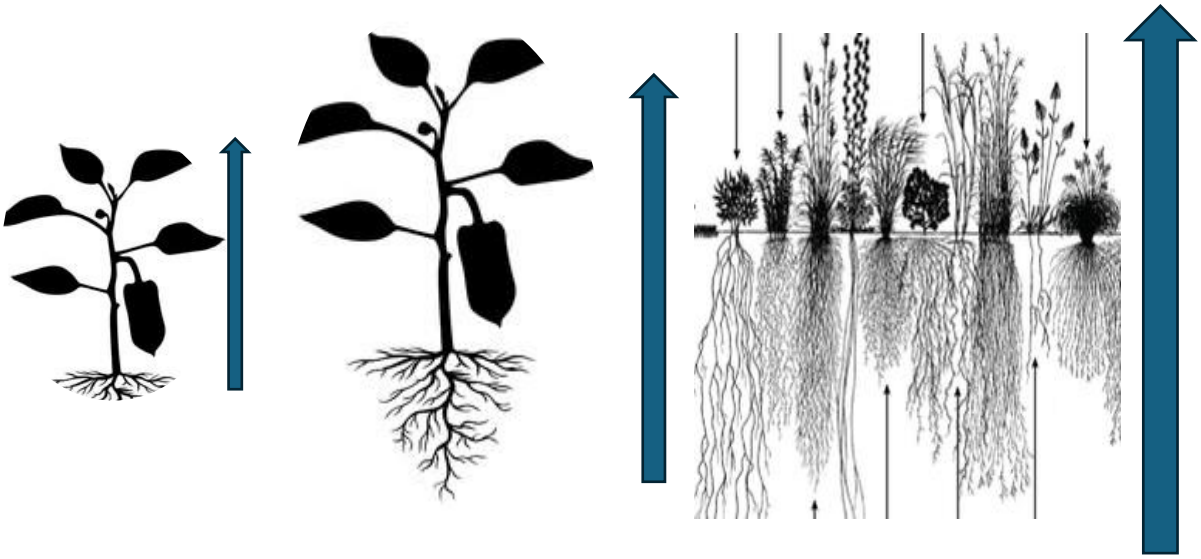
natural systems sustain adequate moisture levels and how can agriculture meet the demand sustainably?

It's easy to irrigate our agricultural fields but this comes at great environmental cost. Abstraction from water bodies is leading to drought in many precious seas and lakes. The Aral Sea, Spain, is a sad case of this, which has had all sorts of repercussions like the release of salts and pesticides into the atmosphere, poisoning land and people for miles around. Due to the inherent openness, mankind must be ever cautious of 'quick fixes' in agriculture. The new agricultural paradigm must look to harnessing natural processes of autocatalysis and centripetality, to draw in resources like water.

Chapter 5 explicitly evidences how moisture levels affect thermodynamic function and identifies a threshold of approx. 10% decline in soil moisture content. That said, in the species rich meadow (chapter 4), despite moisture levels reaching an alarming low level and converging with the disturbed site, thermodynamic function persists, evidenced by the more attenuated temperature regime. This shows how regular monitoring of soil moisture and temperature, can promote the efficient and sustainable use of water; looking not just at the moisture level and assuming an irrigation point from that, but more to the thermodynamic function, and discerning an irrigation regime from this standpoint. Furthermore, in chapter 4, despite converging to a common moisture content, the Meadow remained significantly more attenuated than the disturbed plot. Perhaps indicative of better acquisition of the little water available, factoring in depth of roots and density of root mass could present some interesting relationships to energy dissipation. Due to the seemingly huge impact that moisture has on the soil temperature, research would benefit from further investigation in to controlling moisture content perhaps in drought scenarios, utilizing novel methods like the one presented in chapter 5.

A quite profound example of biological influence on water cycling, is tropical rainforests. They act as hydrological pumps, controlling rain frequencies and most of the humid air. Considering that water movement from the soil increases with plants (Yuan et al., 2021), one starts to wonder about the role of plant-soil:water-energy dynamics. Especially being that it's clear how diverse assemblages seem to mediate energy dissipation rather well in drought scenarios (Chapter 4; Figure 25,Figure 26 and Figure 27).

A diversity of species traits supports diverse water acquisition (Figure 54). Recording plant moisture content and evapotranspiration in the study here, would have supported the argument beter. However, it is fair to assume that with plants water moves from soil to plant and actually in this system, the plants have a certain element of control over the process (stomata). What more plant communiities have heterogenous rooting structures (depth, fine root mass, etc), that promote water acquisition (Figure 54).



Poor root structure monoculture, due to lack of microbial interaction – leads to poor energy dissipation	Improved root structure from organic practice, but still monoculture – improves energy dissipation, but lacks diversity	Diverse and heterogenous community structure more akin to a natural system, with multiple species reaching greater depths and deeper in to pores – vastly improves water acquisition and so evapotranspiration and energy dissipation.

Figure 54 Relationship between evapotranspiration and plant-sol structure and function. Diverse assemblages of species with diverse rooting structures and extensive microbial interaction (right), enables more effective water movement, compared to monocultures with poor structure and lack of microbial interaction (left and middle). Both spatial and temporal distribution of roots and rhizosphere mechanisms, aid complementarity through niche differentiation and facilitation (Homulle et al., 2022).

This concept is however dependant on the understanding that evapotranspiration is a key mechanism behind effective energy dissipation in natural systems (Zotin, 1990;

Jørgensen, 2006c; Aoki, 2012; Hildebrandt *et al*., 2016). Careful investigation into the dynamics of energy flow in water limited situations would further support its application.

7.3.5 Finding the perfect balance between constraint and flexibility

Symmetry in the universe constrains what is possible through time-reversible laws ($E=mc^2$); symmetries are conservative, as transformations can be inverted (Fraassen *et al*., 1989; Longo *et al*., 2012; Korenić *et al*., 2020). Just as in the dead deer analogy, where the energy and mass remain the same (Tiezzi *et al*, 2007). Time-reversible laws, cannot however exert the 'symmetry-breaking selection' needed for progressive order found in living systems (Ulanowicz, 2019); the functional incompleteness (Korenić *et al*., 2020). An unavoidable and irreversible decay of energy defines the entropic nature of the universe and is reflected in the arrow of time (Blum, 1951).

Some authors view the second law as the final cause (sensu Aristotle; Salthe, 1993), or a major direction behind evolutionary change (Schneider and Sagan, 2005), where the sole purpose of living systems is to accelerate entropy production (Swenson, 1989). However, Ulanowicz (2009) argued that classical views of the second law, as the fundamental essence of universal dynamics and order being an accidental consequence, are over simplified versions of its true nature. Entropy does decay the existing configurations, it acts to withdraw and shed constraint, but it also creates new opportunities (Ulanowicz, 2019). It is a measure of the parallel pathways in a diverse trophic network (Rutledge *et al*., 1976; Ulanowicz, 2019).

From a thermodynamic view of growth, one could posit, that departures from equilibrium (Jørgensen *et al*., 2000) and rates of growth are a product of positive feedback. Without the generation of energy gradients, a flow of exergy would not move a system away from equilibrium, it would remain there (Jørgensen *et al*., 2000). However, without throughput, decay and degradation, associated with negative growth (Jørgensen *et al*., 2000), the second law is not satisfied, to say the least. Autocatalysis enables the co-evolution of species that form guilds and in the event that a species or species guild, for whatever reason is diminished, a functionally similar analogue exists to take its place (Elmqvist *et al*., 2003; Ludwig *et al*., 2018). Stability is maintained through spatial and temporal heterogeneity (creating landscape mosaics), in response to the changing environmental conditions (Howison *et al*., 2017; Veldhuis *et al*., 2018).

The continual maintenance of ecological function is through both; mutual necessity (with positive feedback loops among components) at one scale and negative feedback between competing loops at the next scale up (Howison *et al*., 2017; Veldhuis *et al*., 2018). Negative feedback is the basis of cybernetics (Wiener, 1961) and eco-systems up to the highest scale (Lovelock, 1995; Allen and Holling, 2008; Wardwell *et al*., 2008; Sundstrom, 2009; Nash *et al*., 2014; Spanbauer *et al*., 2016; Sundstrom and Allen, 2019). are emphatically cybernetic (Raymond L. Lindeman, 1942; Hutchinson, 1948; Bateson, 1980; Jørgensen *et al*., 2000; Guddemi, 2020).

However, to quote Korenić *et al*., (2020), 'Life is not simply a thermostat controlled by positive and negative feedback' (Lovelock and Margulis, 1974), this does not capture the dual nature of eco-system dynamics (Ulanowicz, 2009b); a symmetry breaking, creation of constraints (such as a membrane) opposed by negative regulation (such as natural selection; Korenić *et al*., 2020). Laws do not determine evolution, they are instrumental and constraining, but not definitive (Ulanowicz, 2014). With this comes the realization that no positivist tools are available to quantify what is perhaps not there, the apophatic character of biodiversity (Ulanowicz, 2012, 2014). This feature cannot yield to historical events, as determinacy opens to vulnerabilities (Ulanowicz, 2012, 2014), nonetheless, integrity is maintained through repair of disturbance (Gunderson and Holling, 2001; Ulanowicz, 2009c) and the system continues to function. What is now required is the redefining of thermodynamic terms to align with the new ecological metaphysic (Ulanowicz, 1999).

When it comes to agriculture, there is no hard answer for farming practice! It is clear that prescriptive agricultural techniques do not have a broad enough application to meet the inherently individual nature of landscapes. If Chapter 4 tells anything, it's that plant-soil systems are inherently heterogeneous and complexity yields to effective energy dissipation (Jørgensen *et al*., 2000). In chapter 4, even the simple transition from bare soil to one species shows an improvement in energy dissipation. Both chapters 4 and 6 show how this small increase in complexity not only improves thermodynamic efficiency but also creates heterogenous features, especially under stress. For example, the plant samples were more variable than bare soil and Sub under stress in Section 4.3.1, similarly LB was far more variable than WrS in Chapter 6 (Figure 50 and Figure 52).

Extensive literature exists on the many elaborate ways in which a multitude of biophysical formulations can impact functioning (slope, aspect, soil type, etc.; (Aalto *et al*., 2013; Bartz *et al*., 2015). Why would the microcosm of agricultural soils behave any differently. With significant compositional and structural differences observed within extremely short spatial ranges (Howison *et al*., 2017; Veldhuis *et al*., 2018; Löbmann *et al*., 2022), how can the possibility of a one size fits all model even be considered.

In conjunction with constraining formations of species guilds and mutual interaction (RAF sets), agricultural systems, like natural systems require flexibility; in the form of competitive loops (Howison *et al*., 2017; Veldhuis *et al*., 2018) and redundancy (Rutledge *et al*., 1976; Naeem, 1998; Elmqvist *et al*., 2003; Petchey *et al*., 2007; Ludwig *et al*., 2018; Biggs *et al*., 2020; Ulanowicz, 2020). These stem from their ontologically and thermodynamically open character (Ulanowicz, 2006; Nielsen and Emmeche, 2013; Nielsen *et al*., 2019, 2020; Biggs *et al*., 2020). This requirement for radical contingency (Ulanowicz, 1999) is useful, particularly for the emergence of life and the evolvability of autocatalytic sets (Hordijk and Steel, 2014; Gatti *et al*., 2018). Organization in the biosphere then is the association of the two antagonistic processes (Longo *et al*., 2015), constraint and flexibility.

How can practitioners expect to maintain ecological function in such simplified systems as agriculture has become?

The combined flexible and constrained behaviors are far from mechanistic and clashes with the conventions on how nature has been perceived (Ulanowicz, 2004). Natural selection is only part of the story (Lotka, 1922, 1925; Calcagno *et al*., 2017; Gatti *et al*., 2017; Veldhuis *et al*., 2018) and redundancy is an important feature of stability (Biggs *et al*., 2020). In fact, what one observes is that a wide variety of eco-systems are more flexible than they are constrained (Zorach and Ulanowicz, 2003; Ulanowicz, 2009c, 2020). This not only confirms the extent of redundancy, but it also deems it necessary. This is where our agricultural systems must take heed. Kaufman spoke of the end of the era of physics, what lies ahead is the era of ecology, a world of contingencies, ‘Circular openness’ perhaps?

“With only positivist tools at one's disposal, one cannot hope to encompass the interplay between constraint and looseness that characterizes sustainability”

(Karl Popper, see Ulanowicz, 2020).

8 References

Aalto, J., le Roux, P. C. and Luoto, M. (2013) 'Vegetation Mediates Soil Temperature and Moisture in Arctic-Alpine Environments.' *Arctic, Antarctic, and Alpine Research*. Taylor & Francis, 45(4) pp. 429–439.

Abu-Hamdeh, N. H. (2003) 'Thermal Properties of Soils as affected by Density and Water Content.' *Biosystems Engineering*, 86(1) pp. 97–102.

Acharya, S., Kaplan, D. A., Casey, S., Cohen, M. J. and Jawitz, J. W. (2015) 'Coupled local facilitation and global hydrologic inhibition drive landscape geometry in a patterned peatland.' *Hydrology and Earth System Sciences*. Copernicus GmbH, 19(5) pp. 2133–2144.

Afshar, F. A., Ayoubi, S. and Jalalian, A. (2010) 'Soil redistribution rate and its relationship with soil organic carbon and total nitrogen using 137Cs technique in a cultivated complex hillslope in western Iran.' *Journal of environmental radioactivity*. Elsevier, 101(8) pp. 606–614.

Agboma, C. and Itenfisu, D. (2020) 'Investigating the Spatio-Temporal dynamics in the soil water storage in Alberta's Agricultural region.' *Journal of Hydrology*, 588, September, p. 125104.

Albrecht, M. and Gotelli, N. J. (2001) 'Spatial and temporal niche partitioning in grassland ants.' *Oecologia*, 126(1) pp. 134–141.

Alexander, M. (1978) 'Introduction to soil microbiology.' *Soil Science*. LWW, 125(5) p. 331.

Al-Kaisi, M. M., Lal, R., Olson, K. R. and Lowery, B. (2017) 'Chapter 1 - Fundamentals and Functions of Soil Environment.' *In* Al-Kaisi, M. M. and Lowery, B. (eds) *Soil Health and Intensification of Agroecosytems*. Academic Press, pp. 1–23.

Al-Kayssi, A. W., Al-Karaghouli, A. A., Hasson, A. M. and Beker, S. A. (1990) 'Influence of soil moisture content on soil temperature and heat storage under greenhouse conditions.' *Journal of Agricultural Engineering Research*, 45, January, pp. 241–252.

Allen, C. R. and Holling, C. S. (2008) *Discontinuities in ecosystems and other complex systems*. Columbia University Press.

Allen, R. G., Pereira, L. S., Raes, D. and Smith, M. (1998) 'Crop evapotranspiration-Guidelines for computing crop water requirements-FAO Irrigation and drainage paper 56.' *Fao, Rome*, 300(9) p. D05109.

Altieri, M. A. (2009) 'Agroecology, small farms, and food sovereignty.' *Monthly review*, 61(3) pp. 102–113.

Amiri, Z., Asgharipour, M. R., Campbell, D. E. and Armin, M. (2020) 'Extended exergy analysis (EAA) of two canola farming systems in Khorramabad, Iran.' *Agricultural Systems*, 180, April, p. 102789.

Amundson, R., Berhe, A. A., Hopmans, J. W., Olson, C., Sztein, A. E. and Sparks, D. L. (2015) 'Soil and human security in the 21st century.' *Science*. American Association for the Advancement of Science, 348(6235) p. 1261071.

Aoki, I. (1991) 'Entropy principle for human development, growth and aging.' *Journal of Theoretical Biology*, 150(2) pp. 215–223.

Aoki, I. (2012) *Entropy Principle for the Development of Complex Biotic Systems: Organisms, Ecosystems, the Earth*. Elsevier.

Ashby, W. R. (1947) 'Principles of the Self-Organizing Dynamic System.' *The Journal of General Psychology*. Routledge, 37(2) pp. 125–128.

Avelar, D., Garrett, P., Ulm, F., Hobson, P. and Penha-Lopes, G. (2020) 'Ecological complexity effects on thermal signature of different Madeira island ecosystems.' *Ecological Complexity*, 43, August, p. 100837.

Ayoubi, S., Emami, N., Ghaffari, N., Honarjoo, N. and Sahrawat, K. L. (2014) 'Pasture degradation effects on soil quality indicators at different hillslope positions in a semiarid region of western Iran.' *Environmental Earth Sciences*. Springer, 71 pp. 375–381.

Azizsoltani, E., Honarjoo, N. and Ayoubi, S. (2019) 'How soil pore distribution could help in soil quality studies as an appropriate indicator.' *Eurasian soil science*. Springer, 52 pp. 654–660.

Balakhnina, T. I., Bennicelli, R. P., Stępniewska, Z., Stępniewski, W. and Fomina, I. R. (2010) 'Oxidative damage and antioxidant defense system in leaves of Vicia faba major L. cv. Bartom during soil flooding and subsequent drainage.' *Plant and soil*. Springer, 327 pp. 293–301.

Baldock, J. A. and Smernik, R. J. (2002) 'Chemical composition and bioavailability of thermally altered *Pinus resinosa* (Red pine) wood.' *Organic Geochemistry*, 33(9) pp. 1093–1109.

Bararzadeh Ledari, M., Saboohi, Y., Valero, A. and Azamian, S. (2020) 'Exergy Analysis of a Bio-System: Soil-Plant Interaction.' *Entropy (Basel, Switzerland)*, 23(1) p. 3.

Barbier, N., Couteron, P., Lefever, R., Deblauwe, V. and Lejeune, O. (2008) 'Spatial Decoupling of Facilitation and Competition at the Origin of Gapped Vegetation Patterns.' *Ecology*, 89(6) pp. 1521–1531.

Bardgett, R. D. and van der Putten, W. H. (2014) 'Belowground biodiversity and ecosystem functioning.' *Nature*. Nature Publishing Group, 515(7528) pp. 505–511.

Bar-On, Y. M., Phillips, R. and Milo, R. (2018) 'The biomass distribution on Earth.' *Proceedings of the National Academy of Sciences*. Proceedings of the National Academy of Sciences, 115(25) pp. 6506–6511.

Barros, N. (2021) 'Thermodynamics of Soil Microbial Metabolism: Applications and Functions.' *Applied Sciences*. Multidisciplinary Digital Publishing Institute, 11(11) p. 4962.

Barry, G. (2014) 'Terrestrial ecosystem loss and biosphere collapse.' *Management of Environmental Quality: An International Journal*, 25, August.

Barry, K. E., Pinter, G. A., Strini, J. W., Yang, K., Lauko, I. G., Schnitzer, S. A., Clark, A. T., Cowles, J., Mori, A. S., Williams, L., Reich, P. B. and Wright, A. J. (2021) 'A graphical null model for scaling biodiversity–ecosystem functioning relationships.' *Journal of Ecology*, 109(3) pp. 1549–1560.

Barth, R. C. and Klemmedson, J. O. (1978) 'Shrub-induced Spatial Patterns of Dry Matter, Nitrogen, and Organic Carbon.' *Soil Science Society of America Journal*, 42(5) pp. 804–809.

Bartz, D., Stockmar, E., Chemnitz, C., Weigelt, J., Beste, A., Brent, Z., Dunbar, M. B., Ehlers, K., Feldt, H., Fuhr, L., Gerke, J., Green, A., Holdinghausen, H., Kotschi, J., Lal, R., Lymbery, P., Mathias, E., Montanarella, L., Mundy, P., Nolte, H., Burbano de Lara, M. D. N., Ostermeier, M., Peinl, H., Rodrigo, A., Sharma, R., Sperk, C., Tomiak, K., Wetter, K. J. and Wilson, J. (2015) *Soil Atlas: Facts and figures about earth, land and fields | Heinrich Böll Stiftung*. 2nd ed., Germany: Heinrich Böll Foundation and Institute for Advanced Sustainability Studies.

Bastianoni, S. (2008) 'Eco-Exergy to Emergy Flow Ratio.' *In* Jørgensen, S. E. and Fath, B. D. (eds) *Encyclopedia of Ecology*. Oxford: Academic Press, pp. 979–983.

Bastianoni, S. and Marchettini, N. (1997) 'Emergy/exergy ratio as a measure of the level of organization of systems.' *Ecological Modelling*, 99(1) pp. 33–40.

Bastida, F., Zsolnay, A., Hernández, T. and García, C. (2008) 'Past, present and future of soil quality indices: a biological perspective.' *Geoderma*. Elsevier, 147(3–4) pp. 159–171.

Bateson, G. (1980) *Mind and Nature: A Necessary Unity*. Bantam Books.

Bathaei, A. and Štreimikienė, D. (2023) 'A Systematic Review of Agricultural Sustainability Indicators.' *Agriculture*. Multidisciplinary Digital Publishing Institute, 13(2) p. 241.

Bauke, S. L., Amelung, W., Bol, R., Brandt, L., Brüggemann, N., Kandeler, E., Meyer, N., Or, D., Schnepf, A., Schloter, M., Schulz, S., Siebers, N., von Sperber, C. and Vereecken, H. (2022) 'Soil water status shapes nutrient cycling in agroecosystems from micrometer to landscape scales.' *Journal of Plant Nutrition and Soil Science*, 185(6) pp. 773–792.

Baveye, P. (2017) 'Quantification of ecosystem services: Beyond all the "guesstimates", how do we get real data?' *Ecosystem Services*, 24 pp. 47–49.

Bayer, C. and Mielniczuk, J. (1997) 'Características químicas do solo afetadas por métodos de preparo e sistemas de cultura.' *Revista brasileira de Ciência do Solo*, 21(1) pp. 105–112.

Bazuin, S., Azadi, H. and Witlox, F. (2011) 'Application of GM crops in Sub-Saharan Africa: lessons learned from Green Revolution.' *Biotechnology advances*. Elsevier, 29(6) pp. 908–912.

Belovsky, G. E. and Slade, J. B. (2000) 'Insect herbivory accelerates nutrient cycling and increases plant production.' *Proceedings of the National Academy of Sciences*. National Academy of Sciences, 97(26). Biological Sciences pp. 14412–14417.

Belsky, A. J. (1994) 'Influences of Trees on Savanna Productivity: Tests of Shade, Nutrients, and Tree-Grass Competition.' *Ecology*, 75(4) pp. 922–932.

Bennett, E., Carpenter, S. R., Gordon, L. J., Ramankutty, N., Balvanera, P., Campbell, B., Cramer, W., Foley, J., Folke, C., Karlberg, L., Liu, J., Lotze-Campen, H., Mueller, N. D., Peterson, G. D., Polasky, S., Rockström, J., Scholes, R. J. and Spierenburg, M. (2014) 'Toward a More Resilient Agriculture.' *The Solutions Journal*, 5(5) pp. 65–75.

Berendse, F., van Ruijven, J., Jongejans, E. and Keesstra, S. (2015) 'Loss of Plant Species Diversity Reduces Soil Erosion Resistance.' *Ecosystems*, 18(5) pp. 881–888.

Berg, M., Ruiter, P. D., Didden, W., Janssen, M., Schouten, T. and Verhoef, H. (2001) 'Community food web, decomposition and nitrogen mineralisation in a stratified Scots pine forest soil.' *Oikos*, 94(1) pp. 130–142.

Bertness, M. D. and Callaway, R. (1994) 'Positive interactions in communities.' *Trends in Ecology & Evolution*. Elsevier, 9(5) pp. 191–193.

Biggs, C. R., Yeager, L. A., Bolser, D. G., Bonsell, C., Dichiera, A. M., Hou, Z., Keyser, S. R., Khursigara, A. J., Lu, K., Muth, A. F., Negrete Jr., B. and Erisman, B. E. (2020) 'Does functional redundancy affect ecological stability and resilience? A review and meta-analysis.' *Ecosphere*, 11(7) p. e03184.

Biggs, E. M., Bruce, E., Boruff, B., Duncan, J. M., Horsley, J., Pauli, N., McNeill, K., Neef, A., Van Ogtrop, F. and Curnow, J. (2015) 'Sustainable development and the water–energy–food nexus: A perspective on livelihoods.' *Environmental Science & Policy*. Elsevier, 54 pp. 389–397.

Billen, G. (1973) 'Etude de l'écométabolisme du mercure dans un milieu d'eau douce.' *Hydrobiological Bulletin*. Springer, 7 pp. 60–68.

Bispo, A., Cluzeau, D., Creamer, R., Dombos, M., Graefe, U., Krogh, P. H., Sousa, J. P., Peres, G., Rutgers, M. and Winding, A. (2009) 'Indicators for monitoring soil biodiversity.' *Integrated environmental assessment and management*. BioOne, 5(4) pp. 717–719.

Blum, H., F. (1951) *Time's Arrow and Evolution*. Mishawaka, Indiana, United States: Better World Books.

Blum, W. E. (2005) 'Functions of soil for society and the environment.' *Reviews in Environmental Science and Bio/Technology*. Springer, 4 pp. 75–79.

Bohrerova, Z., Stralkova, R., Podesvova, J., Bohrer, G. and Pokorny, E. (2004) 'The relationship between redox potential and nitrification under different sequences of crop rotations.' *Soil and Tillage Research*. Elsevier, 77(1) pp. 25–33.

Boltzmann, L. (1905) *Populäre Schriften*. JA Barth.

Bonilla, C., Gómez, E. and Sánchez, M. E. (2002) 'Suelo: Los Organismos Que lo Habitan.' *Universidad Nacional de Colombia: Palmira, Colombia*, 5.

Borrelli, P., Robinson, D. A., Fleischer, L. R., Lugato, E., Ballabio, C., Alewell, C., Meusburger, K., Modugno, S., Schütt, B., Ferro, V., Bagarello, V., Oost, K. V., Montanarella, L. and Panagos, P. (2017) 'An assessment of the global impact of 21st century land use change on soil erosion.' *Nature Communications*, 8(1) p. 2013.

Brakmann, S. (2001) 'Origin of Life, Theories of.' *In* Levin, S. A. (ed.) *Encyclopedia of Biodiversity (Second Edition)*. Waltham: Academic Press, pp. 628–636.

Brokaw, N. and Busing, R. T. (2000) 'Niche versus chance and tree diversity in forest gaps.' *Trends in Ecology & Evolution*, 15(5) pp. 183–188.

Brown, E. J., Kirshner, J. D., Dunlop, L., Friend, R. M., Brooks, S. H., Redeker, K. R., Zimmermann, A., Walton, P. H., Cairo, J. and Veneu, F. (2023) 'Learning through interdisciplinary dialogue: Methodological approaches for bridging epistemological divides.' *Methodological Innovations*, July.

Bruno, J. F., Stachowicz, J. J. and Bertness, M. D. (2003) 'Inclusion of facilitation into ecological theory.' *Trends in Ecology & Evolution*, 18(3) pp. 119–125.

Brzezińska, M. (2004) 'Aeration status of soil and enzyme activity.' *SOIL–PLANT–ATMOSPHERE AERATION AND ENVIRONMENTAL PROBLEMS* p. 55.

Bullock, J. M., Fuentes-Montemayor, E., McCarthy, B., Park, K., Hails, R. S., Woodcock, B. A., Watts, K., Corstanje, R. and Harris, J. (2022) 'Future restoration should enhance ecological complexity and emergent properties at multiple scales.' *Ecography*, 2022(4).

Buonocore, E., Buia, M. C., Russo, G. F. and Franzese, P. P. (2021) 'Exploring the convergence of natural flows for the generation of natural capital stocks in marine ecosystems.' *Ecological Complexity*, 46, March, p. 100928.

Buonocore, E., Donnarumma, L., Appolloni, L., Miccio, A., Russo, G. F. and Franzese, P. P. (2020) 'Marine natural capital and ecosystem services: An environmental accounting model.' *Ecological Modelling*, 424, May, p. 109029.

Butterfield, B. J. and Briggs, J. M. (2009) 'Patch dynamics of soil biotic feedbacks in the Sonoran Desert.' *Journal of Arid Environments*, 73(1) pp. 96–102.

Cadenasso, M. L., Pickett, S. T. A. and Grove, J. M. (2006) 'Dimensions of ecosystem complexity: Heterogeneity, connectivity, and history.' *Ecological Complexity*, 3(1) pp. 1–12.

Calcagno, V., Jarne, P., Loreau, M., Mouquet, N. and David, P. (2017) 'Diversity spurs diversification in ecological communities.' *Nature Communications*. Nature Publishing Group, 8(1) p. 15810.

Callaway, R. M., Brooker, R. W., Choler, P., Kikvidze, Z., Lortie, C. J., Michalet, R., Paolini, L., Pugnaire, F. I., Newingham, B., Aschehoug, E. T., Armas, C., Kikodze, D. and Cook, B. J. (2002) 'Positive interactions among alpine plants increase with stress.' *Nature*. Nature Publishing Group, 417(6891) pp. 844–848.

Camacho, D. C. (2008) 'Esquemas de pagos por servicios ambientales para la conservación de cuencas hidrográficas en el Ecuador.' *Investigación agraria. Sistemas y recursos forestales*. Instituto Nacional de Investigación y Tecnología Agraria y Alimentaria (INIA), 17(1) pp. 54–66.

Cardinale, B. J. (2011) 'Biodiversity improves water quality through niche partitioning.' *Nature*. Nature Publishing Group, 472(7341) pp. 86–89.

Carnwath, G. and Nelson, C. (2017) 'Effects of biotic and abiotic factors on resistance versus resilience of Douglas fir to drought.' *PLOS ONE*. Public Library of Science, 12(10) p. e0185604.

Castell, W. zu and Schrenk, H. (2020) 'Computing the adaptive cycle.' *Scientific Reports*. Nature Publishing Group, 10(1) p. 18175.

Caviedes-Voullième, D. and Hinz, C. (2020) 'From nonequilibrium initial conditions to steady dryland vegetation patterns: How trajectories matter.' *Ecohydrology*, 13(3) p. e2199.

Cha, J. H. and Finkelstein, M. (2018) 'Generalized Polya Process.' *In* Cha, J. H. and Finkelstein, M. (eds) *Point Processes for Reliability Analysis: Shocks and Repairable Systems*. Cham: Springer International Publishing (Springer Series in Reliability Engineering), pp. 247–278.

Chadwick, O. A. and Chorover, J. (2001) 'The chemistry of pedogenic thresholds.' *Geoderma*. Elsevier, 100(3–4) pp. 321–353.

Chaignon, V., Bedin, F. and Hinsinger, P. (2002) 'Copper bioavailability and rhizosphere pH changes as affected by nitrogen supply for tomato and oilseed rape cropped on an acidic and a calcareous soil.' *Plant and Soil*, 243(2) pp. 219–228.

Chance, B., Ghosh, A. K. and Pye, E. K. (2014) *Biological and Biochemical Oscillators*. Academic Press.

Chapin, F. S., Matson, P. A. and Mooney, H. (2002) *Principles of Terrestrial Ecosystem Eology*.

Chapin, F. S., Sala, O. E., Burke, I. C., Grime, J. P., Hooper, D. U., Lauenroth, W. K., Lombard, A., Mooney, H. A., Mosier, A. R., Naeem, S., Pacala, S. W., Roy, J., Steffen, W. L. and Tilman, D. (1998) 'Ecosystem Consequences of Changing Biodiversity.' *BioScience*. [American Institute of Biological Sciences, Oxford University Press], 48(1) pp. 45–52.

Chapin, S. F., Matson, Pamela. A. and Vitousek, Peter. M. (2011) *Principles of Terrestrial Ecosystem Ecology, 2nd Edition - PDF Free Download*. 2nd ed.

Chapman, E. J., Childers, D. L. and Vallino, J. J. (2016) 'How the Second Law of Thermodynamics Has Informed Ecosystem Ecology through Its History.' *BioScience*, 66(1) pp. 27–39.

Chaube, N. R., Chaurasia, S., Tripathy, R., Pandey, D. K., Misra, A., Bhattacharya, B. K., Chauhan, P., Yarakulla, K., Bairagi, G. D., Srivastava, P. K., Teheliani, P. and Ray, S. S. (2019) 'Crop phenology and soil moisture applications of SCATSAT-1.' *Current Science*, 117(6) p. 1022.

Chen, G. Q., Jiang, M. M., Yang, Z. F., Chen, B., Ji, X. and Zhou, J. B. (2009) 'Exergetic assessment for ecological economic system: Chinese agriculture.' *Ecological Modelling*, 220(3) pp. 397–410.

Chen, J., Shiyomi, M., Wuyunna, Hori, Y. and Yamamura, Y. (2015) 'Vegetation and its spatial pattern analysis on salinized grasslands in the semiarid Inner Mongolia steppe.' *Grassland Science*, 61(2) pp. 121–130.

Chen, Y., Huang, X., Lang, X., Tang, R., Zhang, R., Li, S. and Su, J. (2023) 'Effects of plant diversity, soil microbial diversity, and network complexity on ecosystem multifunctionality in a tropical rainforest.' *Frontiers in Plant Science*. Frontiers, 14, September.

Chen, Y., Yao, Z., Sun, Yu, Wang, E., Tian, C., Sun, Yang, Liu, J., Sun, C. and Tian, L. (2022) 'Current Studies of the Effects of Drought Stress on Root Exudates and Rhizosphere Microbiomes of Crop Plant Species.' *International Journal of Molecular Sciences*. Multidisciplinary Digital Publishing Institute, 23(4) p. 2374.

Chesson, P. (2000) 'Mechanisms of Maintenance of Species Diversity.' *Annual Review of Ecology and Systematics*, 31(1) pp. 343–366.

Chesworth, W. (2004) 'Redox, soils, and carbon sequestration.' *Edafología*, 11, January.

Chesworth, W., Cortizas, A. M. and García-Rodeja, E. (2006) 'The redox–pH approach to the geochemistry of the Earth's land surface, with application to peatlands.' *Developments in Earth surface processes*. Elsevier, 9 pp. 175–195.

Christiansen, P. V. (1999) 'Downward causation from macro- to microlevels in physics.' *Downward Causation*. Aarhus Universitetsforlag.

Clark, M. and Tilman, D. (2017) 'Comparative analysis of environmental impacts of agricultural production systems, agricultural input efficiency, and food choice.' *Environmental Research Letters*. IOP Publishing, 12(6) p. 064016.

Cluzeau, D., Guernion, M., Chaussod, R., Martin-Laurent, F., Villenave, C., Cortet, J., Ruiz-Camacho, N., Pernin, C., Mateille, T. and Philippot, L. (2012) 'Integration of biodiversity in soil quality monitoring: Baselines for microbial and soil fauna parameters for different land-use types.' *European Journal of Soil Biology*. Elsevier, 49 pp. 63–72.

Combs, S. M. and Nathan, M. V. (1998) 'Soil organic matter.' *In J.R. Brown (Ed), Reccomended chemical soil test procedure for the North Central Region*. Columbia, MO: NCR Publ. NO. 221 (revised) Missouri Agr. Exp. Sta. SB 1001, pp. 57–58.

Conant, R. T. (2010) *Challenges and opportunities for carbon sequestration in grassland systems*. FAO Rome, Italy.

Cramer, M. D. and Barger, N. N. (2013) 'Are Namibian "Fairy Circles" the Consequence of Self-Organizing Spatial Vegetation Patterning?' *PLOS ONE*. Public Library of Science, 8(8) p. e70876.

Cramer, M. D., Barger, N. N. and Tschinkel, W. R. (2017) 'Edaphic properties enable facilitative and competitive interactions resulting in fairy circle formation.' *Ecography*, 40(10) pp. 1210–1220.

Darwin, C. (2003) *On the Origin of Species, 1859*. London: Routledge.

DeAngelis, D. L., Post, W. M. and Travis, C. C. (2012) *Positive Feedback in Natural Systems*. Springer Science & Business Media.

DeAngelis, K. M., Silver, W. L., Thompson, A. W. and Firestone, M. K. (2010) 'Microbial communities acclimate to recurring changes in soil redox potential status.' *Environmental Microbiology*, 12(12) pp. 3137–3149.

Degn, H. (1967) 'Effect of Bromine Derivatives of Malonic Acid on the Oscillating Reaction of Malonic Acid, Cerium Ions and Bromate.' *Nature*. Nature Publishing Group, 213(5076) pp. 589–590.

Devi, D. (2024) 'Interdependency in Environment.' *In*, pp. 21–26.

Di Bitetti, M. S., De Angelo, C. D., Di Blanco, Y. E. and Paviolo, A. (2010) 'Niche partitioning and species coexistence in a Neotropical felid assemblage.' *Acta Oecologica*, 36(4) pp. 403–412.

Dick, J. and Tan, J. (2021) *Genomic evidence for a chemical link between redox conditions and microbial community composition*.

Dietz, K.-J. (2003) 'Redox control, redox signaling, and redox homeostasis in plant cells.' *Int Rev Cytol*, 228 pp. 141–193.

Dong, S., Shang, Z., Gao, J. and Boone, R. B. (2020) 'Enhancing sustainability of grassland ecosystems through ecological restoration and grazing management in an era of climate change on Qinghai-Tibetan Plateau.' *Agriculture, Ecosystems & Environment*, 287, January, p. 106684.

Doty, L. (2021) *How to Calculate Eco Exergy of Organic Matter and Organisms - Population Dynamics*. Ecology Center. [Online] [Accessed on 14th November 2021] https://www.ecologycenter.us/population-dynamics-2/how-to-calculate-ecoexergy-of-organic-matter-and-organisms.html.

Dou, S., Shan, J., Song, X., Cao, R., Wu, M., Li, C. and Guan, S. (2020) 'Are humic substances soil microbial residues or unique synthesized compounds? A perspective on their distinctiveness.' *Pedosphere*, 30(2) pp. 159–167.

Draganovic, V., Jørgensen, S. E., Boom, R., Jonkers, J., Riesen, G. and van der Goot, A. J. (2013) 'Sustainability assessment of salmonid feed using energy, classical exergy and eco-exergy analysis.' *Ecological indicators*. Elsevier, 34 pp. 277–289.

Duru, M., Therond, O., Martin, G., Martin-Clouaire, R., Magne, M.-A., Justes, E., Journet, E.-P., Aubertot, J.-N., Savary, S., Bergez, J.-E. and Sarthou, J.-P. (2015) 'How to implement biodiversity-based agriculture to enhance ecosystem services: a review.' *Agronomy for Sustainable Development*, 35.

EEA (2021) *Soil moisture deficit*. https://www.eea.europa.eu/ims/soil-moisture-deficit. [Online] [Accessed on 12th June 2023] https://www.eea.europa.eu/ims/soil-moisture-deficit.

Ehrenfeld, J. G., Ravit, B. and Elgersma, K. (2005) 'Feedback in the Plant-Soil System.' *Annual Review of Environment and Resources*, 30(1) pp. 75–115.

Eigen, M. (1971) 'Selforganization of matter and the evolution of biological macromolecules.' *Naturwissenschaften*, 58(10) pp. 465–523.

Eigen, M. and Schuster, P. (1979) 'Emergence of the Hypercycle.' *In* Eigen, M. and Schuster, P. (eds) *The Hypercycle: A Principle of Natural Self-Organization*. Berlin, Heidelberg: Springer, pp. 1–24.

Elagib, N. A. (2010) 'Trends in Intra- and Inter-Annual Temperature Variabilities Across Sudan.' *Ambio*, 39(5–6) pp. 413–429.

Eldridge, D. J., Ding, J., Dorrough, J., Delgado-Baquerizo, M., Sala, O., Gross, N., Le Bagousse-Pinguet, Y., Mallen-Cooper, M., Saiz, H., Asensio, S., Ochoa, V., Gozalo, B., Guirado, E., García-Gómez, M., Valencia, E., Martínez-Valderrama, J., Plaza, C., Abedi, M., Ahmadian, N., Ahumada, R. J., Alcántara, J. M., Amghar, F., Azevedo, L., Ben Salem, F., Berdugo, M., Blaum, N., Boldgiv, B., Bowker, M., Bran, D., Bu, C., Canessa, R., Castillo-Monroy, A. P., Castro, I., Castro-Quezada, P., Cesarz, S., Chibani, R., Conceição, A. A., Darrouzet-Nardi, A., Davila, Y. C., Deák, B., Díaz-Martínez, P., Donoso, D. A., Dougill, A. D., Durán, J., Eisenhauer, N., Ejtehadi, H., Espinosa, C. I., Fajardo, A., Farzam, M., Foronda, A., Franzese, J., Fraser, L. H., Gaitán, J., Geissler, K., Gonzalez, S. L., Gusman-Montalvan, E., Hernández, R. M., Hölzel, N., Hughes, F. M., Jadan, O., Jentsch, A., Ju, M., Kaseke, K. F., Köbel, M., Lehmann, A., Liancourt, P., Linstädter, A., Louw, M. A., Ma, Q., Mabaso, M., Maggs-Kölling, G., Makhalanyane, T. P., Issa, O. M., Marais, E., McClaran, M., Mendoza, B., Mokoka, V., Mora, J. P., Moreno, G., Munson, S., Nunes, A., Oliva, G., Oñatibia, G. R., Osborne, B., Peter, G., Pierre, M., Pueyo, Y., Emiliano Quiroga, R., Reed, S., Rey, A., Rey, P., Gómez, V. M. R., Rolo, V., Rillig, M. C., le Roux, P. C., Ruppert, J. C., Salah, A., Sebei, P. J., Sharkhuu, A., Stavi, I., Stephens, C., Teixido, A. L., Thomas, A. D., Tielbörger, K., Robles, S. T., Travers, S., Valkó, O., van den Brink, L., Velbert, F., von Heßberg, A., Wamiti, W., Wang, D., Wang, L., Wardle, G. M., Yahdjian, L., Zaady, E., Zhang, Y., Zhou, X. and Maestre, F. T. (2024) 'Hotspots of biogeochemical activity

linked to aridity and plant traits across global drylands.' *Nature Plants*. Nature Publishing Group, 10(5) pp. 760–770.

Elferink, M. and Schierhorn, F. (2016) 'Global demand for food is rising. Can we meet it.' *Harvard Business Review*. Harvard Business Publishing, 7(04) p. 2016.

Ellison, D., Pokorný, J. and Wild, M. (2024) 'Even cooler insights: On the power of forests to (water the Earth and) cool the planet.' *Global change biology*, 30, February, p. e17195.

Elmqvist, T., Folke, C., Nyström, M., Peterson, G., Bengtsson, J., Walker, B. and Norberg, J. (2003) 'Response Diversity, Ecosystem Change, and Resilience.' *Frontiers in Ecology and the Environment*, 1, November, pp. 488–494.

Elsasser, M. W. (1981) 'A form of logic suited for biology.' *In Progress in Theoretical Biology, 6*. Academic Press, pp. 23–62.

Elsasser, W. M. (1969) 'Acausal phenomena in physics and biology: A case for reconstruction.' *American Scientist*. Sigma Xi, The Scientific Research Society, 57(4) pp. 502–516.

Elsasser, W. M. (1982) 'The other side of molecular biology.' *Journal of Theoretical Biology*, 96(1) pp. 67–76.

Elser, J. J., Sterner, R. W., Gorokhova, E., Fagan, W. F., Markow, T. A., Cotner, J. B., Harrison, J. F., Hobbie, S. E., Odell, G. M. and Weider, L. W. (2000) 'Biological stoichiometry from genes to ecosystems.' *Ecology Letters*, 3(6) pp. 540–550.

Engel, T. and Reid, P. (2006) *Physical Chemistry, pages 117; 195*. New York: Pearson Benjamin Cummings.

Eppinga, M. B., Rietkerk, M., Borren, W., Lapshina, E. D., Bleuten, W. and Wassen, M. J. (2008) 'Regular Surface Patterning of Peatlands: Confronting Theory with Field Data.' *Ecosystems*, 11(4) pp. 520–536.

Eppinga, M. B., de Ruiter, P. C., Wassen, M. J. and Rietkerk, M. (2009) 'Nutrients and Hydrology Indicate the Driving Mechanisms of Peatland Surface Patterning.' *The American Naturalist*. The University of Chicago Press, 173(6) pp. 803–818.

Epstein, I. R., Pojman, J. A. and Steinbock, O. (2006) 'Introduction: Self-organization in nonequilibrium chemical systems.' *Chaos (Woodbury, N.Y.)*, 16(3) p. 037101.

Faber, J. H., Creamer, R. E., Mulder, C., Römbke, J., Rutgers, M., Sousa, J. P., Stone, D. and Griffiths, B. S. (2013) 'The practicalities and pitfalls of establishing a policy-relevant and cost-effective soil biological monitoring scheme.' *Integrated environmental assessment and management*. Wiley Online Library, 9(2) pp. 276–284.

Fallou, F. A. (1857) 'First Principles of Soil Science; G.' *Schönfield Buchandlung: Dresden, Germany*.

FAO, F. (2018) 'The future of food and agriculture: alternative pathways to 2050.' *Food and Agriculture Organization of the United Nations Rome*.

FAO, IFAD and WFP (2014) *The State of Food Insecurity in the World 2014. Strengthening the enabling environment for food security and nutrition.* Rome, Italy: FAO.

Farouki, O. (1981) *Thermal properties of soils*.

Fath, B. D., Jørgensen, S. E., Patten, B. C. and Straškraba, M. (2004) 'Ecosystem growth and development.' *Biosystems*, 77(1) pp. 213–228.

Fenchel, T., Blackburn, H., King, G. M. and Blackburn, T. H. (2012) *Bacterial biogeochemistry: the ecophysiology of mineral cycling*. Academic press.

Ferri, M. and Arnés García, M. (2023) *From nature-negative to nature-positive production: A conceptual and practical framework for agriculture based on thermodynamics*. Rome, Italy: FAO.

Ferroukhi, R., Nagpal, D., Lopez-Pena, A., Hodges, T., Mohtar, R. H., Daher, B., Mohtar, S. and Keulertz, M. (2015) 'Renewable energy in the water, energy & food nexus.' *IRENA, Abu Dhabi* pp. 1–125.

Fiedler, S., Vepraskas, M. J. and Richardson, J. L. (2007) 'Soil Redox Potential: Importance, Field Measurements, and Observations.' *In* Sparks, D. L. (ed.) *Advances in Agronomy*. Academic Press, pp. 1–54.

Field, D. J., Morgan, C. L. and McBratney, A. B. (2016) *Global soil security*. Springer.

Field, R. J. and Foersterling, H. D. (1986) 'On the oxybromine chemistry rate constants with cerium ions in the Field-Koeroes-Noyes mechanism of the Belousov-Zhabotinskii reaction: the equilibrium HBrO2 + BrO3- + H+ .dblharw. 2BrO.ovrhdot.2 + H2O.' *The Journal of Physical Chemistry*. American Chemical Society, 90(21) pp. 5400–5407.

Fierer, N. and Jackson, R. (2006) 'Fierer N, Jackson RB.. The diversity and biogeography of soil bacterial communities. P Natl Acad Sci USA 103: 626-631.' *Proceedings of the National Academy of Sciences of the United States of America*, 103, February, pp. 626–31.

Finke, D. L. and Snyder, W. E. (2008) 'Niche Partitioning Increases Resource Exploitation by Diverse Communities.' *Science*. American Association for the Advancement of Science, 321(5895). Report pp. 1488–1490.

Fiscus, D. A. and Fath, B. D. (2018) *Foundations for Sustainability: A Coherent Framework of Life–Environment Relations*. Academic Press.

Fisher, J. B., Melton, F., Middleton, E., Hain, C., Anderson, M., Allen, R., McCabe, M. F., Hook, S., Baldocchi, D., Townsend, P. A., Kilic, A., Tu, K., Miralles, D. D., Perret, J., Lagouarde, J.-P., Waliser, D., Purdy, A. J., French, A., Schimel, D., Famiglietti, J. S., Stephens, G. and Wood, E. F. (2017) 'The future of evapotranspiration: Global requirements for ecosystem functioning, carbon and

climate feedbacks, agricultural management, and water resources.' *Water Resources Research*, 53(4) pp. 2618–2626.

Flessa, H. and Fischer, W. R. (1992) 'Plant-induced changes in the redox potentials of rice rhizospheres.' *Plant and Soil*, 143(1) pp. 55–60.

Foley, J. A., DeFries, R., Asner, G. P., Barford, C., Bonan, G., Carpenter, S. R., Chapin, F. S., Coe, M. T., Daily, G. C., Gibbs, H. K., Helkowski, J. H., Holloway, T., Howard, E. A., Kucharik, C. J., Monfreda, C., Patz, J. A., Prentice, I. C., Ramankutty, N. and Snyder, P. K. (2005) 'Global Consequences of Land Use.' *Science*. American Association for the Advancement of Science, 309(5734) pp. 570–574.

Fraassen, B. C. V., Van, F. and Fraassen, M. P. of P. B. C. V. (1989) *Laws and Symmetry*. Clarendon Press.

Gabora, L. (2006) 'Self-other organization:: Why early life did not evolve through natural selection.' *Journal of Theoretical Biology*, 241(3) pp. 443–450.

Gaertner, M., Wilson, J. R. U., Cadotte, M. W., MacIvor, J. S., Zenni, R. D. and Richardson, D. M. (2017) 'Non-native species in urban environments: patterns, processes, impacts and challenges.' *Biological Invasions*, 19(12) pp. 3461–3469.

Gambrell, R. and Patrick Jr, W. (1978) 'Chemical and microbiological properties of anaerobic soils and sediments.' *Plant Life in Anaerobic Environments. Ann Arbor, MI: Ann Arbor Science Publishers* pp. 375–423.

Ganlin, Z. and Huayong, W. U. (2018) 'From "Problems" to "Solutions": Soil Functions for Realization of Sustainable Development Goals.' *Bulletin of Chinese Academy of Sciences (Chinese Version)*, 33(2) pp. 124–134.

Gao, Y., Chen, Y. and Lü, S. (2004) 'Numerical simulation of the critical scale of oasis maintenance and development in the arid regions of northwest China.' *Advances in Atmospheric Sciences*. Springer, 21 pp. 113–124.

García, F. C., Bestion, E., Warfield, R. and Yvon-Durocher, G. (2018) 'Changes in temperature alter the relationship between biodiversity and ecosystem functioning.' *Proceedings of the National Academy of Sciences*, 115(43) pp. 10989–10994.

Garrett, S. D. (1963) 'Soil Fungi and Soil Fertility.' *Soil Fungi and Soil Fertility.*

Gatti, R. C., Fath, B., Hordijk, W., Kauffman, S. and Ulanowicz, R. (2018) 'Niche emergence as an autocatalytic process in the evolution of ecosystems.' *Journal of Theoretical Biology*, 454 pp. 110–117.

Gatti, R. C., Hordijk, W. and Kauffman, S. (2017) 'Biodiversity is autocatalytic.' *Ecological Modelling*, 346 pp. 70–76.

Georgiadis, N. J., Ruess, R. W., McNaughton, S. J. and Western, D. (1989) 'Ecological conditions that determine when grazing stimulates grass production.' *Oecologia*, 81(3) pp. 316–322.

Getzin, S., Erickson, T. E., Yizhaq, H., Muñoz-Rojas, M., Huth, A. and Wiegand, K. (2020) 'Bridging ecology and physics: Australian fairy circles regenerate following model assumptions on ecohydrological feedbacks.' *Journal of Ecology*, 00(n/a) pp. 1–18.

Getzin, S., Wiegand, K., Wiegand, T., Yizhaq, H., Hardenberg, J. von and Meron, E. (2015) 'Adopting a spatially explicit perspective to study the mysterious fairy circles of Namibia.' *Ecography*, 38(1) pp. 1–11.

Getzin, S., Yizhaq, H., Bell, B., Erickson, T. E., Postle, A. C., Katra, I., Tzuk, O., Zelnik, Y. R., Wiegand, K., Wiegand, T. and Meron, E. (2016) 'Discovery of fairy circles in Australia supports self-organization theory.' *Proceedings of the National Academy of Sciences*. National Academy of Sciences, 113(13) pp. 3551–3556.

Getzin, S., Yizhaq, H., Cramer, M. D. and Tschinkel, W. R. (2019) 'Contrasting Global Patterns of Spatially Periodic Fairy Circles and Regular Insect Nests in Drylands.' *Journal of Geophysical Research: Biogeosciences*, 124(11) pp. 3327–3342.

Gibbs, J. W. (1948) *The collected works of J. Willard Gibbs.* New Haven: Yale Univ. Press.

Giovannucci, D., Scherr, S., Nierenberg, D., Hebebrand, C., Shapiro, J., Milder, J. and Wheeler, K. (2012) *Food and Agriculture: The Future of Sustainability*. *SSRN Electronic Journal*.

Giri, V. and Jain, S. (2012) 'The Origin of Large Molecules in Primordial Autocatalytic Reaction Networks.' *PLOS ONE*. Public Library of Science, 7(1) p. e29546.

Glinski, J. (1985) *St~ pniewski, W., 1985. Soil aeration and its role for plants*. Boca Raton, Florida, CRC Press.

Goldford, J. E. and Segrè, D. (2018) 'Modern views of ancient metabolic networks.' *Current Opinion in Systems Biology*. (• Regulatory and metabolic networks • Special Section: Single cell and noise), 8, April, pp. 117–124.

Gómez-Guerrero, A. and Doane, T. (2018) 'Chapter Seven - The Response of Forest Ecosystems to Climate Change.' *In* Horwath, W. R. and Kuzyakov, Y. (eds) *Developments in Soil Science*. Elsevier (Climate Change Impacts on Soil Processes and Ecosystem Properties), pp. 185–206.

González, Y., Peña Moreno, R., Serkin, V. N. and Lara, L. (2023) 'Ecoexergy in the context of environmental sciences.' *AIMS Environmental Science*, 10, January, pp. 516–528.

González-Moreno, P., Pino, J., Carreras, D., Basnou, C., Fernández-Rebollar, I. and Vilà, M. (2013) 'Quantifying the landscape influence on plant invasions in Mediterranean coastal habitats.' *Landscape Ecology*, 28(5) pp. 891–903.

GOV.UK (2013) 'Government forestry policy statement.' *https://www.gov.uk/government/publications/government-forestry-policy-statement*.

GOV.UK (2017) 'Agricultural facts: England regional profiles.' *https://www.gov.uk/government/statistics/agricultural-facts-england-regional-profiles*.

Graaff, M.-A. de, Hornslein, N., Throop, H. L., Kardol, P. and Diepen, L. T. A. van (2019) 'Chapter One - Effects of agricultural intensification on soil biodiversity and implications for ecosystem functioning: A meta-analysis.' *In* Sparks, D. L. (ed.). Academic Press (Advances in Agronomy), pp. 1–44.

Grad, H. (1965) 'On Boltzmann's H-Theorem.' *Journal of the Society for Industrial and Applied Mathematics*. Society for Industrial and Applied Mathematics, 13(1) pp. 259–277.

Grande, U., Piernik, A., Nienartowicz, A. and Buonocore, E. (2023) 'Measuring natural capital value and ecological complexity of lake ecosystems.' *Ecological Modelling*, 482, August, p. 110401.

Green, J. K., Seneviratne, S. I., Berg, A. M., Findell, K. L., Hagemann, S., Lawrence, D. M. and Gentine, P. (2019) 'Large influence of soil moisture on long-term terrestrial carbon uptake.' *Nature*. Nature Publishing Group UK London, 565(7740) pp. 476–479.

Greiser, C., Meineri, E., Luoto, M., Ehrlén, J. and Hylander, K. (2018) 'Monthly microclimate models in a managed boreal forest landscape.' *Agricultural and Forest Meteorology*, 250–251, March, pp. 147–158.

Griffiths, B. S. and Philippot, L. (2013) 'Insights into the resistance and resilience of the soil microbial community.' *FEMS Microbiology Reviews*, 37(2) pp. 112–129.

Griffiths, B. S., Römbke, J., Schmelz, R. M., Scheffczyk, A., Faber, J. H., Bloem, J., Pérès, G., Cluzeau, D., Chabbi, A., Suhadolc, M., Sousa, J. P., Silva, P. M. da, Carvalho, F., Mendes, S., Morais, P., Francisco, R., Pereira, C., Bonkowski, M., Geisen, S., Bardgett, R. D., Vries, F. T. de, Bolger, T., Dirilgen, T., Schmidt, O., Winding, A., Hendriksen, N. B., Johansen, A., Philippot, L., Plassart, P., Bru, D., Thomson, B., Griffiths, R. I., Bailey, M. J., Keith, A., Rutgers, M., Mulder, C., Hannula, S. E., Creamer, R. and Stone, D. (2016) 'Selecting cost effective and policy-relevant biological indicators for European monitoring of soil biodiversity and ecosystem function.' *Ecological Indicators*, 69 pp. 213–223.

Grime, J. and Pierce, S. (2012) *The Evolutionary Strategies That Shape Ecosystems*. *The Evolutionary Strategies that Shape Ecosystems*.

Groot, S. R. D. and Mazur, P. (2013) *Non-Equilibrium Thermodynamics*. Courier Corporation.

Guddemi, P. (2020) *Gregory Bateson on Relational Communication: From Octopuses to Nations*. Springer International Publishing (Biosemiotics).

Gunderson, L. H. (2000) 'Ecological resilience - in theory and application.' *Annual Review of Ecology and Systematics*, 31 pp. 425–439.

Gunderson, L. H. and Holling, C. S. (eds) (2001) *Panarchy: Understanding Transformations in Human and Natural Systems*. 1st Ed. edition, Washington, DC: Island Press.

Gunderson, L. H. and Pritchard, L. (2012) *Resilience and the Behavior of Large-Scale Systems*. Island Press.

Gunderson, L. and Holling, C. (2003) 'Panarchy: Understanding Transformations In Human And Natural Systems.' *Bibliovault OAI Repository, the University of Chicago Press*, 114, December.

Hagen, J. B. (1992) *An Entangled Bank: The Origins of Ecosystem Ecology*. Rutgers University Press.

Haken, H. (1988) 'Pattern Formation: Thermodynamics or Kinetics?' *In* Markus, M., Müller, S. C., and Nicolis, G. (eds) *From Chemical to Biological Organization*. Berlin, Heidelberg: Springer (Springer Series in Synergetics), pp. 6–13.

Haken, H. and Portugali, J. (2016) 'Information and Self-Organization.' *Entropy*, 19, December, p. 18.

Han, J. and Zhou, Z. (2013) 'Dynamics of Soil Water Evaporation during Soil Drying: Laboratory Experiment and Numerical Analysis.' *The Scientific World Journal*. Hindawi, 2013, December, p. e240280.

Hanke, G. T., Holtgrefe, S., Koenig, N., Strodtkoetter, I., Voss, I. and Scheibe, R. (2009) 'Use of transgenic plants to uncover strategies for maintenance of redox homeostasis during photosynthesis.' *Advances in botanical research*. Elsevier, 52 pp. 207–251.

Hansen, J. M., Go, Y.-M. and Jones, D. P. (2006) 'Nuclear and mitochondrial compartmentation of oxidative stress and redox signaling.' *Annu. Rev. Pharmacol. Toxicol.* Annual Reviews, 46 pp. 215–234.

von Hardenberg, J., Meron, E., Shachak, M. and Zarmi, Y. (2001) 'Diversity of Vegetation Patterns and Desertification.' *Physical Review Letters*. American Physical Society, 87(19) p. 198101.

Harmel, R. D., Kenimer, A. L., Searcy, S. W. and Torbert, H. A. (2004) 'Runoff water quality impact of variable rate sidedress nitrogen application.' *Precision Agriculture*. Springer, 5 pp. 247–261.

Harwell, G. R. (2012) 'Estimation of evaporation from open water-a review of selected studies, summary of US Army Corps of Engineers data collection and methods, and evaluation of two methods for estimation of evaporation from five reservoirs in Texas.' *Scientific Investigations Report*. US Geological Survey, (2012–5202).

Hassan, W., Li, Y., Saba, T., Jabbi, F., Wang, B., Cai, A. and Wu, J. (2022) 'Improved and sustainable agroecosystem, food security and environmental resilience through zero tillage with emphasis on soils of temperate and subtropical climate regions: A review.' *International Soil and Water Conservation Research*, 10(3) pp. 530–545.

Hatfield, J. L., Sauer, T. J. and Cruse, R. M. (2017) 'Chapter One - Soil: The Forgotten Piece of the Water, Food, Energy Nexus.' *In* Sparks, D. L. (ed.) *Advances in Agronomy*. Academic Press, pp. 1–46.

Hatten, J. and Liles, G. (2019) 'Chapter 15 - A "healthy" balance – The role of physical and chemical properties in maintaining forest soil function in a changing world.' *In* Busse, M., Giardina, C. P., Morris, D. M., and Page-Dumroese, D. S. (eds) *Developments in Soil Science*. Elsevier (Global Change and Forest Soils), pp. 373–396.

Havlicek, E. (2012) 'Soil biodiversity and bioindication: from complex thinking to simple acting.' *European Journal of Soil Biology*. Elsevier, 49 pp. 80–84.

He, S., Zhang, C., Meng, F.-R., Bourque, C. P.-A., Huang, Z. and Li, X. (2024) 'Impacts of re-vegetation on soil water dynamics in a semiarid region of Northwest China.' *Science of The Total Environment*, 911, February, p. 168496.

Hector, A. and Hooper, R. (2002) 'ECOLOGY: Darwin and the First Ecological Experiment.' *Science (New York, N.Y.)*, 295, February, pp. 639–40.

Hedges, J. I., Eglinton, G., Hatcher, P. G., Kirchman, D. L., Arnosti, C., Derenne, S., Evershed, R. P., Kögel-Knabner, I., de Leeuw, J. W. and Littke, R. (2000) 'The molecularly-uncharacterized component of nonliving organic matter in natural environments.' *Organic geochemistry*. Elsevier, 31(10) pp. 945–958.

Henning, B. G. and Scarfe, A. C. (2013) *Beyond Mechanism: Putting Life Back Into Biology*. Rowman & Littlefield.

Henry, M. and Schwartz, L. (2019) 'Entropy export as the driving force of evolution.' *Substantia* pp. 29–56.

Hesslerová, P., Pokorný, J., Huryna, H. and Harper, D. (2019) 'Wetlands and Forests Regulate Climate via Evapotranspiration.' *In* An, S. and Verhoeven, J. T. A. (eds) *Wetlands: Ecosystem Services, Restoration and Wise Use*. Cham: Springer International Publishing (Ecological Studies), pp. 63–93.

Hildebrandt, A., Kleidon, A. and Bechmann, M. (2016) 'A thermodynamic formulation of root water uptake.' *Hydrology and Earth System Sciences*. Copernicus GmbH, 20(8) pp. 3441–3454.

Hillel, D. (2003) 'Soil Physics.' *In* Meyers, R. A. (ed.) *Encyclopedia of Physical Science and Technology (Third Edition)*. New York: Academic Press, pp. 77–97.

Hinsinger, P., Bengough, A. G., Vetterlein, D. and Young, I. M. (2009) 'Rhizosphere: biophysics, biogeochemistry and ecological relevance.' *Plant and Soil*, 321(1) pp. 117–152.

Ho, M.-W. (2003) *FROM 'MOLECULAR MACHINES' TO COHERENT ORGANISMS*, p. 81.

Hobson, P. and Ibisch, P. (2010) 'AN ALTERNATIVE CONCEPTUAL FRAMEWORK FOR SUSTAINABILITY: SYSTEMICS AND THERMODYNAMICS.' *In*.

Hoffmann, K. (2008) 'An introduction to endoreversible thermodynamics.' *Atti dell'Accademia Peloritana dei Pericolanti - Classe di Scienze Fisiche, Matematiche e Naturali*, 86, February.

Hoffmeyer, J. (1998) 'Surfaces inside surfaces. On the origin of agency and life.' *Cybernetics & Human Knowing*, 5(1) pp. 33–42.

Hoffmeyer, J. (2001) 'Life and reference.' *Biosystems*, 60(1) pp. 123–130.

Holling, C. S. (1973) 'Resilience and Stability of Ecological Systems.' *Annual Review of Ecology and Systematics*. Annual Reviews, 4 pp. 1–23.

Homulle, Z., George, T. S. and Karley, A. J. (2022) 'Root traits with team benefits: understanding belowground interactions in intercropping systems.' *Plant and Soil*, 471(1) pp. 1–26.

Hooper, D. U., Bignell, D. E., Brown, V. K., Brussard, L., Dangerfield, J. M., Wall, D. H., Wardle, D. A., Coleman, D. C., Giller, K. E., Lavelle, P., Van Der Putten, W. H., De Ruiter, P. C., Rusek, J., Silver, W. L., Tiedje, J. M. and Wolters, V. (2000) 'Interactions between Aboveground and Belowground Biodiversity in Terrestrial Ecosystems: Patterns, Mechanisms, and FeedbacksWe assess the evidence for correlation between aboveground and belowground diversity and conclude that a variety of mechanisms could lead to positive, negative, or no relationship—depending on the strength and type of interactions among species.' *BioScience*. Oxford Academic, 50(12) pp. 1049–1061.

Hoover, D. L., Pfennigwerth, A. A. and Duniway, M. C. (2021) 'Drought resistance and resilience: The role of soil moisture–plant interactions and legacies in a dryland ecosystem.' *Journal of Ecology*, 109(9) pp. 3280–3294.

Hordijk, W. (2016) 'Evolution of Autocatalytic Sets in Computational Models of Chemical Reaction Networks.' *Origins of Life and Evolution of Biospheres*, 46(2) pp. 233–245.

Hordijk, W. and Steel, M. (2004) 'Detecting autocatalytic, self-sustaining sets in chemical reaction systems.' *Journal of Theoretical Biology*, 227(4) pp. 451–461.

Hordijk, W. and Steel, M. (2014) 'Conditions for Evolvability of Autocatalytic Sets: A Formal Example and Analysis.' *Origins of Life and Evolution of Biospheres*, 44(2) pp. 111–124.

Hordijk, W. and Steel, M. (2017) 'Chasing the tail: The emergence of autocatalytic networks.' *Biosystems*, 152, February, pp. 1–10.

Hordijk, W., Steel, M. and Kauffman, S. (2012) 'The Structure of Autocatalytic Sets: Evolvability, Enablement, and Emergence.' *Acta Biotheoretica*, 60(4) pp. 379–392.

Hordijk, W., Steel, M. and Kauffman, S. (2013) 'The Origin of Life, Evolution, and Functional Organization.' *In* Pontarotti, P. (ed.) *Evolutionary Biology: Exobiology and Evolutionary Mechanisms*. Berlin, Heidelberg: Springer, pp. 49–60.

Howe, J. A. and Smith, A. P. (2021) '2 - The soil habitat.' *In* Gentry, T. J., Fuhrmann, J. J., and Zuberer, D. A. (eds) *Principles and Applications of Soil Microbiology (Third Edition)*. Elsevier, pp. 23–55.

Howison, R. A., Olff, H., Koppel, J. van de and Smit, C. (2017) 'Biotically driven vegetation mosaics in grazing ecosystems: the battle between bioturbation and biocompaction.' *Ecological Monographs*, 87(3) pp. 363–378.

Hsia, J., Holtz, W. J., Huang, D. C., Arcak, M. and Maharbiz, M. M. (2012) 'A Feedback Quenched Oscillator Produces Turing Patterning with One Diffuser.' *PLOS Computational Biology*. Public Library of Science, 8(1) p. e1002331.

Hu, C., Elias, E., Nawrocki, W. J. and Croce, R. (2023) 'Drought affects both photosystems in Arabidopsis thaliana.' *New Phytologist*. Wiley Online Library, 240(2) pp. 663–675.

Huang, J. and van den Dool, H. M. (1993) 'Monthly precipitation-temperature relations and temperature prediction over the United States.' *Journal of Climate*. American Meteorological Society, 6(6) pp. 1111–1132.

Huera-Lucero, T., Labrador-Moreno, J., Blanco-Salas, J. and Ruiz-Téllez, T. (2020) 'A Framework to Incorporate Biological Soil Quality Indicators into Assessing the Sustainability of Territories in the Ecuadorian Amazon.' *Sustainability*. Multidisciplinary Digital Publishing Institute, 12(7) p. 3007.

Hunt, R., Hodgson, J., Thompson, K., Bungener, P., Dunnett, N. and Askew, A. (2004) 'A new practical tool for deriving a functional signature for herbaceous vegetation.' *Applied Vegetation Science*, 7, November, pp. 163–170.

Husson, O. (2013) 'Redox potential (Eh) and pH as drivers of soil/plant/microorganism systems: a transdisciplinary overview pointing to integrative opportunities for agronomy.' *Plant and Soil*, 362(1) pp. 389–417.

Husson, O., Brunet, A., Babre, D., Charpentier, H., Durand, M. and Sarthou, J.-P. (2018) 'Conservation Agriculture systems alter the electrical characteristics (Eh, pH and EC) of four soil types in France.' *Soil and Tillage Research*, 176, March, pp. 57–68.

Husson, O., Husson, B., Brunet, A., Babre, D., Alary, K., Sarthou, J.-P., Charpentier, H., Durand, M., Benada, J. and Henry, M. (2015) 'Practical improvements in soil redox potential (Eh) measurement for characterisation of soil properties. Application for comparison of conventional and conservation agriculture cropping systems.' *Analytica Chimica Acta*, 906, December, pp. 98–109.

Husson, O., Sarthou, J.-P., Bousset, L., Ratnadass, A., Schmidt, H.-P., Kempf, J., Husson, B., Tingry, S., Aubertot, J.-N., Deguine, J.-P., Goebel, F.-R. and Lamichhane, J. R. (2021) 'Soil and plant health in relation to dynamic sustainment of Eh and pH homeostasis: A review.' *Plant and Soil*, 466(1) pp. 391–447.

Hutchinson, G. E. (1948) 'Circular Causal Systems in Ecology.' *Annals of the New York Academy of Sciences*, 50(4) pp. 221–246.

Hutchinson, G. E. (1957) 'Concluding Remarks.' *Cold Spring Harbor Symposia on Quantitative Biology*. Cold Spring Harbor Laboratory Press, 22, January, pp. 415–427.

Ibisch, P. L., Vega, E. and Herrmann, T. M. (2010) 'Interdependence of biodiversity and development under global change.' *CBD Technical Series*. Convention on Biological Diversity, (54).

Illston, B. G., Basara, J. B. and Crawford, K. C. (2004) 'Seasonal to interannual variations of soil moisture measured in Oklahoma.' *International Journal of Climatology: A Journal of the Royal Meteorological Society*. Wiley Online Library, 24(15) pp. 1883–1896.

IPBES (2019) *Summary for policymakers of the global assessment report on biodiversity and ecosystem services*. Zenodo.

IPCC (2022) *Climate Change 2022: Impacts, Adaptation and Vulnerability*. [Online] [Accessed on 12th January 2025] https://www.ipcc.ch/report/ar6/wg2/chapter/summary-for-policymakers/.

ITPS, F. and (2015) 'Status of the world's soil resources (SWSR)—Main report.' *Food and Agriculture Organization of the United Nations and intergovernmental technical panel on soils*. FAO Rome, Italy, 650.

J, T., Wk, C., H, G., M, H., C, Y., U, M., L, A., C, Frege, F, B., R, W., M, Simon, K, L., C, W., Js, C., J, Duplissy, A, A., J, A., Ak, B., M, B., S, B., A, D., S, E., Rc, F., A, F., C, Fuchs, R, G., M, G., A, H., Cr, H., T, J., H, J., J, Kangasluoma, H, K., J, Kim, M, Krapf, A, K., A, L., M, Lawler, M, Leiminger, S, M., O, M., T, N., A, O., T, P., Fm, P., P, M., Mp, R., L, R., N, S., S, S., K, S., M, Sipilä, Jn, S., G, S., A, T., A, V., Ac, W., E, W., D, W., Pm, W., P, Y., Ks, C., J, C., J, Dommen, J, Kirkby, M, Kulmala, I, R., Dr, W., Nm, D. and U, B. (2016) 'The role of low-volatility organic compounds in initial particle growth in the atmosphere.' *Nature*.

Jänes, H., Kotta, J., Pärnoja, M., Crowe, T. P., Rindi, F. and Orav-Kotta, H. (2017) 'Functional traits of marine macrophytes predict primary production.' *Functional Ecology*, 31(4) pp. 975–986.

Jensen, M. E. and Allen, R. G. (2016) *Evaporation, evapotranspiration, and irrigation water requirements: Task Committee on Revision of Manual 70.* American Society of Civil Engineers (ASCE).

Jiménez, C., Tejedor, M. and Rodríguez, M. (2007) 'Influence of land use changes on the soil temperature regime of Andosols on Tenerife, Canary Islands, Spain.' *European Journal of Soil Science*. Wiley Online Library, 58(2) pp. 445–449.

Jiménez-Gutiérrez, J. M., Valero, F., Ruiz-Martínez, J. and Montávez, J. P. (2021) 'Temperature Response to Changes in Vegetation Fraction Cover in a Regional Climate Model.' *Atmosphere*. Multidisciplinary Digital Publishing Institute, 12(5) p. 599.

John, D. A. and Babu, G. R. (2021) 'Lessons From the Aftermaths of Green Revolution on Food System and Health.' *Frontiers in Sustainable Food Systems*, 5, February, p. 644559.

Johnson, C. N., Balmford, A., Brook, B. W., Buettel, J. C., Galetti, M., Guangchun, L. and Wilmshurst, J. M. (2017) 'Biodiversity losses and conservation responses in the Anthropocene | Science,' 356(6335) pp. 270–275.

Jones, C. G., Lawton, J. H. and Shachak, M. (1994) 'Organisms as Ecosystem Engineers.' *Oikos*. [Nordic Society Oikos, Wiley], 69(3) pp. 373–386.

Jónsson, J. Ö. G., Davíðsdóttir, B., Jónsdóttir, E. M., Kristinsdóttir, S. M. and Ragnarsdóttir, K. V. (2016) 'Soil indicators for sustainable development: A transdisciplinary approach for indicator development using expert stakeholders.' *Agriculture, Ecosystems & Environment*, 232, September, pp. 179–189.

Joo, J., Jeong, S., Zheng, C., Park, C.-E., Park, H. and Kim, H. (2020) 'Emergence of significant soil moisture depletion in the near future.' *Environmental Research Letters*, 15, December.

Jordan, C. F. (2016) 'The Farm as a Thermodynamic System: Implications of the Maximum Power Principle.' *BioPhysical Economics and Resource Quality*, 1(2) p. 9.

Jørgensen, S. E. (1990) 'Ecosystem theory, ecological buffer capacity, uncertainty and complexity.' *Ecological Modelling*. (ISEM's 7th International Conference on the State of the Art in Ecological Modelling), 52, January, pp. 125–133.

Jørgensen, S. E. (1992) 'Parameters, ecological constraints and exergy.' *Ecological Modelling*. Elsevier, 62(1–3) pp. 163–170.

Jørgensen, S. E. (1995) 'Exergy and ecological buffer capacities as measures of ecosystem health.' *Ecosystem health*, 1(3) pp. 150–160.

Jørgensen, S. E. (2002) *Integration of Ecosystem Theories: A Pattern: A Pattern*. Springer Science & Business Media.

Jørgensen, S. E. (2006a) 'An integrated ecosystem theory.' *Annals of the European Academy of Science*. Citeseer, 2007 pp. 19–33.

Jørgensen, S. E. (2006b) 'Application of holistic thermodynamic indicators.' *Ecological Indicators*. (Theoretical fundamentals of consistent applications in environmental management), 6(1) pp. 24–29.

Jørgensen, S. E. (2006c) 'Application of holistic thermodynamic indicators.' *Ecological Indicators*, 6(1) pp. 24–29.

Jørgensen, S. E. (2007) 'Description of aquatic ecosystem's development by eco-exergy and exergy destruction.' *Ecological Modelling*. Elsevier, 204(1–2) pp. 22–28.

Jørgensen, S. E. (2008a) 'Exergy.' *In* Jørgensen, Sven Erik and Fath, B. D. (eds) *Encyclopedia of Ecology*. Oxford: Academic Press, pp. 1498–1509.

Jørgensen, S. E. (2008b) 'Exergy.' *In* Jørgensen, Sven Erik and Fath, B. D. (eds) *Encyclopedia of Ecology*. Oxford: Academic Press, pp. 1498–1509.

Jørgensen, S. E. (2010) 'Ecosystem services, sustainability and thermodynamic indicators.' *Ecological Complexity*. (Ecosystem Services – Bridging Ecology, Economy and Social Sciences), 7(3) pp. 311–313.

Jørgensen, S. E., Bastianoni, S., Müller, F., Patten, B. C., Fath, B. D., Marques, J. C., Nielsen, S. N., Tiezzi, E. and Ulanowicz, R. E. (2007) '4 - Ecosystems have directionality.' *In* Jørgensen, S. E., Bastianoni, S., Müller, F., Patten, B. C., Fath, B. D., Marques, J. C., Nielsen, S. N., Tiezzi, E., and Ulanowicz, R. E. (eds) *A New Ecology*. Amsterdam: Elsevier Science B.V., pp. 59–78.

Jørgensen, S. E. and Fath, B. D. (2004) 'Application of thermodynamic principles in ecology.' *Ecological complexity*. Elsevier, 1(4) pp. 267–280.

Jørgensen, S. E., Ladegaard, N., Debeljak, M. and Marques, J. C. (2005) 'Calculations of exergy for organisms.' *Ecological Modelling*, 185(2–4) pp. 165–175.

Jørgensen, S. E. and Mejer, H. (1977) 'Ecological buffer capacity.' *Ecological Modelling*, 3(1) pp. 39–61.

Jørgensen, S. E. and Nielsen, S. N. (2007) 'Application of exergy as thermodynamic indicator in ecology.' *Energy*, 32(5) pp. 673–685.

Jørgensen, Sven E. and Nielsen, S. N. (2007) *Application of exergy as thermodynamic indicator in ecology | Request PDF*. ResearchGate. [Online] [Accessed on 3rd April 2019] https://www.researchgate.net/publication/239347538_Application_of_exergy_as_thermodynamic_indicator_in_ecology.

Jørgensen, S. E., Nielsen, S. N. and Mejer, H. (1995) 'Emergy, environ, exergy and ecological modelling.' *Ecological modelling*. Elsevier, 77(2–3) pp. 99–109.

Jørgensen, S. E., Patten, B. C. and Straškraba, M. (2000) 'Ecosystems emerging:: 4. growth.' *Ecological Modelling*, 126(2) pp. 249–284.

Jørgensen, S. and Svirezhev, Y. (2004) *Towards a Thermodynamic Theory for Ecological Systems*. Pergamon.

Jouzi, Z., Azadi, H., Taheri, F., Zarafshani, K., Gebrehiwot, K., Van Passel, S. and Lebailly, P. (2017) 'Organic Farming and Small-Scale Farmers: Main Opportunities and Challenges.' *Ecological Economics*, 132, February, pp. 144–154.

Joyce, J. J. (1979) 'Symposium on arthroscopy. Foreword.' *The Orthopedic Clinics of North America*, 10(3) pp. 503–504.

von der Kammer, F., Thöming, J. and Förstner, U. (2000) 'Redox Buffer Capacity Concept as a Tool for the Assessment of Long-Term Effects in Natural Attenuation / Intrinsic Remediation.' *In* Schüring, J., Schulz, H. D., Fischer, W. R., Böttcher, J., and Duijnisveld, W. H. M. (eds) *Redox: Fundamentals, Processes and Applications*. Berlin, Heidelberg: Springer, pp. 189–202.

Kandlbinder, A., Wormuth, D., Baier, M., Scheibe, R. and Dietz, K.-J. (2003) 'Redox control of chloroplast and nuclear gene expression.'

Karakuş, O. (2023) 'On advances, challenges and potentials of remote sensing image analysis in marine debris and suspected plastics monitoring.' *Frontiers in Remote Sensing*. Frontiers, 4, November.

Karlen, D. L., Mausbach, M. J., Doran, J. W., Cline, R. G., Harris, R. F. and Schuman, G. E. (1997) 'Soil quality: a concept, definition, and framework for evaluation (a guest editorial).' *Soil Science Society of America Journal*. Wiley Online Library, 61(1) pp. 4–10.

Kashem, M. and Singh, B. (2001) 'Metal availability in contaminated soils: I. Effects of floodingand organic matter on changes in Eh, pH and solubility of Cd, Ni andZn.' *Nutrient Cycling in Agroecosystems*. Springer, 61 pp. 247–255.

Kassam, A. and Kassam, L. (2021) '10 - Paradigms of agriculture.' *In* Kassam, A. and Kassam, L. (eds) *Rethinking Food and Agriculture*. Woodhead Publishing (Woodhead Publishing Series in Food Science, Technology and Nutrition), pp. 181–218.

Kauffman, S. A. (1986) 'Autocatalytic sets of proteins.' *Journal of Theoretical Biology*, 119(1) pp. 1–24.

Kauffman, S. A. (2019) *A World Beyond Physics: The Emergence and Evolution of Life*. Oxford University Press.

Kauffman, S. and Macready, W. (1995) 'Technological evolution and adaptive organizations: Ideas from biology may find applications in economics.' *Complexity*, 1(2) pp. 26–43.

Kay, J. J. and Schneider, E. D. (1992) 'Thermodynamics and Measures of Ecological Integrity.' *In* McKenzie, D. H., Hyatt, D. E., and McDonald, V. J. (eds) *Ecological Indicators: Volume 1*. Boston, MA: Springer US, pp. 159–182.

Keesstra, S. D., Bouma, J., Wallinga, J., Tittonell, P., Smith, P., Cerdà, A., Montanarella, L., Quinton, J., Pachepsky, Y. and Van Der Putten, W. H. (2016) 'Forum paper: The significance of soils and soil science towards realization of the UN sustainable development goals (SDGS).' *Soil Discussions*. Göttingen, Germany, 2016 pp. 1–28.

Keiluweit, M., Wanzek, T., Kleber, M., Nico, P. and Fendorf, S. (2017) 'Anaerobic microsites have an unaccounted role in soil carbon stabilization.' *Nature communications*. Nature Publishing Group UK London, 8(1) p. 1771.

Khormali, F., Ajami, M., Ayoubi, S., Srinivasarao, C. and Wani, S. P. (2009) 'Role of deforestation and hillslope position on soil quality attributes of loess-derived

soils in Golestan province, Iran.' *Agriculture, ecosystems & environment*. Elsevier, 134(3–4) pp. 178–189.

Kimbrough, D. E., Kouame, Y., Moheban, P. and Springthorpe, S. (2006) 'The effect of electrolysis and oxidation–reduction potential on microbial survival, growth, and disinfection.' *International journal of environment and pollution*. Inderscience Publishers, 27(1–3) pp. 211–221.

King, N. and Jones, A. (2023) 'Introduction.' *In* King, N. and Jones, A. (eds) *Future Energy Options from a Systems Perspective*. Cham: Springer Nature Switzerland, pp. 1–31.

Klausmeier, C. A. (1999) 'Regular and Irregular Patterns in Semiarid Vegetation.' *Science*. American Association for the Advancement of Science, 284(5421). Report pp. 1826–1828.

Kleidon, A. (2012) 'How does the Earth system generate and maintain thermodynamic disequilibrium and what does it imply for the future of the planet?' *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*. Royal Society, 370(1962) pp. 1012–1040.

Kögel-Knabner, I., Guggenberger, G., Kleber, M., Kandeler, E., Kalbitz, K., Scheu, S., Eusterhues, K. and Leinweber, P. (2008) 'Organo-mineral associations in temperate soils: Integrating biology, mineralogy, and organic matter chemistry.' *Journal of Plant Nutrition and Soil Science*, 171(1) pp. 61–82.

Koorevaar, P., Menelik, G. and Dirksen, C. (eds) (1983) '7 Heat Transport in Soil.' *In Developments in Soil Science*. Elsevier (Elements of Soil Physics), pp. 193–207.

Korenić, A., Perović, S., Ćirković, M. M. and Miquel, P.-A. (2020) 'Symmetry breaking and functional incompleteness in biological systems.' *Progress in Biophysics and Molecular Biology*, 150, January, pp. 1–12.

Kralova, M., Masscheleyn, P. and Patrick Jr, W. (1992) 'Redox potential as an indicator of electron availability for microbial activity and nitrogen transformations in aerobic soil.' *Zentralblatt für Mikrobiologie*. Elsevier, 147(6) pp. 388–399.

Kravchenko, A. N., Negassa, W. C., Guber, A. K. and Rivers, M. L. (2015) 'Protection of soil carbon within macro-aggregates depends on intra-aggregate pore characteristics.' *Scientific Reports*. Nature Publishing Group, 5(1) p. 16261.

Kubečka, J., Ayoubi, D., Tang, Z., Knattrup, Y., Engsvang, M., Wu, H. and Elm, J. (2024) 'Accurate modeling of the potential energy surface of atmospheric molecular clusters boosted by neural networks.' *Environmental Science. Advances*, 3(10) pp. 1438–1451.

Kurakin, A. (2011) 'The self-organizing fractal theory as a universal discovery method: the phenomenon of life.' *Theoretical Biology and Medical Modelling*. Springer, 8 pp. 1–66.

Kv, U., Km, R. and Naik, D. (2019) 'Role of soil physical, chemical and biological properties for soil health improvement and sustainable agriculture.' *Journal of Pharmacognosy and Phytochemistry*. AkiNik Publications, 8(5) pp. 1256–1267.

Kylafis, G. and Loreau, M. (2010) 'Niche construction in the light of niche theory.' *Ecology letters*, 14, November, pp. 82–90.

Laanbroek, H. (1990) 'Bacterial cycling of minerals that affect plant growth in waterlogged soils: a review.' *Aquatic Botany*. Elsevier, 38(1) pp. 109–125.

Lacroix, E. M., Rossi, R. J., Bossio, D. and Fendorf, S. (2021) 'Effects of moisture and physical disturbance on pore-scale oxygen content and anaerobic metabolisms in upland soils.' *Science of The Total Environment*. Elsevier, 780 p. 146572.

Laguë, M. M., Quetin, G. R. and Boos, W. R. (2023) 'Reduced terrestrial evaporation increases atmospheric water vapor by generating cloud feedbacks.' *Environmental Research Letters*. IOP Publishing, 18(7) p. 074021.

Lal, R. (1974) 'Effects of constant and fluctuating soil temperature on growth, development and nutrient uptake of maize seedlings.' *Plant and Soil*, 40(3) pp. 589–606.

Lal, R. (2004) 'Soil carbon sequestration impacts on global climate change and food security.' *science*. American Association for the Advancement of Science, 304(5677) pp. 1623–1627.

Lambers, H., Chapin, F. S. and Pons, T. L. (2008) *Plant physiological ecology*. Springer.

LandIS (n.d.) *LandIS - Land Information System - National Soils Inventory - NSI*. https://www.landis.org.uk/data/nsi.cfm. [Online] [Accessed on 19th March 2024] https://www.landis.org.uk/data/nsi.cfm.

Landis, D. A. (2017) 'Designing agricultural landscapes for biodiversity-based ecosystem services.' *Basic and Applied Ecology*, 18 pp. 1–12.

Lefever, R. and Lejeune, O. (1997) 'On the origin of tiger bush.' *Bulletin of Mathematical Biology*, 59(2) pp. 263–294.

Lehmann, P. (2023) 'Water evaporation from bare soil.' *In* Goss, M. J. and Oliver, M. (eds) *Encyclopedia of Soils in the Environment (Second Edition)*. Oxford: Academic Press, pp. 490–500.

Lejeune, O., Tlidi, M. and Couteron, P. (2002) 'Localized vegetation patches: A self-organized response to resource scarcity.' *Physical Review E*. American Physical Society, 66(1) p. 010901.

Levin, S. A. (1998) 'Ecosystems and the Biosphere as Complex Adaptive Systems.' *Ecosystems*, 1(5) pp. 431–436.

Levin, S. A., Carpenter, S. R., Godfray, H. C. J., Kinzig, A. P., Loreau, M., Losos, J. B., Walker, B. and Wilcove, D. S. (2012) *The Princeton Guide to Ecology*. Princeton University Press.

Levine, J. and HilleRisLambers, J. (2009) 'The importance of niches for the maintenance of species diversity.' *Nature*, 461, September, pp. 254–7.

Li, J., Zhang, H., Xie, W., Liu, C., Liu, X., Zhang, X., Li, L. and Pan, G. (2024) 'Elevated CO2 increases soil redox potential by promoting root radial oxygen loss in paddy field.' *Journal of Environmental Sciences*, 136, February, pp. 11–20.

Li, W., Brunner, P., Hendricks Franssen, H.-J., Li, Z., Wang, Z., Zhang, Z. and Wang, W. (2020) 'Potential evaporation dynamics over saturated bare soil and an open water surface.' *Journal of Hydrology*, 590, November, p. 125140.

Liang, J., Wang, G., Singh, S., Jagadamma, S., Gu, L., Schadt, C. W., Wood, J. D., Hanson, P. J. and Mayes, M. A. (2021) 'Intensified Soil Moisture Extremes Decrease Soil Organic Carbon Decomposition: A Mechanistic Modeling Analysis.' *Journal of Geophysical Research: Biogeosciences*, 126(8) p. e2021JG006392.

Lin, H., Tu, C., Fang, J., Gioli, B., Loubet, B., Gruening, C., Zhou, G., Beringer, J., Huang, J., Dušek, J., Liddell, M., Buysse, P., Shi, P., Song, Q., Han, S., Magliulo, V., Li, Y. and Grace, J. (2020) 'Forests buffer thermal fluctuation better than non-forests.' *Agricultural and Forest Meteorology*, 288–289, July, p. 107994.

Lin, H., Zhang, H. and Song, Q. (2018a) 'Transition from abstract thermodynamic concepts to perceivable ecological indicators.' *Ecological Indicators*, 88, May, pp. 37–42.

Lin, H., Zhang, H. and Song, Q. (2018b) 'Transition from abstract thermodynamic concepts to perceivable ecological indicators.' *Ecological Indicators*, 88, May, pp. 37–42.

Lincoln, T. A. and Joyce, G. F. (2009) 'Self-Sustained Replication of an RNA Enzyme.' *Science*. American Association for the Advancement of Science, 323(5918). Report pp. 1229–1232.

Lindeman, Raymond L. (1942) 'The Trophic-Dynamic Aspect of Ecology.' *Ecology*. Ecological Society of America, 23(4) pp. 399–417.

Lindeman, Raymond L (1942) 'The Trophic-Dynamic Aspect of Ecology' p. 20.

Lisitsyn, V. I. and Matveev, N. N. (2022) 'Entropy Production Using Ecological and Physiological Models of Stand Growth Dynamics as an Example.' *Forests*. Multidisciplinary Digital Publishing Institute, 13(11) p. 1948.

Löbmann, M. T., Maring, L., Prokop, G., Brils, J., Bender, J., Bispo, A. and Helming, K. (2022) 'Systems knowledge for sustainable soil and land management.' *Science of The Total Environment*, 822, May, p. 153389.

Longo, G., Montévil, M. and Kauffman, S. (2012) 'No entailing laws, but enablement in the evolution of the biosphere.' *In Proceedings of the 14th annual*

conference companion on Genetic and evolutionary computation. New York, NY, USA: Association for Computing Machinery (GECCO '12), pp. 1379–1392.

Longo, G., Montévil, M., Sonnenschein, C. and Soto, A. M. (2015) 'In search of principles for a Theory of Organisms.' *Journal of Biosciences*, 40(5) pp. 955–968.

Loreau, M. (1998) 'Ecosystem development explained by competition within and between material cycles.' *Proceedings of the Royal Society of London. Series B: Biological Sciences*. Royal Society, 265(1390) pp. 33–38.

Loreau, M. (2010) 'Linking biodiversity and ecosystems: towards a unifying ecological theory.' *Philosophical Transactions of the Royal Society B: Biological Sciences*. Royal Society, 365(1537) pp. 49–60.

Lotka, A. J. (1922) 'Contribution to the Energetics of Evolution.' *Proceedings of the National Academy of Sciences*. National Academy of Sciences, 8(6). Biology pp. 147–151.

Lotka, A. J. (1925) 'Elements of Physical Biology.' *Nature*. Nature Publishing Group, 116(2917) pp. 461–461.

Lovelock, J. (1995) *Gaia: A New Look at Life on Earth*. Oxford University Press.

Lovelock, J. E. and Margulis, L. (1974) 'Atmospheric homeostasis by and for the biosphere: the gaia hypothesis.' *Tellus*, 26(1–2) pp. 2–10.

Lovley, D. R., Fraga, J. L., Blunt-Harris, E. L., Hayes, L. A., Phillips, E. J. P. and Coates, J. D. (1998) 'Humic Substances as a Mediator for Microbially Catalyzed Metal Reduction.' *Acta hydrochimica et hydrobiologica*, 26(3) pp. 152–157.

Lu, H. F., Wang, Z. H., Campbell, D. E., Ren, H. and Wang, J. (2011) 'Emergy and eco-exergy evaluation of four forest restoration modes in southeast China.' *Ecological Engineering*, 37(2) pp. 277–285.

Ludwig, M., Wilmes, P. and Schrader, S. (2018) 'Measuring soil sustainability via soil resilience.' *Science of The Total Environment*, 626, June, pp. 1484–1493.

Lueder, S., Narasimhan, K., Olivo, J., Cabrera, D., Jurado, J. G., Greenstein, L. and Karubian, J. (2022) 'Functional Traits, Species Diversity and Species Composition of a Neotropical Palm Community Vary in Relation to Forest Age.' *Frontiers in Ecology and Evolution*. Frontiers, 10, April.

Luisi, P. L. (1998) 'About Various Definitions of Life.' *Origins of life and evolution of the biosphere*, 28(4) pp. 613–622.

Luna Juncal, M. J., Masino, P., Bertone, E. and Stewart, R. A. (2023) 'Towards nutrient neutrality: A review of agricultural runoff mitigation strategies and the development of a decision-making framework.' *Science of The Total Environment*, 874, May, p. 162408.

Lv, X., Zhang, S., Zhang, L., Guo, S., Ma, Y. and Zhou, T. (2023) 'Water flow promotes nutrient release and microbial community assembly during *Hydrilla*

verticillata decomposition.' *Journal of Cleaner Production*, 429, December, p. 139464.

MacArthur, R. (1955) 'Fluctuations of Animal Populations and a Measure of Community Stability.' *Ecology*. Ecological Society of America, 36(3) pp. 533–536.

MacArthur, R. H. (1958) 'Population Ecology of Some Warblers of Northeastern Coniferous Forests.' *Ecology*. Ecological Society of America, 39(4) pp. 599–619.

Macías, F. and Camps Arbestain, M. (2010) 'Soil carbon sequestration in a changing global environment.' *Mitigation and Adaptation Strategies for Global Change*, 15(6) pp. 511–529.

Maestre, F. T., Valladares, F. and Reynolds, J. F. (2005) 'Is the change of plant–plant interactions with abiotic stress predictable? A meta-analysis of field results in arid environments.' *Journal of Ecology*, 93(4) pp. 748–757.

Maillard, O., Vides-Almonacid, R., Salazar, A. and Larrea-Alcázar, D. (2022) 'Effect of Deforestation on Land Surface Temperature in the Chiquitania Region, Bolivia.' *Land*, 12, December, p. 2.

Mansfeldt, T. (2003) 'In situ long-term redox potential measurements in a dyked marsh soil.' *Journal of Plant Nutrition and Soil Science*. Wiley Online Library, 166(2) pp. 210–219.

Marchi, M., Jørgensen, S. E., Bécares, E., Corsi, I., Marchettini, N. and Bastianoni, S. (2011) 'Dynamic model of Lake Chozas (León, NW Spain)—Decrease in eco-exergy from clear to turbid phase due to introduction of exotic crayfish.' *Ecological Modelling*. Elsevier, 222(16) pp. 3002–3010.

Marchin, R. M., Ossola, A., Leishman, M. R. and Ellsworth, D. S. (2020) 'A Simple Method for Simulating Drought Effects on Plants.' *Frontiers in Plant Science*, 10.

Marques, J. C. and Jørgensen, S. E. (2002) 'Three selected ecological observations interpreted in terms of a thermodynamic hypothesis. Contribution to a general theoretical framework.' *Ecological Modelling*. Elsevier, 158(3) pp. 213–221.

Marschner, H. (1991) 'Mechanisms of adaptation of plants to acid soils.' *Plant and soil*. Springer, 134 pp. 1–20.

Marschner, P. (2012) *Mineral Nutrition of Higher Plants*. Third, Imprint: Academic Press.

Martinez-Turanzas, G. A., Coffin, D. P. and Burke, I. C. (1997) 'Development of microtopography in a semi-arid grassland: Effects of disturbance size and soil texture.' *Plant and Soil*, 191(2) pp. 163–171.

Martins, C. S. C., Delgado-Baquerizo, M., Jayaramaiah, R. H., Tao, D., Wang, J.-T., Sáez-Sandino, T., Liu, H., Maestre, F. T., Reich, P. B. and Singh, B. K. (2024) 'Aboveground and belowground biodiversity have complementary effects on

ecosystem functions across global grasslands.' *PLOS Biology*. Public Library of Science, 22(8) p. e3002736.

Martyushev, L. M. and Seleznev, V. D. (2006) 'Maximum entropy production principle in physics, chemistry and biology.' *Physics Reports*, 426(1) pp. 1–45.

Marull, J., Pino, J., Melero, Y. and Tello, E. (2023) 'Using thermodynamics to understand the links between energy, information, structure and biodiversity in a human-transformed landscape.' *Ecological Modelling*, 476, February, p. 110257.

Mattila, T. J. (2023) 'Redox potential as a soil health indicator – how does it compare to microbial activity and soil structure?' *Plant and Soil*, September.

Maurice, K., Laurent-Webb, L., Dehail, A., Bourceret, A., Boivin, S., Boukcim, H., Selosse, M.-A. and Ducousso, M. (2023) 'Fertility islands, keys to the establishment of plant and microbial diversity in a highly alkaline hot desert.' *Journal of Arid Environments*, 219, December, p. 105074.

Mazancourt, C. de, Loreau, M. and Abbadie, L. (1998) 'Grazing Optimization and Nutrient Cycling: When Do Herbivores Enhance Plant Production?' *Ecology*, 79(7) pp. 2242–2252.

McCormick, R. and Kapustka, L. A. (2016) 'The answer is 42… What is THE question?' *Journal of Environmental Studies and Sciences*. Springer, 6 pp. 208–213.

McInnes, K. (2002) 'Temperature measurement.' *Encyclopedia of Soil Science* pp. 1302–1304.

McKinney, M. L. (2006) 'Urbanization as a major cause of biotic homogenization.' *Biological Conservation*. (Urbanization), 127(3) pp. 247–260.

McNamara, H. (2014) 'An estimate of energy dissipation due to soil-moisture hysteresis.' *Water Resources Research*, 50(1) pp. 725–735.

McNaughton, S. J., Banyikwa, F. F. and McNaughton, M. M. (1997) 'Promotion of the Cycling of Diet-Enhancing Nutrients by African Grazers.' *Science*. American Association for the Advancement of Science, 278(5344). Report pp. 1798–1800.

Melián, C. J., Matthews, B., de Andreazzi, C. S., Rodríguez, J. P., Harmon, L. J. and Fortuna, M. A. (2018) 'Deciphering the Interdependence between Ecological and Evolutionary Networks.' *Trends in Ecology & Evolution*, 33(7) pp. 504–512.

Meng, L., Chambers, J., Koven, C., Pastorello, G., Gimenez, B., Jardine, K., Tang, Y., McDowell, N., Negron-Juarez, R., Longo, M., Araujo, A., Tomasella, J., Fontes, C., Mohan, M. and Higuchi, N. (2022) 'Soil moisture thresholds explain a shift from light-limited to water-limited sap velocity in the Central Amazon during the 2015–16 El Niño drought.' *Environmental Research Letters*. IOP Publishing, 17(6) p. 064023.

Meredith, S. A., Yoneda, T., Hancock, A. M., Connell, S. D., Evans, S. D., Morigaki, K. and Adams, P. G. (2021) 'Model Lipid Membranes Assembled from

Natural Plant Thylakoids into 2D Microarray Patterns as a Platform to Assess the Organization and Photophysics of Light-Harvesting Proteins.' *Small*, 17(14) p. 2006608.

Merikanto, J., Spracklen, D. V., Mann, G. W., Pickering, S. J. and Carslaw, K. S. (2009) 'Impact of nucleation on global CCN.' *Atmospheric Chemistry & Physics*, 9, November, pp. 8601–8616.

Meron, E. (2016) 'Pattern formation – A missing link in the study of ecosystem response to environmental changes.' *Mathematical Biosciences*, 271, January, pp. 1–18.

MET Office (n.d.) *Weather and Climate*. [Online] https://www.metoffice.gov.uk/weather/forecast/gcpffxw47#?date=2024-04-09.

Michaelian, K. (2015) 'Photon Dissipation Rates as an Indicator of Ecosystem Health.' *In* Armon, R. H. and Hänninen, O. (eds) *Environmental Indicators*. Dordrecht: Springer Netherlands, pp. 15–36.

Michaelides, E. (ed.) (2021) 'Exergy in Biological Systems.' *In Exergy Analysis for Energy Conversion Systems*. Cambridge: Cambridge University Press, pp. 201–250.

Mitsch, W. J., Day, J. W., Gilliam, J. W., Groffman, P. M., Hey, D. L., Randall, G. W. and Wang, N. (2001) 'Reducing Nitrogen Loading to the Gulf of Mexico from the Mississippi River Basin: Strategies to Counter a Persistent Ecological Problem: Ecotechnology—the use of natural ecosystems to solve environmental problems—should be a part of efforts to shrink the zone of hypoxia in the Gulf of Mexico.' *BioScience*. American Institute of Biological Sciences, 51(5) pp. 373–388.

Molozzi, J., Salas, F., Callisto, M. and Marques, J. C. (2013) 'Thermodynamic oriented ecological indicators: Application of Eco-Exergy and Specific Eco-Exergy in capturing environmental changes between disturbed and non-disturbed tropical reservoirs.' *Ecological Indicators*, 24 pp. 543–551.

Mora, J. L. and Lázaro, R. (2013) 'Evidence of a threshold in soil erodibility generating differences in vegetation development and resilience between two semiarid grasslands.' *Journal of Arid Environments*, 89, February, pp. 57–66.

Morowitz, H. J., Kostelnik, J. D., Yang, J. and Cody, G. D. (2000) 'The origin of intermediary metabolism.' *Proceedings of the National Academy of Sciences*. National Academy of Sciences, 97(14). Biological Sciences pp. 7704–7708.

Mossel, E. and Steel, M. (2005) 'Random biochemical networks: the probability of self-sustaining autocatalysis.' *Journal of Theoretical Biology*, 233(3) pp. 327–336.

Mu, J., Zeng, Y., Wu, Q., Niklas, K. J. and Niu, K. (2016) 'Traditional grazing regimes promote biodiversity and increase nectar production in Tibetan alpine meadows.' *Agriculture, Ecosystems & Environment*, 233, October, pp. 336–342.

Müller, F. (1998) 'Gradients in ecological systems.' *Ecological Modelling*, 108(1) pp. 3–21.

Myhre, G., Lund Myhre, C., Samset, B. H. and Storelvmo, T. (2013) 'Aerosols and their Relation to Global Climate and Climate Sensitivity.' *ResearchGate*, 4(7).

Naeem, S. (1998) 'Species redundancy and ecosystem reliability.' *Conservation biology*. Wiley Online Library, 12(1) pp. 39–45.

Naiman, R. J., Décamps, H., McClain, M. E. and Likens, G. E. (2005) '4 - Structural Patterns.' *In* Naiman, R. J., Décamps, H., McClain, M. E., and Likens, G. E. (eds) *Riparia*. Burlington: Academic Press, pp. 79–123.

Nascimento, C. M., Demattê, J. A. M., Mello, F. A. O., Rosas, J. T. F., Tayebi, M., Bellinaso, H., Greschuk, L. T., Albarracín, H. S. R. and Ostovari, Y. (2022) 'Soil degradation detected by temporal satellite image in São Paulo state, Brazil.' *Journal of South American Earth Sciences*, 120, December, p. 104036.

Nash, K. L., Allen, C. R., Angeler, D. G., Barichievy, C., Eason, T., Garmestani, A. S., Graham, N. A., Granholm, D., Knutson, M. and Nelson, R. J. (2014) 'Discontinuities, cross-scale patterns, and the organization of ecosystems.' *Ecology*. Wiley Online Library, 95(3) pp. 654–667.

National Statistics (2023) 'Woodland Statistics.' https://www.forestresearch.gov.uk/tools-and-resources/statistics/statistics-by-topic/woodland-statistics/.

Newbold, T., Adams, G. L., Albaladejo Robles, G., Boakes, E. H., Braga Ferreira, G., Chapman, A. S. A., Etard, A., Gibb, R., Millard, J., Outhwaite, C. L. and Williams, J. J. (2019) 'Climate and land-use change homogenise terrestrial biodiversity, with consequences for ecosystem functioning and human well-being.' *Emerging Topics in Life Sciences*, 3(2) pp. 207–219.

Newbold, T., Hudson, L., Hill, S., Contu, S., Lysenko, I., Senior, R., Börger, L., Bennett, D., Choimes, A., Collen, B., Day, J., De Palma, A., Diaz, S., Echeverria-Londono, S., Edgar, M., Feldman, A., Garon, M., Harrison, M., Alhusseini, T. and Purvis, A. (2015) 'Global effects of land use on local terrestrial biodiversity.' *Nature*, 520, April, pp. 45–50.

Newbold, T., Hudson, L. N., Arnell, A. P., Contu, S., De Palma, A., Ferrier, S., Hill, S. L. L., Hoskins, A. J., Lysenko, I., Phillips, H. R. P., Burton, V. J., Chng, C. W. T., Emerson, S., Gao, D., Pask-Hale, G., Hutton, J., Jung, M., Sanchez-Ortiz, K., Simmons, B. I., Whitmee, S., Zhang, H., Scharlemann, J. P. W. and Purvis, A. (2016) 'Has land use pushed terrestrial biodiversity beyond the planetary boundary? A global assessment.' *Science*. American Association for the Advancement of Science, 353(6296) pp. 288–291.

Nicolis, G. and Prigogine, I. (1989) *Exploring Complexity: An Introduction*. W H Freeman & Company.

Nielsen, S. N. (2019) 'Reductions in ecology and thermodynamics. On the problems arising when shifting the concept of exergy to other hierarchical levels and domains.' *Ecological Indicators*, 100 pp. 118–134.

Nielsen, S. N. and Emmeche, C. (2013) 'Ontic Openness as Key Factor in the Evolution of Biological Systems.' *In* Pontarotti, P. (ed.) *Evolutionary Biology: Exobiology and Evolutionary Mechanisms*. Berlin, Heidelberg: Springer, pp. 21–36.

Nielsen, S. N., Fath, B. D., Bastianoni, S., Marques, J. C., Muller, F., Patten, B. D., Ulanowicz, R. E., Jørgensen, S. E. and Tiezzi, E. (2019) *A New Ecology: Systems Perspective*. 2nd ed., Elsevier.

Nielsen, S. N. and Müller, F. (2009) 'Understanding the functional principles of nature—Proposing another type of ecosystem services.' *Ecological Modelling*, 220(16) pp. 1913–1925.

Nielsen, S. N., Müller, F., Marques, J. C., Bastianoni, S. and Jørgensen, S. E. (2020) 'Thermodynamics in Ecology—An Introductory Review.' *Entropy*, 22(8) p. 820.

Noctor, G., Veljovic-Jovanovic, S. and Foyer, C. H. (2000) 'Peroxide processing in photosynthesis: antioxidant coupling and redox signalling.' *Philosophical Transactions of the Royal Society of London. Series B: Biological Sciences*. The Royal Society, 355(1402) pp. 1465–1475.

Norris, C., Hobson and Ibisch, P. L. (2012) 'Microclimate and vegetation function as indicators of forest thermodynamic efficiency.' *Journal of Applied Ecology*, 49(3) pp. 562–570.

Norris Catherine, Hobson Peter, and Ibisch Pierre L. (2012) 'Microclimate and vegetation function as indicators of forest thermodynamic efficiency.' *Journal of Applied Ecology*, 49(3) pp. 562–570.

Nourry, M. (2008) 'Measuring sustainable development: Some empirical evidence for France from eight alternative indicators.' *Ecological economics*. Elsevier, 67(3) pp. 441–456.

Nunes-Neto, N., Moreno, A. and El-Hani, C. N. (2014) 'Function in ecology: an organizational approach.' *Biology & Philosophy*, 29(1) pp. 123–141.

Ochoa-Hueso, R., Eldridge, D. J., Delgado-Baquerizo, M., Soliveres, S., Bowker, M. A., Gross, N., Le Bagousse-Pinguet, Y., Quero, J. L., García-Gómez, M., Valencia, E., Arredondo, T., Beinticinco, L., Bran, D., Cea, A., Coaguila, D., Dougill, A. J., Espinosa, C. I., Gaitán, J., Guuroh, R. T., Guzman, E., Gutiérrez, J. R., Hernández, R. M., Huber-Sannwald, E., Jeffries, T., Linstädter, A., Mau, R. L., Monerris, J., Prina, A., Pucheta, E., Stavi, I., Thomas, A. D., Zaady, E., Singh, B. K. and Maestre, F. T. (2018) 'Soil fungal abundance and plant functional traits drive fertile island formation in global drylands.' *Journal of Ecology*, 106(1) pp. 242–253.

Odling-Smee, J., Erwin, D. H., Palkovacs, E. P., Feldman, M. W. and Laland, K. N. (2013) 'Niche Construction Theory: A Practical Guide for Ecologists.' *The Quarterly Review of Biology*. The University of Chicago Press, 88(1) pp. 3–28.

Odum, E. P. (1969) 'The Strategy of Ecosystem Development.' *Science*, 164(3877) pp. 262–270.

Odum, E. P., P, O. E. and SCAR, Q. 541 O. 1971 (1971) *Fundamentals of Ecology*. Saunders.

Odum, H. T. (1988) 'Self-Organization, Transformity, and Information.' *Science*, 242(4882) pp. 1132–1139.

Odum, H. T. (1995) *Environmental Accounting: Emergy and Environmental Decision Making*. 1st edition, New York: Wiley.

Oglesby, J. P. (1997) 'Redox buffering by soil organic matter.' *Abstract of Papers of the American Chemistry Society*, 213 pp. 147–156.

Oliver, T. H. (2016) 'How much biodiversity loss is too much?' *Science*. American Association for the Advancement of Science, 353(6296) pp. 220–221.

O'Neill, R. and Hall, C. (1996) 'Maximum Power: The Ideas and Applications of H. T. Odum.' *Ecology*, 77, October, p. 2263.

O'Neill, R. V., Deangelis, D. L., Waide, J. B., Allen, T. F. H. and Allen, G. E. (1986) *A Hierarchical Concept of Ecosystems*. Princeton University Press.

ONS.GOV.UK (2023) 'Energy use: fossil fuels by fuel type and industry - Office for National Statistics.' https://www.ons.gov.uk/economy/environmentalaccounts/datasets/ukenvironmentalaccountsfuelusebytypeandindustry. [Online] [Accessed on 18th March 2024] https://www.ons.gov.uk/economy/environmentalaccounts/datasets/ukenvironmentalaccountsfuelusebytypeandindustry.

Or, D. and Lehmann, P. (2019) 'Surface Evaporative Capacitance: How Soil Type and Rainfall Characteristics Affect Global-Scale Surface Evaporation.' *Water Resources Research*, 55(1) pp. 519–539.

Orgiazzi, A. and Panagos, P. (2018) 'Soil biodiversity and soil erosion: It is time to get married.' *Global Ecology and Biogeography*, 27(10) pp. 1155–1167.

Paris, B., Vandorou, F., Balafoutis, A. T., Vaiopoulos, K., Kyriakarakos, G., Manolakos, D. and Papadakis, G. (2022) 'Energy use in open-field agriculture in the EU: A critical review recommending energy efficiency measures and renewable energy sources adoption.' *Renewable and Sustainable Energy Reviews*, 158, April, p. 112098.

Parkinson, J. S. and Blair, D. F. (1993) 'Does E. coli have a nose?' *Science*. American Association for the Advancement of Science, 259(5102) pp. 1701–1703.

Parrish, J. D., Braun, D. P. and Unnasch, R. S. (2003) 'Are We Conserving What We Say We Are? Measuring Ecological Integrity within Protected Areas.' *BioScience*, 53(9) pp. 851–860.

Patel, V. K., Kuttippurath, J. and Kashyap, R. (2024) 'Rise in water vapour driven by moisture transport facilitates water availability for the greening of global deserts.' *Science of The Total Environment*, 946, October, p. 174111.

Pattee, H. H. (1997) 'The physics of symbols and the evolution of semiotic controls.' *Proc. Workshop on Control Mechanisms for Complex …*.

Pattee, H. H. (2012) 'The Problem of Observables in Models of Biological Organizations.' *In* Pattee, H. H. and Rączaszek-Leonardi, J. (eds) *LAWS, LANGUAGE and LIFE: Howard Pattee's classic papers on the physics of symbols with contemporary commentary*. Dordrecht: Springer Netherlands (Biosemiotics), pp. 245–259.

Pauluis, O. M. (2005) '9 Water Vapor and Entropy Production in the Earth's Atmosphere.' *In* Kleidon, A. and Lorenz, R. D. (eds) *Non-equilibrium Thermodynamics and the Production of Entropy: Life, Earth, and Beyond*. Berlin, Heidelberg: Springer (Understanding Complex Systems), pp. 107–119.

Peipoch, M., Brauns, M., Hauer, F. R., Weitere, M. and Valett, H. M. (2015) 'Ecological Simplification: Human Influences on Riverscape Complexity.' *BioScience*. Oxford Academic, 65(11) pp. 1057–1065.

Peirce, C. S. (1892) 'The Doctrine of Necessity Examined.' *The Monist*. Oxford Academic, 2(3) pp. 321–337.

Peng, J., Tang, J., Xie, S., Wang, Y., Liao, J., Chen, C., Sun, C., Mao, J., Zhou, Q. and Niu, S. (2024) 'Evidence for the acclimation of ecosystem photosynthesis to soil moisture.' *Nature Communications*. Nature Publishing Group, 15(1) p. 9795.

Peng, Z., Plum, A. M., Gagrani, P. and Baum, D. A. (2020) 'An ecological framework for the analysis of prebiotic chemical reaction networks.' *Journal of Theoretical Biology*, 507 p. 110451.

Petchey, O. L., Evans, K. L., Fishburn, I. S. and Gaston, K. J. (2007) 'Low functional diversity and no redundancy in British avian assemblages.' *Journal of Animal Ecology*. JSTOR pp. 977–985.

Peterson, G. D. (2000) 'Scaling Ecological Dynamics: Self-Organization, Hierarchical Structure, and Ecological Resilience.' *Climatic Change*, 44(3) pp. 291–309.

Pett-Ridge, J. and Firestone, M. (2005) 'Redox fluctuation structures microbial communities in a wet tropical soil.' *Applied and environmental microbiology*. Am Soc Microbiol, 71(11) pp. 6998–7007.

Pham, H.-G., Chuah, S.-H. and Feeny, S. (2021) 'Factors affecting the adoption of sustainable agricultural practices: Findings from panel data for Vietnam.' *Ecological Economics*, 184, June, p. 107000.

Pidello, A. (2003) 'Environmental redox potential and redox capacity concepts using a simple polarographic experiment.' *Journal of chemical education*. ACS Publications, 80(1) p. 68.

Pimentel, D. (2006) 'Soil Erosion: A Food and Environmental Threat.' *Environment, Development and Sustainability*, 8(1) pp. 119–137.

Pingali, P. L. (2012) 'Green Revolution: Impacts, limits, and the path ahead.' *Proceedings of the National Academy of Sciences*. Proceedings of the National Academy of Sciences, 109(31) pp. 12302–12308.

Pinke, Z., Decsi, B., Kardos, M. K., Kern, Z., Kozma, Z., Pásztor, L. and Ács, T. (2022) 'Changing patterns of soil water content and relationship with national wheat and maize production in Europe.' *European Journal of Agronomy*, 140, October, p. 126579.

Pokorný, J., Brom, J., Cermák, J., Hesslerová, P., Huryna, H., Nadezhdina, N. and Rejšková, A. (2010) 'Solar energy dissipation and temperature control by water and plants.' *International Journal of Water*, 5, January, pp. 311–336.

Popper, K. (1990) 'A World of Propensities - Two New Views on Causality.' *In* Popper, K. (ed.) *A World of Propensities*. Thoemmes, pp. 24–329.

Pörtner, H.-O., Roberts, D. C. and Adams, H. (2022) 'Climate Change 2022: Impacts, Adaptation and Vulnerability.'

Post, D. M., Doyle, M. W., Sabo, J. L. and Finlay, J. C. (2007) 'The problem of boundaries in defining ecosystems: A potential landmine for uniting geomorphology and ecology.' *Geomorphology*. (36th Binghamton Geomorphology Symposium), 89(1) pp. 111–126.

Post, D. M. and Palkovacs, E. P. (2009) 'Eco-evolutionary feedbacks in community and ecosystem ecology: interactions between the ecological theatre and the evolutionary play.' *Philosophical Transactions of the Royal Society B: Biological Sciences*. Royal Society, 364(1523) pp. 1629–1640.

Potter, M. C. (1911) 'Electrical effects accompanying the decomposition of organic compounds.' *Proceedings of the royal society of London. Series b, containing papers of a biological character*. The Royal Society London, 84(571) pp. 260–276.

Pourbaix, M. J. N. (1945) 'Thermodynamique des solutions aqueuses diluées: Représentation graphique du rôle du pH et du potentiel.'

Power, M. E., Tilman, D., Estes, J. A., Menge, B. A., Bond, W. J., Mills, L. S., Daily, G., Castilla, J. C., Lubchenco, J. and Paine, R. T. (1996) 'Challenges in the Quest for KeystonesIdentifying keystone species is difficult—but essential to understanding how loss of species will affect ecosystems.' *BioScience*. Oxford Academic, 46(8) pp. 609–620.

Prigogine, I. (1955) *Introduction to thermodynamics of irreversible processes*. New York: Interscience Publishers.

Prigogine, I. (1967) 'Introduction to thermodynamics of irreversible processes.' *New York: Interscience*.

Prigogine, I. (2017) *Non-Equilibrium Statistical Mechanics*. Courier Dover Publications.

Prigogine, I. and Nicolis, G. (1977) 'Self-organization.' *Non-Equilibrium System*.

Prigogine, I. and Nicolis, G. (1985) 'Self-Organisation in Nonequilibrium Systems: Towards A Dynamics of Complexity.' *In* Hazewinkel, M., Jurkovich, R., and Paelinck, J. H. P. (eds) *Bifurcation Analysis: Principles, Applications and Synthesis*. Dordrecht: Springer Netherlands, pp. 3–12.

Prigogine, I., Nicolis, G. and Babloyantz, A. (1972) 'Thermodynamics of evolution.' *Physics Today*, 25(11) pp. 23–28.

Prigogine, I., Prigogine, I. V. and Stengers, I. (1984) *Order Out of Chaos: Man's New Dialogue with Nature*. Bantam Books.

Prigogine, I. and Rysselberghe, P. V. (1963) 'Introduction to Thermodynamics of Irreversible Processes.' *Journal of The Electrochemical Society*. IOP Publishing, 110(4) p. 97C.

Pulleman, M., Creamer, R., Hamer, U., Helder, J., Pelosi, C., Pérès, G. and Rutgers, M. (2012) 'Soil biodiversity, biological indicators and soil ecosystem services—an overview of European approaches.' *Current Opinion in Environmental Sustainability*, 4(5) pp. 529–538.

Puzachenko, Y. G., Sandlersky, R. B., Krenke, A. N. and Olchev, A. (2016) 'Assessing the thermodynamic variables of landscapes in the southwest part of East European plain in Russia using the MODIS multispectral band measurements.' *Ecological modelling*. Elsevier, 319 pp. 255–274.

Qian, H., Zhu, W., Fan, S., Liu, C., Lu, X., Wang, Z., Huang, D. and Chen, W. (2017) 'Prediction models for chemical exergy of biomass on dry basis from ultimate analysis using available electron concepts.' *Energy*, 131, July, pp. 251–258.

Qin, T., Feng, J., Zhang, X., Li, C., Fan, J., Zhang, C., Dong, B., Wang, H. and Yan, D. (2023) 'Continued decline of global soil moisture content, with obvious soil stratification and regional difference.' *Science of The Total Environment*, 864, March, p. 160982.

Qingming, W., Shan, J., Jiaqi, Z., Guohua, H., Yong, Z., Yongnan, Z., Xin, H., Haihong, L., Lizhen, W., Fan, H. and Changhai, Q. (2022) 'Effects of vegetation restoration on evapotranspiration water consumption in mountainous areas and assessment of its remaining restoration space.' *Journal of Hydrology*, 605, February, p. 127259.

Quinn, R., Parker, A. and Rushton, K. (2018) 'Evaporation from bare soil: Lysimeter experiments in sand dams interpreted using conceptual and numerical models.' *Journal of Hydrology*, 564, September, pp. 909–915.

Rabotnova, I. L. and Schwartz, W. (1962) 'The importance of physical-chemical factors (pH and rH2) for the life activity of microorganisms.' *VEB Gustav Fischer Verlag, Berlin* p. 296.

Ramankutty, N. and Foley, J. A. (1999) 'Estimating historical changes in global land cover: Croplands from 1700 to 1992.' *Global Biogeochemical Cycles*, 13(4) pp. 997–1027.

Randle-Boggis, R. J., Ashton, P. D. and Helgason, T. (2017) 'Increasing flooding frequency alters soil microbial communities and functions under laboratory conditions.' *MicrobiologyOpen*, 7(1) p. e00548.

Ratliff, L. F., Ritchie, J. T. and Cassel, D. K. (1983) 'Field-Measured Limits of Soil Water Availability as Related to Laboratory-Measured Properties.' *Soil Science Society of America Journal*, 47(4) pp. 770–775.

Ravi, S., Wang, L., Kaseke, K. F., Buynevich, I. V. and Marais, E. (2017) 'Ecohydrological interactions within "fairy circles" in the Namib Desert: Revisiting the self-organization hypothesis.' *Journal of Geophysical Research: Biogeosciences*, 122(2) pp. 405–414.

Rejano, F., Casquero-Vera, J. A., Lyamani, H., Andrews, E., Casans, A., Pérez-Ramírez, D., Alados-Arboledas, L., Titos, G. and Olmo, F. J. (2023) 'Impact of urban aerosols on the cloud condensation activity using a clustering model.' *Science of The Total Environment*, 858, February, p. 159657.

Rietkerk, M., Boerlijst, M. C., van Langevelde, F., HilleRisLambers, R., de Koppel, J. van, Kumar, L., Prins, H. H. T. and de Roos, A. M. (2002) 'Self-Organization of Vegetation in Arid Ecosystems.' *The American Naturalist*. The University of Chicago Press, 160(4) pp. 524–530.

Rillig, M. C. and Mummey, D. L. (2006) 'Mycorrhizas and soil structure.' *New Phytologist*, 171(1) pp. 41–53.

Ritz, K., Black, H. I., Campbell, C. D., Harris, J. A. and Wood, C. (2009) 'Selecting biological indicators for monitoring soils: a framework for balancing scientific and technical opinion to assist policy development.' *Ecological Indicators*. Elsevier, 9(6) pp. 1212–1221.

Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin III, F. S., Lambin, E., Lenton, T. M., Scheffer, M., Folke, C. and Schellnhuber, H. J. (2009) 'Planetary boundaries: exploring the safe operating space for humanity.' *Ecology and society*. JSTOR, 14(2).

Rockström, J., Williams, J., Daily, G., Noble, A., Matthews, N., Gordon, L., Wetterstrand, H., DeClerck, F., Shah, M., Steduto, P., de Fraiture, C., Hatibu, N., Unver, O., Bird, J., Sibanda, L. and Smith, J. (2017) 'Sustainable intensification of agriculture for human prosperity and global sustainability.' *Ambio*, 46(1) pp. 4–17.

Romano, N. and Santini, A. (2002) 'Water retention and storage: Field.' *In*, pp. 721–738.

Romero, J. C. and Linares, P. (2014) 'Exergy as a global energy sustainability indicator. A review of the state of the art.' *Renewable and Sustainable Energy Reviews*, 33, May, pp. 427–442.

Rosen, R. (1991) *Life Itself: A Comprehensive Inquiry Into the Nature, Origin, and Fabrication of Life*. Columbia University Press.

Rossi, F. and Liveri, M. L. T. (2009) 'Chemical self-organization in self-assembling biomimetic systems.' *Ecological Modelling*. (Selected Papers from the Workshop on 'Emergence of Novelties', 9-16 October 2008, Pacina, Siena, Italy), 220(16) pp. 1857–1864.

de Ruiter, P. C., Neutel, A.-M. and Moore, J. C. (1994) 'Modelling food webs and nutrient cycling in agro-ecosystems.' *Trends in Ecology & Evolution*, 9(10) pp. 378–383.

Ruiz-Reynés, D., Gomila, D., Sintes, T., Hernández-García, E., Marbà, N. and Duarte, C. M. (2017) 'Fairy circle landscapes under the sea.' *Science Advances*. American Association for the Advancement of Science, 3(8). Research Article p. e1603262.

Rundgren, G. (2002) *Organic agriculture and food security*. IFOAM.

Rutledge, R. W., Basore, B. L. and Mulholland, R. J. (1976) 'Ecological stability: An information theory viewpoint.' *Journal of Theoretical Biology*, 57(2) pp. 355–371.

Sabienė, N., Kušlienė, G. and Zaleckas, E. (2010) 'The influence of land use on soil organic carbon and nitrogen content and redox potential.' *Žemdirbystė= Agriculture*, 97(3) pp. 15–24.

Sahagian, D. (2017) 'The magic of fairy circles: Built or created?' *Journal of Geophysical Research: Biogeosciences*, 122(5) pp. 1294–1295.

Salthe, S. N. (1993) *Development and Evolution: Complexity and Change in Biology*. MIT Press.

Sanchez, G. and Puigdefabregas, J. (1994) 'Interactions of plant growth and sediment movement on slopes in a semi-arid environment.' *Geomorphology*, 9(3) pp. 243–260.

Sanderman, J. and Berhe, A. A. (2017) 'The soil carbon erosion paradox.' *Nature Climate Change*. Nature Publishing Group UK London, 7(5) pp. 317–319.

Sanderson, E. W., Jaiteh, M., Levy, M. A., Redford, K. H., Wannebo, A. V. and Woolmer, G. (2002) 'The Human Footprint and the Last of the Wild: The human footprint is a global map of human influence on the land surface, which suggests that human beings are stewards of nature, whether we like it or not.' *BioScience*, 52(10) pp. 891–904.

Santos, F., Abney, R., Barnes, M., Bogie, N., Ghezzehei, T. A., Jin, L., Moreland, K., Sulman, B. N. and Berhe, A. A. (2019) 'Chapter 9 - The role of the physical properties of soil in determining biogeochemical responses to soil warming.' *In*

Mohan, J. E. (ed.) *Ecosystem Consequences of Soil Warming*. Academic Press, pp. 209–244.

Sauer, T. and Horton, R. (2005) 'Soil Heat Flux,' January.

Savant, N. K. and Ellis, R. (1964) 'Changes in redox potential and phosphorus availability in submerged soils.'

Savva, Y., Szlávecz, K., Pouyat, R., Groffman, P. and Heisler, G. (2010) 'Effects of Land Use and Vegetation Cover on Soil Temperature in an Urban Ecosystem.' *Soil Science Society of America Journal*, 74, March.

Scheibe, R., Backhausen, J. E., Emmerlich, V. and Holtgrefe, S. (2005) 'Strategies to maintain redox homeostasis during photosynthesis under changing conditions.' *Journal of experimental botany*. Oxford University Press, 56(416) pp. 1481–1489.

Schick, A., Porembski, S., Hobson, Peter R. and Ibisch, P. L. (2019) 'Classification of key ecological attributes and stresses of biodiversity for ecosystem-based conservation assessments and management.' *Ecological complexity*. Elsevier, 38 pp. 98–111.

Schick, A., Porembski, S., Hobson, Peter R and Ibisch, P. L. (2019) 'Classification of key ecological attributes and stresses of biodiversity for ecosystem-based conservation assessments and management.' *Ecological Complexity*, 38, April, pp. 98–111.

Schlesinger, W. H., Reynolds, J. F., Cunningham, G. L., Huenneke, L. F., Jarrell, W. M., Virginia, R. A. and Whitford, W. G. (1990) 'Biological Feedbacks in Global Desertification.' *Science*. American Association for the Advancement of Science, 247(4946). Articles pp. 1043–1048.

Schneider, Eric D. and Kay, J. J. (1994) 'Complexity and thermodynamics: Towards a new ecology.' *Futures*. (Special Issue Complexity: Fad or Future?), 26(6) pp. 626–647.

Schneider, E.D and Kay, J. J. (1994) 'Life as a manifestation of the second law of thermodynamics.' *Mathematical and Computer Modelling*, 19(6) pp. 25–48.

Schneider, E. D. and Kay, J. J. (1994) 'Life as a manifestation of the second law of thermodynamics.' *Mathematical and Computer Modelling*, 19(6) pp. 25–48.

Schneider, E. D. and Kay, J. J. (1995) 'Order from disorder: the thermodynamics of complexity in biology.' *In* O'Neill, L. A. J. and Murphy, M. P. (eds) *What is Life? The Next Fifty Years: Speculations on the Future of Biology*. Cambridge: Cambridge University Press, pp. 161–174.

Schneider, E. D. and Sagan, D. (2005) *Into the Cool: Energy Flow, Thermodynamics, and Life*. University of Chicago Press.

Schrama, M., Quist, C. W., Arjen de Groot, G., Cieraad, E., Ashworth, D., Laros, I., Hansen, L. H., Leff, J., Fierer, N. and Bardgett, R. D. (2023) 'Cessation of grazing causes biodiversity loss and homogenization of soil food webs.'

Proceedings of the Royal Society B: Biological Sciences. Royal Society, 290(2011) p. 20231345.

Schrödinger, E. (1944) 'What is life ? The physical aspect of the living cell.' *What is life ? The physical aspect of the living cell.* Cambridge : University Press.

Schulte, E. E. and Hopkins, B. G. (1996) 'Estimation of Soil Organic Matter by Weight Loss-On-Ignition.' *In Soil Organic Matter: Analysis and Interpretation*. John Wiley & Sons, Ltd. 3, pp. 21–31.

Schwertmann, U. and Murad, E. (1983) 'Effect of pH on the formation of goethite and hematite from ferrihydrite.' *Clays and Clay Minerals*. Cambridge University Press & Assessment, 31(4) pp. 277–284.

Sciubba, E. (2004) 'From Engineering Economics to Extended Exergy Accounting: A Possible Path from Monetary to Resource-Based Costing.' *Journal of Industrial Ecology*, 8(4) pp. 19–40.

Sciubba, E. and Ulgiati, S. (2005) 'Emergy and exergy analyses: Complementary methods or irreducible ideological options?' *Energy*, 30(10) pp. 1953–1988.

Sexstone, A. J., Revsbech, N. P., Parkin, T. B. and Tiedje, J. M. (1985) 'Direct measurement of oxygen profiles and denitrification rates in soil aggregates.' *Soil science society of America journal*. Wiley Online Library, 49(3) pp. 645–651.

Shannon, C. E. (1948) 'A Mathematical Theory of Communication.' *Bell System Technical Journal*, 27(4) pp. 623–656.

Shaw, E. (2005) *Hydrology in practice*. CRC press.

Shepard, M. (2015) 'Summary of evidence: Soils - EIN012.' *Natural Englnd Publications*.

Shu, Y., Jiang, L., Liu, F. and Lv, G. (2022) 'Effects of plant diversity and abiotic factors on the multifunctionality of an arid desert ecosystem.' *PLOS ONE*. Public Library of Science, 17(6) p. e0266320.

Silow, E. A. and Mokry, A. V. (2010) 'Exergy as a Tool for Ecosystem Health Assessment.' *Entropy*, 12(4) pp. 902–925.

Silvertown, J. (2004) 'Plant coexistence and the niche.' *Trends in Ecology & Evolution*, 19(11) pp. 605–611.

Šimon, T. (2007) 'Quantitative and qualitative characterization of soil organic matter in the long-term fallow experiment with different fertilization and tillage.' *Archives of Agronomy and Soil Science*. Taylor & Francis, 53(3) pp. 241–251.

Sirimungkala, A., Försterling, H.-D., Dlask, V. and Field, R. J. (1999) 'Bromination Reactions Important in the Mechanism of the Belousov−Zhabotinsky System.' *The Journal of Physical Chemistry A*. American Chemical Society, 103(8) pp. 1038–1043.

Smit, C., Buyens, I. P. R. and le Roux, P. C. (2023) 'Vegetation patch dynamics in rangelands: How feedbacks between large herbivores, vegetation and soil fauna alter patches over space and through time.' *Applied Vegetation Science*, 26(4) p. e12747.

Smith, E. and Morowitz, H. J. (2016) *The Origin and Nature of Life on Earth: The Emergence of the Fourth Geosphere*. Cambridge: Cambridge University Press.

Snakin, V. V. and Dubinin, A. G. (1980) 'Use of the oxidation potential of soils for the thermodynamic characterization of the biogeocenotic processes.' *Doklady Academii Nauk SSSR*, 252(2) pp. 464–466.

Snakin, V. V., Prisyazhnaya, A. and Kovács-Láng, E. (2001) *Soil liquid phase composition*. Elsevier.

Soares, M. and Rousk, J. (2019) 'Microbial growth and carbon use efficiency in soil: links to fungal-bacterial dominance, SOC-quality and stoichiometry.' *Soil Biology and Biochemistry*. Elsevier, 131 pp. 195–205.

Soares, P. M. M. and Lima, D. C. A. (2022) 'Water scarcity down to earth surface in a Mediterranean climate: The extreme future of soil moisture in Portugal.' *Journal of Hydrology*, 615, December, p. 128731.

Spanbauer, T. L., Allen, C. R., Angeler, D. G., Eason, T., Fritz, S. C., Garmestani, A. S., Nash, K. L., Stone, J. R., Stow, C. A. and Sundstrom, S. M. (2016) 'Body size distributions signal a regime shift in a lake ecosystem.' *Proceedings of the Royal Society B: Biological Sciences*. The Royal Society, 283(1833) p. 20160249.

Sparks, D. L. (2001) 'Elucidating the fundamental chemistry of soils: past and recent achievements and future frontiers.' *Geoderma*. Elsevier, 100(3–4) pp. 303–319.

Srivastava, P. K., Han, D., Rico Ramirez, M. A. and Islam, T. (2013) 'Appraisal of SMOS soil moisture at a catchment scale in a temperate maritime climate.' *Journal of Hydrology*, 498, August, pp. 292–304.

Steffen, W., Broadgate, W., Deutsch, L., Gaffney, O. and Ludwig, C. (2015) 'The trajectory of the Anthropocene: The Great Acceleration.' *The Anthropocene Review*. SAGE Publications, 2(1) pp. 81–98.

Steinberg, D. A., Pouyat, R. V., Parmelee, R. W. and Groffman, P. M. (1997) 'Earthworm abundance and nitrogen mineralization rates along an urban-rural land use gradient.' *Soil Biology and Biochemistry*. (5th International Symposium on Earthworm Ecology), 29(3) pp. 427–430.

Sterner, R. W. and Elser, J. J. (2002) *Ecological Stoichiometry: The Biology of Elements from Molecules to the Biosphere*. Princeton University Press.

Stone, D., Ritz, K., Griffiths, B. G., Orgiazzi, A. and Creamer, R. E. (2016) 'Selection of biological indicators appropriate for European soil monitoring.' *Applied Soil Ecology*, 97 pp. 12–22.

Stoutjesdijk, P. and Barkman, J. J. (2014) *Microclimate, Vegetation & Fauna*. BRILL.

Stumn, W. (1966) 'Redox potential as an environmental parameter; conceptual significance and operational limitation.' *In*. Munich, pp. 1–16.

Suman, S., Srivastava, P. K., Petropoulos, G. P., Pandey, D. K. and O'Neill, P. E. (2020) 'Appraisal of SMAP Operational Soil Moisture Product from a Global Perspective.' *Remote Sensing*. Multidisciplinary Digital Publishing Institute, 12(12) p. 1977.

Sundstrom, S. M. (2009) 'The textural discontinuity hypothesis and its relationship to biodiversity, extinction risk, and ecosystem resilience.' *University of Calgary*.

Sundstrom, S. M. and Allen, C. R. (2019) 'The adaptive cycle: More than a metaphor.' *Ecological Complexity*, 39, 08-01, p. 100767.

Svirezhev, Y. M. (2000) 'Thermodynamics and ecology.' *Ecological Modelling*, 132(1) pp. 11–22.

Swenson, R. (1989) 'Emergent attractors and the law of maximum entropy production: Foundations to a theory of general evolution.' *Systems Research*, 6(3) pp. 187–197.

Tang, C. and Chen, D. (2017) 'Interaction between Soil Moisture and Air Temperature in the Mississippi River Basin.' *Journal of water resource and protection*, 9(10) pp. 1119–1131.

Tang, D., Zou, X., Liu, X., Liu, P., Zhamangulova, N., Xu, X. and Zhao, Y. (2015) 'Integrated ecosystem health assessment based on eco-exergy theory: A case study of the Jiangsu coastal area.' *Ecological Indicators*, 48, January, pp. 107–119.

Tano, B. F., Brou, C. Y., Dossou-Yovo, E. R., Saito, K., Futakuchi, K., Wopereis, M. C. S. and Husson, O. (2020) 'Spatial and Temporal Variability of Soil Redox Potential, pH and Electrical Conductivity across a Toposequence in the Savanna of West Africa.' *Agronomy*. Multidisciplinary Digital Publishing Institute, 10(11) p. 1787.

Tapia-Báez, R. G. (2015) 'Diversidad de Escarabajos Copronecrófagos y Estado de Consevación de la Microcuenca del Río Pindo.' *Universisdad Tecnológica Equinoccial: Quito, Ecuador*.

Tfaily, M. M., Chu, R. K., Tolić, N., Roscioli, K. M., Anderton, C. R., Paša-Tolić, L., Robinson, E. W. and Hess, N. J. (2015) 'Advanced solvent based methods for molecular characterization of soil organic matter by high-resolution mass spectrometry.' *Analytical chemistry*. ACS Publications, 87(10) pp. 5206–5215.

Tiedemann, A. R. and Klemmedson, J. O. (1986) 'Long-term Effects of Mesquite Removal on Soil Characteristics: I. Nutrients and Bulk Density.' *Soil Science Society of America Journal*, 50(2) pp. 472–475.

Tiezzi, E., Pulselli, R. and Tiezzi, E. (2007) 'Mathematical modelling applied to ecosystems: the Gödel's theorem.' *In*, pp. 55–59.

Tittonell, P., Vanlauwe, B., Corbeels, M. and Giller, K. E. (2008) 'Yield gaps, nutrient use efficiencies and response to fertilisers by maize across heterogeneous smallholder farms of western Kenya.' *Plant and Soil*, 313(1) pp. 19–37.

Tóth, G., Hermann, T., da Silva, M. R. and Montanarella, L. (2018) 'Monitoring soil for sustainable development and land degradation neutrality.' *Environmental Monitoring and Assessment*, 190(2) p. 57.

Tribouillois, H., Fort, F., Cruz, P., Charles, R., Flores, O., Garnier, E. and Justes, E. (2015a) 'A Functional Characterisation of a Wide Range of Cover Crop Species: Growth and Nitrogen Acquisition Rates, Leaf Traits and Ecological Strategies.' *PLoS ONE*, 10, March, pp. 1–17.

Tribouillois, H., Fort, F., Cruz, P., Charles, R., Flores, O., Garnier, E. and Justes, E. (2015b) 'A Functional Characterisation of a Wide Range of Cover Crop Species: Growth and Nitrogen Acquisition Rates, Leaf Traits and Ecological Strategies.' *PLoS ONE*, 10, March, pp. 1–17.

Turing, A. M. (1952) 'The chemical basis of morphogenesis.' *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences*. Royal Society, 237(641) pp. 37–72.

Turner, B. (2021) 'Soil as an Archetype of Complexity: A Systems Approach to Improve Insights, Learning, and Management of Coupled Biogeochemical Processes and Environmental Externalities.' *Soil Systems*, 5, July.

Twining, J. R., Zaw, M., Russell, R. and Wilde, K. (2004) 'Seasonal changes of redox potential and microbial activity in two agricultural soils of tropical Australia: some implications for soil-to-plant transfer of radionuclides.' *Journal of Environmental Radioactivity*. (South Pacific Environmental Radioactivity Association: 2002 Conference), 76(1) pp. 265–272.

UDES, Population Division (2015) 'World Population Prospects: The 2015 Revision, Key Findings and Advance Tables' p. Working Paper No. ESA/P/WP.241.

Ulanowicz, R. (2000) 'Ascendency: A measure of ecosystem performance.' *In A handbook of Eco-system Theories and Management*. Boca Raton: Lewis Publishers, pp. 303–315.

Ulanowicz, R. (2006) 'Process Ecology: A Transactional Worldview.' *International Journal of Ecodynamics*, 1, January, pp. 114–125.

Ulanowicz, R. (2007) 'Ecosystems Becoming.' *International Journal of Ecodynamics*, 2, November, pp. 153–164.

Ulanowicz, R. (2011) 'Process and ontological priorities in evolution.' *In*, pp. 321–336.

Ulanowicz, R. E. (1995) 'Utricularia's secret: the advantage of positive feedback in oligotrophic environments.' *Ecological Modelling*, 79(1) pp. 49–57.

Ulanowicz, R. E. (1997) *Ecology, the Ascendent Perspective*. Columbia University Press.

Ulanowicz, R. E. (1999) 'Life after Newton: an ecological metaphysic.' *Biosystems*, 50(2) pp. 127–142.

Ulanowicz, R. E. (2004) 'On the nature of ecodynamics.' *Ecological Complexity*, 1(4) pp. 341–354.

Ulanowicz, R. E. (2009a) *A Third Window: Natural Life Beyond Newton and Darwin*. Illustrated edition, West Conshohocken, Pa: Templeton Foundation Press,U.S.

Ulanowicz, R. E. (2009b) 'Increasing entropy: heat death or perpetual harmonies?' *International Journal of Design & Nature and Ecodynamics*, 4(2) pp. 83–96.

Ulanowicz, R. E. (2009c) 'The dual nature of ecosystem dynamics.' *Ecological Modelling*, 220(16) pp. 1886–1892.

Ulanowicz, R. E. (2012) *Growth and Development: Ecosystems Phenomenology*. Springer Science & Business Media.

Ulanowicz, R. E. (2014) 'Reckoning the nonexistent: Putting the science right.' *Ecological Modelling*, 293 pp. 22–30.

Ulanowicz, R. E. (2016) 'Process Ecology: Philosophy Passes into Praxis.' *Process Studies*. University of Illinois Press, 45(2) pp. 199–222.

Ulanowicz, R. E. (2018) 'Dimensions Missing from Ecology.' *Philosophies*. Multidisciplinary Digital Publishing Institute, 3(3) p. 24.

Ulanowicz, R. E. (2019) 'The tripartite nature of causalities in ecosystem dynamics.' *Current Opinion in Systems Biology*, 13 pp. 129–135.

Ulanowicz, R. E. (2020) 'Quantifying sustainable balance in ecosystem configurations.' *Current Research in Environmental Sustainability*, 1 pp. 1–6.

Ulanowicz, R. E. and Abarca-Arenas, L. G. (1997) 'An informational synthesis of ecosystem structure and function.' *Ecological Modelling*, 95(1) pp. 1–10.

Ulanowicz, R. E. and Hannon, B. M. (1987) 'Life and the production of entropy.' *Proceedings of the Royal society of London. Series B. Biological sciences*. The Royal Society London, 232(1267) pp. 181–192.

Ulanowicz, R. E., Jørgensen, S. E. and Fath, B. D. (2006) 'Exergy, information and aggradation: An ecosystems reconciliation.' *Ecological Modelling*, 198(3–4) pp. 520–524.

Ulgiati, S. and Brown, M. (2009) 'Emergy and ecosystem complexity.' *Communications in Nonlinear Science and Numerical Simulation*, 14, January, pp. 310–321.

Valero, Antonio, Palacino, B., Ascaso, S. and Valero, Alicia (2022) 'Exergy assessment of topsoil fertility.' *Ecological Modelling*, 464, February, p. 109802.

Valin, H., Sands, R. D., Van der Mensbrugghe, D., Nelson, G. C., Ahammad, H., Blanc, E., Bodirsky, B., Fujimori, S., Hasegawa, T. and Havlik, P. (2014) 'The future of food demand: understanding differences in global economic models.' *Agricultural Economics*. Wiley Online Library, 45(1) pp. 51–67.

Vallejo-Quintero, V. E. (2013) 'IMPORTANCIA Y UTILIDAD DE LA EVALUACIÓN DE LA CALIDAD DE SUELOS MEDIANTE EL COMPONENTE MICROBIANO: EXPERIENCIAS EN SISTEMAS SILVOPASTORILES.' *Colombia Forestal*. Facultad del Medio Ambiente y Recursos Naturales, Universidad Distrital Francisco José de Caldas., 16(1) pp. 83–99.

Vallino, J. J. and Algar, C. K. (2016) 'The Thermodynamics of Marine Biogeochemical Cycles: Lotka Revisited.' *Annual Review of Marine Science*, 8(1) pp. 333–356.

Van Wijk, W. R. and De Vries, D. A. (1963) 'Periodic temperature variations in a homogeneous soil.' *Physics of plant environment*. North-Holland Amsterdam, 1 pp. 103–143.

Vasas, V., Fernando, C., Santos, M., Kauffman, S. and Szathmáry, E. (2012) 'Evolution before genes.' *Biology Direct*, 7(1) p. 1.

Vasas, V., Szathmáry, E. and Santos, M. (2010) 'Lack of evolvability in self-sustaining autocatalytic networks constraints metabolism-first scenarios for the origin of life.' *Proceedings of the National Academy of Sciences*. National Academy of Sciences, 107(4). Biological Sciences pp. 1470–1475.

Védère, C., Lebrun, M., Honvault, N., Aubertin, M.-L., Girardin, C., Garnier, P., Dignac, M.-F., Houben, D. and Rumpel, C. (2022) 'How does soil water status influence the fate of soil organic matter? A review of processes across scales.' *Earth-Science Reviews*, 234, November, p. 104214.

Veldhuis, M. P., Berg, M. P., Loreau, M. and Olff, H. (2018) 'Ecological autocatalysis: a central principle in ecosystem organization?' *Ecological Monographs*, 88(3) pp. 304–319.

Verheijen, F. G. A., Jones, R. J. A., Rickson, R. J. and Smith, C. J. (2009) 'Tolerable versus actual soil erosion rates in Europe.' *Earth-Science Reviews*, 94(1) pp. 23–38.

Verhoef, H. A. and Morin, P. J. (2010) *Community Ecology: Processes, Models, and Applications*. Oxford University Press.

Vermeulen, S. J., Campbell, B. M. and Ingram, J. S. I. (2012) 'Climate Change and Food Systems.' *Annual Review of Environment and Resources*, 37(1) pp. 195–222.

Vihervaara, P., Franzese, P. P. and Buonocore, E. (2019) 'Information, energy, and eco-exergy as indicators of ecosystem complexity.' *Ecological Modelling*, 395, March, pp. 23–27.

Vincent, S. G. T., Jennerjahn, T. and Ramasamy, K. (2021) 'Chapter 3 - Environmental variables and factors regulating microbial structure and functions.' *In* Vincent, S. G. T., Jennerjahn, T., and Ramasamy, K. (eds) *Microbial Communities in Coastal Sediments*. Elsevier, pp. 79–117.

Violle, C., Navas, M.-L., Vile, D., Kazakou, E., Fortunel, C., Hummel, I. and Garnier, E. (2007) 'Let the concept of trait be functional!' *Oikos*. Wiley Online Library, 116(5) pp. 882–892.

Virgo, N. and Harvey, I. (2007) 'Entropy Production in Ecosystems.' *In* Almeida e Costa, F., Rocha, L. M., Costa, E., Harvey, I., and Coutinho, A. (eds) *Advances in Artificial Life*. Berlin, Heidelberg: Springer (Lecture Notes in Computer Science), pp. 123–132.

Vitousek, S., Buscombe, D., Vos, K., Barnard, P. L., Ritchie, A. C. and Warrick, J. A. (2023) 'The future of coastal monitoring through satellite remote sensing.' *Cambridge Prisms: Coastal Futures*, 1, January, p. e10.

Vlieghe, K. and Picker, M. (2019) 'Do high soil temperatures on Namibian fairy circle discs explain the absence of vegetation?' *PLOS ONE*. Public Library of Science, 14(5) p. e0217153.

Vopravil, J., Formánek, P., Heřmanovská, D., Khel, T. and Jacko, K. (2022) 'The impact of agricultural land afforestation on air temperatures near the surface.' *Journal of Forest Science*. Journal of Forest Science, 68(12) pp. 485–495.

Vos, V. C. A., Ruijven, J. van, Berg, M. P., Peeters, E. T. H. M. and Berendse, F. (2011) 'Macro-detritivore identity drives leaf litter diversity effects.' *Oikos*, 120(7) pp. 1092–1098.

Wall, D. H., Nielsen, U. N. and Six, J. (2015) 'Soil biodiversity and human health.' *Nature*, 528(7580) pp. 69–76.

Wang, A. and Shi, X. (2019) 'A multilayer soil moisture dataset based on the gravimetric method in China and its characteristics.' *Journal of Hydrometeorology*. American Meteorological Society, 20(8) pp. 1721–1736.

Wang, C., Zhao, C., Xu, Z., Wang, Y. and Peng, H. (2013) 'Effect of vegetation on soil water retention and storage in a semi-arid alpine forest catchment.' *Journal of Arid Land*, 5(2) pp. 207–219.

Wang, J., Lu, H., Lin, Y., Campbell, D. E., Cai, H. and Ren, H. (2021) 'Dynamics of community structure and bio-thermodynamic health of soil organisms following subtropical forest succession.' *Journal of Environmental Management*, 280, February, p. 111647.

Wang, J., Zhen, J., Hu, W., Chen, S., Lizaga, I., Zeraatpisheh, M. and Yang, X. (2023) 'Remote sensing of soil degradation: Progress and perspective.' *International Soil and Water Conservation Research*, March.

Wang, L., Delgado-Baquerizo, M., Zhao, X., Zhang, M., Song, Y., Cai, J., Chang, Q., Li, Z., Chen, Y., Liu, J., Zhu, H., Wang, D., Han, G., Liang, C., Wang, C. and Xin, X. (2020) 'Livestock overgrazing disrupts the positive associations between soil biodiversity and nitrogen availability.' *Functional Ecology*, 34(8) pp. 1713–1720.

Wang, Y., Zhang, Y., Yu, X., Jia, G., Liu, Z., Sun, L., Zheng, P. and Zhu, X. (2021) 'Grassland soil moisture fluctuation and its relationship with evapotranspiration.' *Ecological Indicators*, 131, November, p. 108196.

Wardwell, D. A., Allen, C. R., Peterson, G. D. and Tyre, A. J. (2008) 'A test of the cross-scale resilience model: functional richness in Mediterranean-climate ecosystems.' *Ecological Complexity*. Elsevier, 5(2) pp. 165–182.

Weigelt, J., Müller, A., Beckh, C. and Töpfer, K. (2014) *Soils in the Nexus. A Crucial Resource for Water, Energy and Food Security*. oekom verlag.

Weil, R. and Brady, N. (2017) *The Nature and Properties of Soils. 15th edition*.

Whitham, T. G., Bailey, J. K., Schweitzer, J. A., Shuster, S. M., Bangert, R. K., LeRoy, C. J., Lonsdorf, E. V., Allan, G. J., DiFazio, S. P., Potts, B. M., Fischer, D. G., Gehring, C. A., Lindroth, R. L., Marks, J. C., Hart, S. C., Wimp, G. M. and Wooley, S. C. (2006) 'A framework for community and ecosystem genetics: from genes to ecosystems.' *Nature Reviews Genetics*. Nature Publishing Group, 7(7) pp. 510–523.

Wiener, N. (1961) *Cybernetics Or Control and Communication in the Animal and the Machine*. MIT Press.

van Wijk, W. R., Larson, W. E. and Burrows, W. C. (1959) 'Soil Temperature and the Early Growth of Corn from Mulched and Unmulched Soil.' *Soil Science Society of America Journal*, 23(6) pp. 428–434.

Willett, W., Rockström, J., Loken, B., Springmann, M., Lang, T., Vermeulen, S., Garnett, T., Tilman, D., DeClerck, F., Wood, A., Jonell, M., Clark, M., Gordon, L. J., Fanzo, J., Hawkes, C., Zurayk, R., Rivera, J. A., Vries, W. D., Sibanda, L. M., Afshin, A., Chaudhary, A., Herrero, M., Agustina, R., Branca, F., Lartey, A., Fan, S., Crona, B., Fox, E., Bignet, V., Troell, M., Lindahl, T., Singh, S., Cornell, S. E., Reddy, K. S., Narain, S., Nishtar, S. and Murray, C. J. L. (2019) 'Food in the Anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems.' *The Lancet*. Elsevier, 393(10170) pp. 447–492.

Williford, K., Grice, K., Holman, A. and Mcelwain, J. (2014) 'An organic record of terrestrial ecosystem collapse and recovery at the Triassic–Jurassic boundary in East Greenland.' *Geochimica et Cosmochimica Acta*, 127, February, pp. 251–263.

Wilmoth, J. L. (2021) 'Redox Heterogeneity Entangles Soil and Climate Interactions.' *Sustainability*. Multidisciplinary Digital Publishing Institute, 13(18) p. 10084.

Woods, J., Williams, A., Hughes, J. K., Black, M. and Murphy, R. (2010) 'Energy and the food system.' *Philosophical Transactions of the Royal Society B: Biological Sciences*, 365(1554) pp. 2991–3006.

Woolley, T. E., Baker, R. E. and Maini, P. K. (2017) 'Turing's Theory of Morphogenesis: Where We Started, Where We Are and Where We Want to Go.' *In* Cooper, S. B. and Soskova, M. I. (eds) *The Incomputable: Journeys Beyond the Turing Barrier*. Cham: Springer International Publishing (Theory and Applications of Computability), pp. 219–235.

Wu, Z., Wu, X., Yang, Z. and Ouyang, L. (2017) 'A simple thermodynamic model for evaluating the ecological restoration effect on a manganese tailing wasteland.' *Ecological Modelling*, 346, February, pp. 20–29.

Xu, C., Qu, J. J., Hao, X., Zhu, Z. and Gutenberg, L. (2020) 'Surface soil temperature seasonal variation estimation in a forested area using combined satellite observations and in-situ measurements.' *International Journal of Applied Earth Observation and Geoinformation*, 91 p. 102156.

Xu, F., Yang, Z. F., Chen, B. and Zhao, Y. W. (2011) 'Ecosystem health assessment of the plant-dominated Baiyangdian Lake based on eco-exergy.' *Ecological Modelling*, 222(1) pp. 201–209.

Xu, Z., Wu, Z., He, H., Guo, X. and Zhang, Y. (2021) 'Comparison of soil moisture at different depths for drought monitoring based on improved soil moisture anomaly percentage index.' *Water Science and Engineering*, 14(3) pp. 171–183.

Yang, Z., Liu, X., Zhou, M., Ai, D., Wang, G., Wang, Y., Chu, C. and Lundholm, J. T. (2015) 'The effect of environmental heterogeneity on species richness depends on community position along the environmental gradient.' *Scientific Reports*, 5, October, p. 15723.

Yarrow, M. M. and Salthe, S. N. (2008) 'Ecological boundaries in the context of hierarchy theory.' *Biosystems*, 92(3) pp. 233–244.

Yildiz, C., Bilgin, V. A., Yılmaz, B. and Özilgen, M. (2020) 'Organisms live at far-from-equilibrium with their surroundings while maintaining homeostasis, importing exergy and exporting entropy.' *International Journal of Exergy*. Inderscience Publishers, 31(3) pp. 287–301.

Yin, J., Zhan, X., Hain, C. R., Liu, J. and Anderson, M. C. (2018) 'A method for objectively integrating soil moisture satellite observations and model simulations toward a blended drought index.' *Water Resources Research*. Wiley Online Library, 54(9) pp. 6772–6791.

Yizhaq, H. and Bel, G. (2016) 'Effects of quenched disorder on critical transitions in pattern-forming systems.' *New Journal of Physics*. IOP Publishing, 18(2) p. 023004.

Yizhaq, H., Stavi, I., Swet, N., Zaady, E. and Katra, I. (2019) 'Vegetation ring formation by water overland flow in water-limited environments: Field measurements and mathematical modelling.' *Ecohydrology*, 12(7) p. e2135.

Yuan, A., Kumar, S. D., Wang, Haotian, Wang, S., Impa, S., Wang, Hao, Guo, J., Wang, Y., Yang, Q., Liu, X. J. A., Jagadish SV, K. and Shao, R. (2024) 'Dynamic interplay among soil nutrients, rhizosphere metabolites, and microbes shape drought and heat stress responses in summer maize.' *Soil Biology and Biochemistry*, 191, April, p. 109357.

Yuan, K., Zhu, Q., Zheng, S., Zhao, L., Chen, M., Riley, W. J., Cai, X., Ma, H., Li, F., Wu, H. and Chen, L. (2021) 'Deforestation reshapes land-surface energy-flux partitioning.' *Environmental Research Letters*. IOP Publishing, 16(2) p. 024014.

Yuan, X., Ma, Z., Pan, M. and Shi, C. (2015) 'Microwave remote sensing of short-term droughts during crop growing seasons.' *Geophysical Research Letters*. Wiley Online Library, 42(11) pp. 4394–4401.

Zabel, R. A. and Morrell, J. J. (2020) 'Chapter Six - The decay setting: Some structural, chemical, and moisture features of wood features of wood in relation to decay development.' *In* Zabel, R. A. and Morrell, J. J. (eds) *Wood Microbiology (Second Edition)*. San Diego: Academic Press, pp. 149–183.

Zaccarelli, N., Petrosillo, I. and Zurlini, G. (2008) 'Retrospective Analysis.' *In* Jørgensen, S. E. and Fath, B. D. (eds) *Encyclopedia of Ecology*. Oxford: Academic Press, pp. 3020–3029.

Zaikin, A. N. and Zhabotinsky, A. M. (1970) 'Concentration Wave Propagation in Two-dimensional Liquid-phase Self-oscillating System.' *Nature*. Nature Publishing Group, 225(5232) pp. 535–537.

Zari, M. P. (2017) '1 - Utilizing relationships between ecosystem services, built environments, and building materials.' *In* Petrović, E. K., Vale, B., and Zari, M. P. (eds) *Materials for a Healthy, Ecological and Sustainable Built Environment*. Woodhead Publishing (Woodhead Publishing Series in Civil and Structural Engineering), pp. 3–27.

Zelnik, Y. R., Meron, E. and Bel, G. (2015) 'Gradual regime shifts in fairy circles.' *Proceedings of the National Academy of Sciences*. National Academy of Sciences, 112(40). Physical Sciences pp. 12327–12331.

Zhabotinsky, A. M. (1964) '"Периодический процесс окисления малоновой кислоты растворе" [Periodical process of oxidation of malonic acid solution].' *Биофизика*, (9) pp. 306–311.

Zhang, B., Jin, P., Qiao, H., Hayat, T., Alsaedi, A. and Ahmad, B. (2019) 'Exergy analysis of Chinese agriculture.' *Ecological Indicators*, 105, October, pp. 279–291.

Zhang, C., Wang, Y., Jia, X., Shao, M. and An, Z. (2020) 'Impacts of shrub introduction on soil properties and implications for dryland revegetation.' *Science of The Total Environment*, 742, November, p. 140498.

Zhang, H., Wang, E., Zhou, D., Luo, Z. and Zhang, Z. (2016) 'Rising soil temperature in China and its potential ecological impact.' *Scientific Reports*, 6(1) p. 35530.

Zhang, Hao, Jiang, N., Zhang, S., Zhu, X., Wang, H., Xiu, W., Zhao, J., Liu, H., Zhang, Haifang and Dianlin, Y. (2024) 'Soil bacterial community composition is altered more by soil nutrient availability than pH following long-term nutrient addition in a temperate steppe.' *Frontiers in Microbiology*, 15, September.

Zhang, J., Gurkan, Z. and Jørgensen, S. E. (2010) 'Application of eco-exergy for assessment of ecosystem health and development of structurally dynamic models.' *Ecological Modelling*, 221(4) pp. 693–702.

Zhang, Y., Parazoo, N. C., Williams, A. P., Zhou, S. and Gentine, P. (2020) 'Large and projected strengthening moisture limitation on end-of-season photosynthesis.' *Proceedings of the National Academy of Sciences*. National Acad Sciences, 117(17) pp. 9216–9222.

Zhang, Y., Wang, H., Cai, Y., Yang, Q. and Lv, G. (2022) 'Fertile Island Effect by Three Typical Woody Plants on Wetlands of Ebinur Lake, northwestern China.' *Frontiers in Environmental Science*. Frontiers, 10, November.

Zhang, Z., Pan, Z., Pan, F., Zhang, J., Han, G., Huang, N., Wang, J., Pan, Y., Wang, Z. and Peng, R. (2020) 'The Change Characteristics and Interactions of Soil Moisture and Temperature in the Farmland in Wuchuan County, Inner Mongolia, China.' *Atmosphere*. Multidisciplinary Digital Publishing Institute, 11(5) p. 503.

Zhao, L., Gao, X., He, N. and Zhao, X. (2022) 'Ecohydrological advantage of young apple tree-based agroforestry and its response to extreme droughts on the semiarid Loess Plateau.' *Agricultural and Forest Meteorology*, 321, June, p. 108969.

Zhou, M., Liu, C., Wang, J., Meng, Q., Yuan, Y., Ma, X., Liu, X., Zhu, Y., Ding, G., Zhang, J., Zeng, X. and Du, W. (2020) 'Soil aggregates stability and storage of soil organic carbon respond to cropping systems on Black Soils of Northeast China.' *Scientific Reports*, 10, January, p. 265.

Zhou, P. and Ang, B. W. (2008) 'Indicators for assessing sustainability performance.' *Handbook of performability engineering*. Springer pp. 905–918.

Zorach, A. C. and Ulanowicz, R. E. (2003) 'Quantifying the complexity of flow networks: How many roles are there?' *Complexity*, 8(3) pp. 68–76.

Zotin, A. I. (1990) *Thermodynamic Bases of Biological Processes: Physiological Reactions and Adaptations*. *Thermodynamic Bases of Biological Processes*. De Gruyter.

Appendix A - Summary statistics and data anlaysis of 'Temperature indices of growth phase for controlled experiments'

Figure 16

Sensor	2021-05-01	2021-05-02	2021-05-03	2021-05-04	2021-05-05	2021-05-06	2021-05-07	2021-05-08	2021-05-09	2021-05-10	2021-05-11	2021-05-12	2021-05-13	2021-05-14	2021-05-15	2021-05-16	2021-05-17	2021-05-18	2021-05-19	2021-05-20
C1	15.98632653	14.110612	13.453061	18.187347	14.643265	17.864898	14.933265	13.474694	22.211224	22.267959	19.620408	23.196939	16.52	14.862755	14.812245	17.952449	16.012857	17.362245	18.512653	14.168878
C2	15.11326531	13.161224	13.13	15.554694	13.446531	15.448163	13.566735	13.118776	20.063878	20.409796	18.467551	17.753878	16.20551	14.371327	14.549796	16.888367	15.174898	16.132653	17.238571	13.672653
C3	12.25571429	13.931429	13.164898	13.778571	14.002857	14.164286	14.453265	12.847143	20.733469	20.619184	18.682449	19.373469	15.806327	13.959592	14.247143	17.271224	14.645714	15.933673	17.152041	13.526531
C4	15.25	13.604694	13.22449	15.749388	14.278367	15.949796	13.791429	13.112857	19.977959	20.265918	18.047347	21.599184	16.08	14.235102	14.410612	16.638163	15.184082	14.958571	17.336735	13.378367
C5	11.84265306	14.049592	13.22	15.168776	14.933469	16.406122	14.35102	12.532449	21.989592	21.598776	20.133673	19.472653	14.899796	13.971224	14.276531	17.925306	14.65	16.759592	17.442857	13.587347
C6	13.8244898	12.422449	12.81898	14.967551	12.801224	14.439184	12.999796	12.729592	19.705102	19.93449	17.580408	17.66551	15.902245	13.976531	14.202653	16.22102	14.759184	16.812449	16.672245	13.026735
C7	11.70734694	12.967755	12.762653	15.460612	13.358776	15.712653	13.210612	12.943469	20.700408	21.565918	18.126939	21.866327	15.778367	13.837143	14.192857	16.743878	14.504286	14.842857	16.707959	13.222449
C8	11.44693878	11.862653	13.18551	13.4306	11.211667	13.614082	11.862959	12.993469	20.149184	20.339388	18.015306	17.888776	15.967347	14.015714	14.299796	16.929184	14.843265	14.391837	16.224898	13.457755
L&M1	14.92469388	13.710408	12.876531	16.394898	13.849184	16.979388	18.068571	13.100204	21.986531	21.555102	18.895714	22.553673	15.114286	14.211429	14.312653	17.586735	15.125918	16.86102	17.127551	13.811837
L&M2	14.61	12.798571	13.021837	15.198163	13.216735	17.023469	16.139592	13.04	20.378571	21.386122	19.656327	21.978776	15.996939	14.164694	14.268367	17.205714	15.106735	15.592857	17.106531	13.44398
L&M3	15.77938776	10.846327	12.898163	14.36449	11.736939	13.976122	14.128163	12.669184	18.551633	19.363469	16.582041	19.562449	15.315306	14.193265	13.765102	15.976735	14.663878	14.640816	15.822653	13.124898
L&M4	13.90836735	11.89449	12.537959	14.797347	13.182449	15.002653	15.00898	12.969184	19.476122	20.310408	17.538367	20.937551	15.655306	14.205408	14.16102	16.402653	15.024694	15.84449	17.301837	13.425306
L&M5	13.9477551	12.488367	12.710816	16.470204	13.787755	16.765918	16.332857	12.777347	20.158571	20.992653	19.906122	20.562653	15.712653	13.895918	13.951429	16.166939	16.364286	15.067959	16.183878	12.878163
L&M6	12.10142857	11.986531	12.915102	16.704694	13.889388	17.232449	13.755102	13.148367	21.182245	21.719796	19.824898	22.072857	15.845306	14.135102	14.216735	16.721224	16.500408	15.494082	16.621224	13.641224
L&M7	13.51102041	12.383265	13.343061	15.196939	12.698163	14.882449	14.487347	12.866531	20.526122	20.509184	17.532857	21.201224	15.613878	14.483673	14.17551	16.766122	14.713469	15.830612	16.138163	13.443061
L+1	15.17673469	13.351224	13.491633	15.873265	13.852653	16.740612	17.326531	13.105102	20.687959	21.53	18.406122	22.577347	16.123469	14.32602	14.462449	17.151224	15.755306	16.80102	17.671633	13.806327
L+2	13.99632653	12.463469	13.380612	15.825102	12.583878	15.83551	16.207959	12.692449	20.429184	20.752653	18.869592	21.014286	15.738163	14.072755	15.472245	16.502653	14.739388	15.690816	16.311429	13.514592
L+3	15.39306122	13.451633	13.226122	17.113469	13.820612	15.387755	13.376531	13.232857	20.515714	21.927755	18.070816	21.992857	16.069184	14.40949	14.304082	16.450204	16.713673	15.562449	17.090816	13.412041
L+4	13.11857143	11.31	13.37102	12.850408	12.246939	12.90102	12.844082	12.671837	18.759592	18.77	16.572041	19.618367	15.30102	14.061837	14.683061	15.372245	14.601429	14.50449	15.740204	12.611224
L+5	14.04326531	12.426735	13.14449	16.158367	13.12449	15.618776	15.785306	12.845306	19.732653	20.141837	18.793061	20.050204	15.638571	14.41	13.940204	16.04551	16.459592	15.080408	16.603061	13.267347
L+6	12.42163265	13.650816	13.585714	15.516731	11.4225	10.842157	12.135889	12.656531	21.626735	21.440408	19.887143	22.602245	15.558776	14.229388	14.109184	17.143061	16.194694	16.406327	16.119184	13.343469
L+7	12.87367347	11.472653	13.26	14.023673	12.367143	12.81551	14.012857	13.089796	18.815918	19.592449	16.686327	19.742245	15.490408	13.968367	14.700612	15.531429	15.463878	14.819388	15.432449	12.833469
L+8	14.36428571	13.182449	13.115918	15.414082	13.474694	15.744286	14.576735	12.712041	20.673673	20.615918	19.036939	18.094286	15.829184	13.704694	14.029184	16.989796	14.759388	16.271837	16.878367	13.582857
L1	13.40571429	14.276735	13.666327	17.383673	14.815306	17.903673	14.710612	13.532041	21.957143	22.403265	21.401837	22.912857	16.371224	14.611531	14.722449	17.237143	17.389796	15.734694	17.801429	13.905918
L2	12.38979592	14.241224	13.394694	13.749608	11.933673	10.902979	13.113265	12.713878	21.322245	20.998367	19.327143	19.37449	15.875918	14.060612	14.149388	17.941224	14.877347	17.009184	16.840816	13.722041
L3	13.55693878	11.527143	13.309592	15.41449	12.296122	14.200408	14.696327	12.837755	19.240204	20.083878	17.120204	20.389388	15.569184	14.400816	14.785306	15.700408	15.849796	14.88551	16.142857	13.060408
L4	12.26979592	12.639592	13.169592	13.589184	12.250566	10.410444	13.20398	12.715306	20.536939	20.350612	18.553061	17.247959	15.698776	14.11551	13.879592	16.95898	15.908163	16.389592	15.955306	13.209388
L5	12.1777551	13.587755	13.306735	13.721224	13.65449	16.356531	14.024592	12.791837	21.633265	22.108776	18.908571	18.939388	15.835306	13.740612	14.033673	17.286122	14.746327	16.085714	16.663878	13.373061
M1	14.74040816	13.228163	13.074898	15.766122	14.606939	16.708571	17.964694	13.092449	20.892449	21.900204	19.136327	22.538163	15.370816	14.627755	14.717347	17.599388	15.367959	16.251633	17.882041	14.079184
M2	12.63591837	13.735918	13.096939	17.426939	14.659592	17.299592	14.52898	13.086939	21.938367	22.597551	19.263878	22.820204	16.012245	14.412857	14.43551	17.097551	15.317755	15.636531	17.490816	13.573673
M3	11.44681818	13.531837	12.991224	13.593889	12.09449	10.985385	12.164634	12.537551	21.563265	21.305918	19.658776	17.798776	14.756122	13.849592	14.089796	17.238571	14.427347	16.40551	16.684286	13.389388
M4	14.54755102	12.976327	12.663673	14.998571	13.494286	15.026327	13.793878	12.882653	20.118163	20.243673	18.05102	18.301837	15.85102	14.121122	14.243469	17.033265	15.151633	17.273878	17.148367	13.553265
M5	13.82244898	12.384694	12.806327	14.316122	13.446939	14.518163	15.246531	12.518571	19.466122	19.906939	17.858163	17.801837	15.452041	13.719592	13.906122	16.533673	14.712245	15.309592	16.405714	13.037347
M6	11.90877551	12.706939	12.68449	13.383265	13.034286	15.943061	12.940204	12.84	20.041633	21.051429	18.866939	21.20449	15.472041	13.785306	13.964898	16.379796	16.090408	15.551429	16.668367	13.044286
M7	11.55183673	12.420408	12.897143	13.105962	11.248125	10.631765	11.893444	12.476939	20.571224	20.320612	18.228571	18.737143	14.650204	13.744694	13.83449	17.044286	14.223878	16.194082	16.105306	13.444082
M8	12.90795918	11.876531	12.529184	14.237959	12.676694	14.473061	14.540204	12.539796	19.547959	19.960816	17.753061	20.857143	15.439592	13.523061	13.754694	16.19898	14.381429	15.551224	15.871837	12.986939
Sh1	12.68183673	13.256939	13.267347	13.874074	11.973542	11.1568	13.033182	12.876735	22.24102	21.491429	19.493265	17.758163	14.957347	13.978776	14.279592	17.423469	15.030204	17.770204	17.148776	13.588571
Sh2	16.2344898	14.789796	13.271837	14.879184	13.320612	14.761429	14.652857	13.281224	19.139796	19.506735	16.701429	19.785102	15.546122	14.362551	13.852857	15.757551	15.908571	14.900408	16.042041	13.222041
Sh3	14.92265306	13.362245	13.281224	17.320204	14.139796	16.960816	15.205918	13.318163	21.553469	22.422857	19.345918	22.373061	16.357551	14.40898	14.50449	16.987143	15.4	15.328163	17.275306	13.567143
Sh4	12.63673469	11.291429	12.931837	13.944082	12.233061	13.032653	13.696735	12.75449	18.776531	18.728776	16.676327	19.669388	15.477755	13.931837	13.650816	15.501429	14.44449	14.840816	15.690204	13.037551
Sh5	11.76489796	12.334286	12.91	13.469815	11.246875	10.5546	12.042273	12.623061	20.826531	20.851429	18.888776	17.266327	15.598571	13.727551	14.052653	17.907959	14.316122	16.488367	16.230612	13.386327
Sh6	12.53142857	11.416327	12.116327	14.322857	11.862449	14.369184	14.554898	12.34898	19.392449	19.515102	17.419796	20.201633	15.124082	13.300204	13.490612	15.516735	14.104694	14.71551	15.459592	12.903673
Sub1	14.79734694	12.973878	12.696735	15.593878	13.258367	15.375918	13.488367	13.044082	19.849592	20.133878	18.282449	17.836939	15.94551	14.243265	14.36898	16.804898	14.950408	16.346122	17.668163	13.309388
Sub2	12.22877551	12.760408	13.027755	15.390377	11.596531	10.567755	12.475778	12.830204	21.601429	21.916327	20.133061	20.034082	14.814286	14.008163	14.297551	18.26551	14.748571	17.074082	17.557551	13.792653
Sub3	14.15979592	12.422041	12.743061	16.92898	12.741429	16.109592	14.059796	12.984082	20.883265	21.042245	17.607959	21.57	15.827347	14.27898	14.421633	16.898367	14.979388	15.570408	17.850612	13.619286
Sub4	13.85714286	12.272653	12.929184	15.398367	12.965102	15.33898	15.25449	13.075918	20.443061	20.11551	18.019388	17.196122	15.933061	14.077959	14.396531	16.628776	14.703061	15.262653	16.54449	13.473878
Sub5	12.34897959	12.351633	12.977347	13.729184	14.040556	9.8225	14.144082	12.847143	21.814898	22.046531	19.889796	19.964082	14.788163	13.923878	14.325918	18.688163	14.666122	17.115714	17.512653	13.873878

Average	01-May-21	02-May-21	03-May-21	04-May-21	05-May-21	06-May-21	07-May-21	08-May-21	09-May-21	10-May-21	11-May-21	12-May-21	13-May-21	14-May-21	15-May-21	16-May-21	17-May-21	18-May-21	19-May-21	20-May-21
BSMEAN	13.42834184	13.263801	13.119949	15.287192	13.58452	15.449898	13.646135	12.969056	20.691352	20.875179	18.58426	19.852092	15.894949	14.153673	14.373954	17.071199	14.971786	15.899235	17.160995	13.505089
TI&BJMEAN	14.11180758	12.301137	12.900496	15.589534	13.194373	15.98035	15.41723	12.938688	20.322828	20.833819	18.562332	21.267026	15.607668	14.184213	14.121545	16.689446	15.357055	15.618834	16.614548	13.395496
TI+MEAN	13.92344388	12.663622	13.321939	15.346887	12.861614	14.485703	14.533236	12.87574	20.155179	20.596378	18.290255	20.71148	15.718597	14.147819	14.462628	16.398265	15.585918	15.642092	16.480893	13.296416
TIMEAN	12.76	13.25449	13.369388	14.771636	12.990032	13.954807	13.949755	12.918163	20.937959	21.18898	19.062163	19.772816	15.870082	14.185816	14.314082	17.024776	15.754286	16.020939	16.680857	13.454163
BJMEAN	12.94521452	12.857602	12.842985	14.603604	13.157419	14.448241	14.134071	12.746862	20.517398	20.910893	18.602092	20.007449	15.37551	13.972997	14.118291	16.890689	14.959082	16.021735	16.782092	13.38852
ShMEAN	13.4620068	12.741837	12.963095	14.635036	12.462723	13.47258	13.86431	12.867109	20.321633	20.419388	18.087585	19.508946	15.510238	13.95165	13.971837	16.515714	14.867347	15.673912	16.307755	13.284218
SubMEAN	13.47840816	12.556122	12.874816	15.408157	12.920397	13.442949	13.884502	12.956286	20.918449	21.050898	18.786531	19.320245	15.461673	14.106449	14.362122	17.457143	14.80951	16.273796	17.426694	13.613816
Ambient	6.5	7.8	8.9	9	6.6	6.6	8.7	11.4	15.1	12.7	11.7	11.9	10.7	9.6	10.2	10.8	11.4	10.9	11.5	10.5

Standard Deviatior	2021-05-01	2021-05-02	2021-05-03	2021-05-04	2021-05-05	2021-05-06	2021-05-07	2021-05-08	2021-05-09	2021-05-10	2021-05-11	2021-05-12	2021-05-13	2021-05-14	2021-05-15	2021-05-16	2021-05-17	2021-05-18	2021-05-19	2021-05-20
BSMEAN	1.83750103	0.8164159	0.2256943	1.4424789	1.1898993	1.3685287	0.9724485	0.2835607	0.9385843	0.8251261	0.8723034	2.1283387	0.4688055	0.333458	0.2129973	0.6114584	0.4870166	1.0719324	0.6828307	0.3386794
TI&BJMEAN	1.166238511	0.880918	0.2512608	0.9222588	0.7783429	1.3196748	1.5190734	0.1756498	1.1129513	0.8343407	1.3377648	1.026809	0.3028297	0.1716853	0.1947656	0.5688835	0.7575196	0.6970195	0.5798199	0.3109342
TI+MEAN	1.065685435	0.9011396	0.1652595	1.3256664	0.8550122	2.041161	1.7882969	0.2320431	0.9887252	1.0644612	1.1515491	1.6129553	0.2822947	0.244134	0.497912	0.698338	0.8296572	0.8123102	0.7338923	0.3945871
TIMEAN	0.664909501	1.1716999	0.1845484	1.6418054	1.2162795	3.2900724	0.7742366	0.3471863	1.0854781	1.0345238	1.5490535	2.089748	0.3050709	0.3340222	0.4133251	0.8233406	1.0597992	0.7886481	0.7241243	0.3526247
BJMEAN	1.30480945	0.6299007	0.2071137	1.4365978	1.1697582	2.4602653	1.9520053	0.260181	0.9013708	0.9785945	0.7198781	2.0954627	0.4721614	0.3804812	0.3289091	0.4746309	0.6359112	0.643184	0.6863047	0.3673485
ShMEAN	1.723719415	1.3320009	0.4494241	1.3986717	1.0657585	2.3959884	1.1779055	0.3783477	1.4215382	1.4041836	1.3084547	1.8373653	0.4863929	0.4132119	0.3830799	1.0569917	0.7012398	1.2155831	0.7511026	0.2802243
SubMEAN	1.138476987	0.2984966	0.14657	1.1365251	0.8882046	2.9923518	1.014446	0.1124738	0.8123683	0.9295432	1.1469499	1.7816832	0.6047207	0.151896	0.0506276	0.9477229	0.1451857	0.8473015	0.5101007	0.2301651

N	2021-05-01	2021-05-02	2021-05-03	2021-05-04	2021-05-05	2021-05-06	2021-05-07	2021-05-08	2021-05-09	2021-05-10	2021-05-11	2021-05-12	2021-05-13	2021-05-14	2021-05-15	2021-05-16	2021-05-17	2021-05-18	2021-05-19	2021-05-20
	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7
	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5

Confidence Limts	2021-05-01	2021-05-02	2021-05-03	2021-05-04	2021-05-05	2021-05-06	2021-05-07	2021-05-08	2021-05-09	2021-05-10	2021-05-11	2021-05-12	2021-05-13	2021-05-14	2021-05-15	2021-05-16	2021-05-17	2021-05-18	2021-05-19	2021-05-20	
	1.273299853	0.565737	0.1563953	0.9995685	0.824543	0.9483246	0.67386	0.1964939	0.6503938	0.5717727	0.6044643	1.4748364	0.3248597	0.2310703	0.1475969	0.4237112	0.3374791	0.7427976	0.4731688	0.2346885	0.59275
	0.863945704	0.6525812	0.1861332	0.6832064	0.5765939	0.9776108	1.1253247	0.1301208	0.8244707	0.6180769	0.9910119	0.7606568	0.2243353	0.1271839	0.1442817	0.421427	0.5611681	0.5163498	0.4295287	0.230339	0.55222
	0.73846876	0.6244464	0.1145169	0.9186231	0.5924823	1.4144264	1.2392038	0.1607947	0.685139	0.7376204	0.7979682	1.1177005	0.1956167	0.1691731	0.345029	0.4839146	0.5749126	0.5628919	0.5085521	0.2734299	0.61275
	0.582808165	1.0270214	0.1617608	1.4390795	1.0660964	2.8838226	0.6786358	0.3043166	0.9514461	0.9067834	1.3577803	1.8317113	0.2674015	0.292778	0.3622888	0.7216766	0.9289379	0.6912678	0.6347112	0.3090835	0.86997
	0.904170203	0.4364909	0.1435198	0.9954932	0.8105862	1.7048455	1.3526458	0.1802929	0.6246066	0.6781189	0.4988409	1.4520549	0.3271852	0.2636552	0.2279182	0.3288964	0.4406559	0.4456956	0.4755761	0.2545548	0.62729
	1.379237444	1.0658031	0.3596076	1.1191499	0.8527687	1.9171548	0.9425034	0.3027356	1.1374465	1.1235603	1.0469626	1.4701714	0.3891882	0.3306323	0.3065221	0.845754	0.5610984	0.9726511	0.6009962	0.224222	0.84741
	0.997900741	0.261639	0.1284719	0.9961898	0.7785313	2.6228638	0.8891848	0.0985858	0.7120591	0.8147656	1.0053274	1.5616855	0.5300513	0.1331403	0.0443762	0.8307005	0.1272586	0.7426788	0.4471148	0.2017449	0.69621

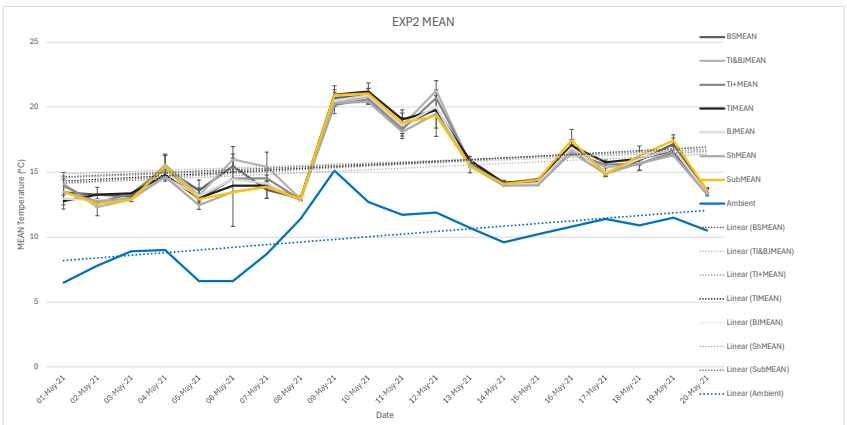
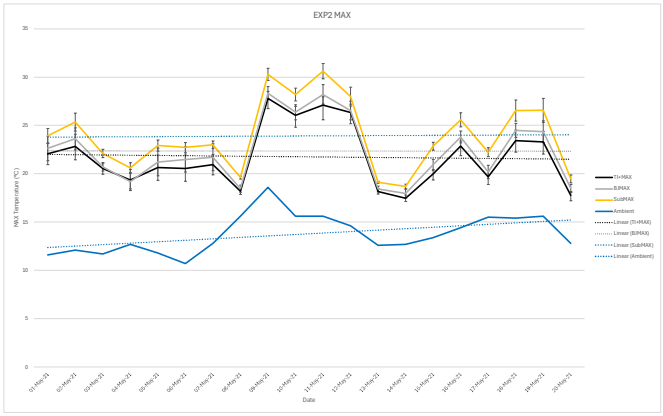


Figure 17

Sensor	2021-05-01	2021-05-02	2021-05-03	2021-05-04	2021-05-05	2021-05-06	2021-05-07	2021-05-08	2021-05-09	2021-05-10	2021-05-11	2021-05-12	2021-05-13	2021-05-14	2021-05-15	2021-05-16	2021-05-17	2021-05-18	2021-05-19	2021-05-20
C1	25.87	27	22.37	22.87	25.69	26.25	25.69	20.06	31.31	29.56	31.75	28.87	19.56	19.62	23.25	26.06	23.44	27.75	29.37	19.81
C2	24.56	24.75	21.56	20.87	23	22.25	23.19	19.25	28.94	27.25	29.12	26.87	19.06	18.62	21.56	24.31	21	24.81	24.75	18.75
C3	23.5	24.87	21.25	18.94	22	20.75	22.06	18.62	28.81	26.75	29	27.81	18.62	18.12	21.75	24.94	21.12	26.12	25.25	18.81
C4	23.87	24.87	21.37	20.69	23.12	22.37	22.31	19.06	28.69	26.69	28.44	26.06	18.87	18.37	21.25	23.62	20.75	24.62	25.81	18.5
C5	23.87	25.44	21.94	19.75	21.81	22.56	21.94	18.94	30.56	28.37	31.19	28.62	18.81	18.56	22.44	26.31	22.06	26.87	25.87	19.56
C6	21.5	22.25	20.37	19.19	20.75	20.31	21.19	18.56	27.62	26.06	27.56	26	18.56	17.81	20.94	23.81	20.75	25.5	23.87	17.81
C7	21.62	23.5	21.5	20.12	21.5	20.62	21.94	19.31	28.5	25.62	26.56	26.56	18.94	18.19	21.31	23.87	20.56	25.87	24.12	18.62
C8	21.94	22.94	21.5	18.5	19.75	19.5	19.81	19.06	28.31	25.69	26.94	26.06	18.75	17.94	21.12	23.81	19.5	22.69	22.44	18.81
L&M1	22.75	24	20.69	19.94	21.25	23.25	21.69	18.69	29.19	27.56	29.19	27.81	18.5	18.37	21.06	24.37	20.62	25.19	25.12	18.94
L&M2	23.56	23.56	20.94	20.12	21.37	22.44	21.62	18.87	28.25	26.56	27.94	27.37	18.75	18.44	21.06	23.81	20.37	24.87	24.19	18.81
L&M3	19.06	19.19	18.56	16.94	17.44	19.06	18.5	17.5	26	24	25.37	24.37	17.69	17.37	19.75	22.19	18.75	21.56	22.5	17.5
L&M4	22.25	22.5	20.31	19.31	20.94	21.44	20.94	18.69	28.12	25.94	27.94	26.12	18.56	18.31	21.19	23.62	21.06	24.81	26.75	18.56
L&M5	21.81	22.44	20.56	20.94	21.06	23.19	21.56	18.69	28.37	27.37	28	27.06	18.5	17.87	20.44	22.94	20.06	22.75	23.44	17.56
L&M6	22	23.75	21.12	19.56	22	21	22.06	19.06	28.12	26.5	27.25	27	18.81	17.94	20.37	22.87	20.12	23.94	23.69	18.25
L&M7	20.12	21.44	20.25	17.44	18.19	18.5	18.81	18.06	27.5	25.37	27.12	25.87	18.12	17.44	20.19	23.12	18.94	22.12	22.75	18.12
L+1	24.5	24.75	21.44	21.62	23.25	23.87	23.44	18.94	29.44	27.69	29.5	27.81	18.81	18.62	21.25	24.5	21.69	25.87	27.06	19.06
L+2	22.56	23.06	20.31	19.5	20.75	21.44	21	17.94	28.25	27.06	28.12	27.5	18.12	17.62	20.25	22.94	19.75	23.44	23.19	18
L+3	24.56	24.94	21	21.06	22.81	22.56	22.69	18.69	28.87	27.69	28.62	28.19	18.69	18.06	20.37	23.06	20.81	23.31	25.06	18.06
L+4	21.5	20.87	19.69	18.44	19.56	18.87	20.06	17.75	26.25	24.25	25.06	24.19	17.75	17	19.06	21.25	18.37	21.62	21.56	16.69
L+5	21.44	22.31	20.31	19.94	20.62	21.5	20.87	18.12	27.75	26.25	27.12	26.5	18.19	17.56	19.81	22.94	20.19	23.19	24.44	17.31
L+6	22	23.37	20.75	18	19.44	19.25	20.12	18	27.62	25.5	26.56	26.19	18.06	17.75	20.31	23.75	19.44	24.5	22.37	18.44
L+7	19.62	20.19	19.69	17.94	18.25	18	18.94	17.94	25.87	23.62	24.19	24.37	17.81	16.69	18.75	21.19	18.31	21.69	21.06	17
L+8	22.75	25.12	21.94	20.62	23	22.06	22.81	18.94	29.94	28	30.12	27.5	18.56	17.62	21.31	25	20.87	26.25	25.44	18.75
L1	24.5	25.56	21.5	20.81	23.81	22.62	24.37	19	28.5	26.87	27.44	27.94	19	18.75	21.06	23.94	21.56	26.19	26.06	18.69
L2	24.56	25.56	21.75	19.06	21.87	21.31	22.06	18.44	28.44	25.94	27.62	27.75	18.44	18.06	20.94	24.87	20.5	25.94	24	18.87
L3	21.81	20.81	19.75	19	18.81	20.62	20.31	17.87	27.19	25.5	26.81	25.44	17.94	17.37	19.5	21.75	19.06	22.12	22.69	17.25
L4	23.69	25.31	21.62	18.31	21.31	20.37	21.81	18.44	27.75	25.12	26.12	27.5	18.25	17.31	19.87	23.31	18.87	24.37	21.69	18.12
L5	22.37	24.94	21.94	19.69	22.37	21.44	22.5	18.81	30.12	28.12	30.12	27.94	18.44	17.56	21	24.87	20.31	25.81	25	18.69
M1	23.5	23.94	21.19	21.25	21.81	24.31	22.69	19.12	29.75	28.06	30.75	28	19.06	19.06	22.06	25.06	21.19	25.06	26.37	19.62
M2	24.31	25.62	21.44	21.06	23.94	23.94	24.69	19.31	29.75	28.12	29.44	28.81	18.94	18.75	21.69	24.19	21.5	25.06	26.19	18.37
M3	25.75	26.19	21.25	18.56	24.44	22.69	24.37	18.44	28.44	25.87	28.12	27.44	18.69	18	21.56	24.75	20.75	26.06	24.87	18.81
M4	22.75	22.87	20.44	19.25	21.25	20.94	21.56	18.56	27.94	26.06	28	26	18.56	18.25	21	23.75	20.87	24.81	25.62	18.62
M5	21.12	22	19.69	18.06	19.44	20.31	20.06	17.87	27.62	25.94	27.75	25.19	17.94	17.56	20.25	23	19.69	23.87	23.06	17.87
M6	21	22.25	20.19	18.69	20.37	19.69	20.62	18.37	27.06	25.06	25.81	25.31	18.19	17.5	20.06	22.37	19.31	24.37	23.56	17.62
M7	22.06	24.06	20.81	17.5	19.62	19.44	19.81	18.19	27.75	25.44	27.44	26.19	18.06	17.56	20.56	23.87	19.25	24.25	22.25	18.69
M8	20.44	21.94	20.62	19	18.81	20.56	19.81	17.87	28.44	26.37	28.37	25.31	18	17.12	20.25	23.37	18.94	22.44	22.87	18.19
Sh1	25.06	26.19	21.5	19.12	23.25	22.37	23.94	18.69	28.75	26.06	28	28	18.44	18.37	21.25	24.75	21.06	26.75	24.31	18.94
Sh2	20.37	19.56	18.75	18.5	17.81	20.5	19.44	17.75	26.5	25	26.25	24.94	17.94	17.37	19.56	22	19.06	21.12	23.25	17.44
Sh3	23.69	25.06	22	21.69	23.81	24	23.62	19.75	30.25	28.31	30.44	28.06	19.56	18.44	21.31	24.19	21.12	24.25	25.81	18.44
Sh4	18.94	19.37	19.12	17.75	18.31	18	18.56	17.81	26.06	24.25	25.69	24.06	17.94	16.94	18.94	21.31	18.56	21.62	21.37	17.12
Sh5	22.19	24.25	21.25	18.19	21	20.81	21.37	18.5	28.87	26.56	28.12	27.5	18.31	17.56	21.25	25	19.75	25	23.06	18.94
Sh6	19.81	21	19.75	18.75	19.31	19.56	19.69	18.25	27.19	25.06	26.25	24.81	17.94	16.87	19.44	21.87	18.81	22.19	21.62	17.81
Sub1	24.06	25	21.5	21.12	23.37	22.69	23.37	19.37	29.37	27.5	29.81	26.94	18.94	18.81	22.12	24.75	22.37	26.56	27	18.87
Sub2	25.31	26.56	22.31	19.69	22.81	22.5	23.12	19.5	30.25	27.69	30.25	28.75	19.25	18.75	23.06	26.06	22.25	27.37	26.62	19.81
Sub3	23.69	24.94	21.69	21.12	23.37	23.75	23.19	19.62	30	28.12	30.25	27.94	19.19	19.06	23.12	25.31	22.87	26.12	28.44	19.31
Sub4	22.94	24	22.25	20.87	21.81	22.44	22.19	19.81	30.44	28.25	30.62	26.87	19.06	18.31	22.69	25	21.37	24.69	24.5	19.31
Sub5	23.56	26.25	22.75	20.19	23.25	22.19	23.06	19.69	31.37	29.44	32.13	29.44	19.12	18.44	23.25	26.81	22.31	27.94	26.31	20.06
Average	01-May-21	02-May-21	03-May-21	04-May-21	05-May-21	06-May-21	07-May-21	08-May-21	09-May-21	10-May-21	11-May-21	12-May-21	13-May-21	14-May-21	15-May-21	16-May-21	17-May-21	18-May-21	19-May-21	20-May-21
BSMAX	23.34125	24.4525	21.4825	20.11625	22.2025	21.82625	22.26625	19.1075	29.0925	26.99875	28.82	27.10625	18.89625	18.40375	21.7025	24.59125	21.1475	25.52875	25.185	18.83375
TI&BJMAX	21.65	22.411429	20.347143	19.178571	20.321429	21.268571	20.74	18.508571	27.935714	26.185714	27.544286	26.514286	18.418571	17.962857	20.58	23.274286	19.988571	23.605714	24.062857	18.2485714
TI+MAX	22.06142857	22.837143	20.527143	19.357143	20.632857	20.525714	20.927143	18.197143	27.792857	26.052857	27.112857	26.348571	18.168571	17.471429	19.98	22.875714	19.677143	23.428571	23.302857	17.75
TIMAX	23.386	24.436	21.312	19.374	21.634	21.272	22.21	18.512	28.4	26.31	27.622	27.314	18.414	17.81	20.474	23.748	20.06	24.886	23.888	18.324
BJMAX	22.61625	23.60875	20.70375	19.17125	21.21	21.485	21.70125	18.46625	28.34375	26.365	28.21	26.53125	18.43	17.975	20.92875	23.795	20.1875	24.49	24.34875	18.47375
ShMAX	21.67666667	22.571667	20.395	19	20.581667	20.873333	21.103333	18.458333	27.936667	25.873333	27.458333	26.228333	18.355	17.591667	20.291667	23.186667	19.726667	23.488333	23.236667	18.115
SubMAX	23.912	25.35	22.1	20.598	22.922	22.714	22.986	19.598	30.286	28.2	30.612	27.988	19.112	18.674	22.848	25.586	22.234	26.536	26.574	19.472
Ambient	11.6	12.1	11.7	12.7	11.8	10.7	12.8	15.6	18.6	15.6	15.6	14.6	12.6	12.7	13.4	14.4	15.5	15.4	15.6	12.8
Standard Deviation									09-May-21	10-May-21	11-May-21	12-May-21	13-May-21	14-May-21	15-May-21	16-May-21	17-May-21	18-May-21	19-May-21	20-May-21
BSMAX	1.548302642	1.5093968	0.5742013	1.3871032	1.7909913	2.1012577	1.6913303	0.4688207	1.2228509	1.3709062	1.8783808	1.1750251	0.3135482	0.5663653	0.7783453	1.0687969	1.1641152	1.5399762	2.0342075	0.62034409
TI&BJMAX	1.550010753	1.6814917	0.8481689	1.4586115	1.7584598	1.8988806	1.4648208	0.5403526	0.9887173	1.2269998	1.17071	1.1628536	0.3907868	0.4374058	0.538145	0.7166788	0.8512819	1.4603066	1.4746493	0.56881246
TI+MAX	1.507276004	1.8762526	0.792185	1.2613447	1.7611144	1.7807101	1.4150114	0.4419168	1.4194449	1.6832282	2.0571721	1.5633663	0.3520146	0.4670628	0.8651589	1.341875	1.0494874	1.6058791	1.7271818	0.76533217
TIMAX	1.247770011	2.042824	0.8883961	0.93975	1.8311417	0.8782767	1.4613521	0.4328626	1.1018847	1.2040349	1.5156253	1.0630522	0.3861088	0.6025363	0.7332667	1.2979291	1.1093016	1.7016257	1.748791	0.66353598
BJMAX	1.827745977	1.6382084	0.5923787	1.3393649	2.0830609	1.9047685	2.0024588	0.5271741	0.9754843	1.1358068	1.4445365	1.3813186	0.4409406	0.6713739	0.7629723	0.8879511	0.9973214	1.0607275	1.614129	0.61872998
ShMAX	2.385168058	2.9628325	1.3620389	1.3986851	2.5368044	2.1042972	2.2664569	0.7333871	1.6141582	1.4493539	1.7702363	1.8157138	0.6289595	0.6813345	1.0919234	1.6372253	1.1283203	2.2040455	1.6675451	0.77531284
SubMAX	0.879526283	1.0472822	0.5042817	0.6344052	0.662963	0.6060776	0.4599239	0.1699117	0.7281689	0.7577269	0.895779	1.1224393	0.1198749	0.3002166	0.457023	0.8428108	0.542107	1.249812	1.4174555	0.4676751
N																				
BSMAX	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
TI&BJMAX	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7
TI+MAX	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7
TIMAX	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
BJMAX	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
ShMAX	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
SubMAX	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
Confidence Limits																				
BSMAX	1.072899276	1.0459394	0.3978939	0.9611958	1.2410709	1.4560705	1.1720106	0.3248702	0.8473769	0.9499721	1.3016275	0.8142359	0.2172739	0.3924639	0.5393559	0.7406248	0.8066759	1.0671295	1.409608	0.42986862
TI&BJMAX	1.148242935	1.2456436	0.6283208	1.0805347	1.3026613	1.4066846	1.0851345	0.4002915	0.7324386	0.9089575	0.8672582	0.8614382	0.2894936	0.3240288	0.398656	0.5309134	0.6306269	1.0817904	1.0924154	0.42137443
TI+MAX	1.116585172	1.3899218	0.5868481	0.9344001	1.3046278	1.3191443	1.0482358	0.3273705	1.0515202	1.24693	1.5239464	1.1581367	0.2607713	0.3459986	0.6409069	0.9940567	0.7774569	1.18963	1.2794907	0.56695559
TIMAX	1.093695854	1.7905813	0.7786116	0.823712	1.605037	0.7698293	1.2809081	0.3794138	0.9658268	1.0553637	1.3284797	0.9317892	0.3384331	0.5281367	0.6427248	1.1376641	0.9723278	1.4915133	1.5328547	0.58160425
BJMAX	1.29654007	1.1351996	0.4104899	0.9281154	1.4434611	1.3199129	1.3876076	0.3653069	0.6759637	0.7870595	1.0009943	0.9571874	0.3055506	0.4652298	0.5287031	0.6153074	0.6910958	0.7350332	1.1185138	0.42875012
ShMAX	1.908496864	2.3707162	1.0898381	1.1191606	2.029829	1.6837575	1.8135099	0.5868211	1.2915718	1.1597033	1.416458	1.4528469	0.5032631	0.5451711	0.8737046	1.310029	0.9028277	1.7635713	1.3342895	0.62036808
SubMAX	0.770926365	0.9179665	0.4420142	0.5560705	0.5811021	0.5312406	0.4031337	0.1489315	0.6382565	0.6641647	0.7851705	0.9838434	0.1050731	0.2631466	0.4005909	0.7387426	0.475169	1.0954884	1.2424317	0.40992777



TI+	BJ	Sub
24.5	23.5	24.06
22.56	24.31	25.31
24.56	25.75	23.69
21.5	22.75	22.94
21.44	21.12	23.56
22	21	25
19.62	22.06	26.56
22.75	20.44	24.94
24.75	23.94	24
23.06	25.62	26.25
24.94	26.19	21.5
20.87	22.87	22.31
22.31	22	21.69
23.37	22.25	22.25
20.19	24.06	22.75
25.12	21.94	21.12
21.44	21.19	19.69
20.31	21.44	21.12
21	21.25	20.87
19.69	20.44	20.19
20.31	19.69	23.37
20.75	20.19	22.81
19.69	20.81	23.37
21.94	20.62	21.81
21.62	21.25	23.25
19.5	21.06	22.69
21.06	18.56	22.5
18.44	19.25	23.75
19.94	18.06	22.44
18	18.69	22.19
17.94	17.5	23.37
20.62	19	23.12
23.25	21.81	23.19
20.75	23.94	22.19
22.81	24.44	23.06
19.56	21.25	19.37
20.62	19.44	19.5
19.44	20.37	19.62
18.25	19.62	19.81
23	18.81	19.69
23.87	24.31	29.37
21.44	23.94	30.25
22.56	22.69	30
18.87	20.94	30.44
21.5	20.31	31.37
19.25	19.69	27.5
18	19.44	27.69
22.06	20.56	28.12
23.44	22.69	28.25
21	24.69	29.44
22.69	24.37	29.81
20.06	21.56	30.25
20.87	20.06	30.25
20.12	20.62	30.62
18.94	19.81	32.13
22.81	19.81	26.94
18.94	19.12	28.75
17.94	19.31	27.94
18.69	18.44	26.87
17.75	18.56	29.44
18.12	17.87	18.94
18	18.37	19.25
17.94	18.19	19.19
18.94	17.87	19.06
29.44	29.75	19.12
28.25	29.75	18.81
28.87	28.44	18.75
26.25	27.94	19.06
27.75	27.62	18.31
27.62	27.06	18.44
25.87	27.75	22.12
29.94	28.44	23.06
27.69	28.06	23.12
27.06	28.12	22.69
27.69	25.87	23.25
24.25	26.06	24.75
26.25	25.94	26.06
25.5	25.06	25.31
23.62	25.44	25
28	26.37	26.81
29.5	30.75	22.37
28.12	29.44	22.25
28.62	28.12	22.87
25.06	28	21.37
27.12	27.75	22.31
26.56	25.81	26.56
24.19	27.44	27.37
30.12	28.37	26.12
27.81	28	24.69
27.5	28.81	27.94
28.19	27.44	27
24.19	26	26.62
26.5	25.19	28.44
26.19	25.31	24.5
24.37	26.19	26.31
27.5	25.31	18.87
18.81	19.06	19.81
18.12	18.94	19.31
18.69	18.69	19.31
17.75	18.56	20.06
18.19	17.94	
18.06	18.19	
17.81	18.06	
18.56	18	
18.62	19.06	
17.62	18.75	
18.06	18	
17	18.25	
17.56	17.56	
17.75	17.5	
16.69	17.56	
17.62	17.12	
21.25	22.06	
20.25	21.69	
20.37	21.56	
19.06	21	
19.81	20.25	
20.31	20.06	
18.75	20.56	
21.31	20.25	
24.5	25.06	
22.94	24.19	
23.06	24.75	
21.25	23.75	
22.94	23	
23.75	22.37	
21.19	23.87	
25	23.37	
21.69	21.19	
19.75	21.5	
20.81	20.75	
18.37	20.87	
20.19	19.69	
19.44	19.31	
18.31	19.25	
20.87	18.94	
25.87	25.06	
23.44	25.06	
23.31	26.06	
21.62	24.81	
23.19	23.87	
24.5	24.37	
21.69	24.25	
26.25	22.44	
27.06	26.37	
23.19	26.19	
25.06	24.87	
21.56	25.62	
24.44	23.06	
22.37	23.56	
21.06	22.25	
25.44	22.87	
19.06	19.62	
18	18.37	
18.06	18.81	
16.69	18.62	
17.31	17.87	
18.44	17.62	
17	18.69	
18.75	18.19	

Turkey's Pairwise

	TI+	BJ
TI+	0.618	4.92E-05
BJ	1.323	0.001307
Sub	6.162	5.002

Figure 18

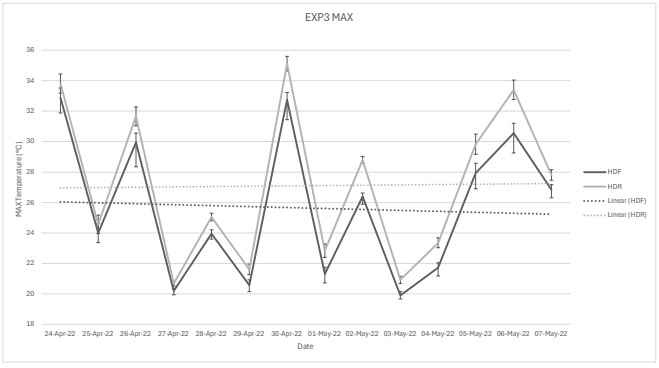
Sensor	2022-04-24 24-Apr-22	2022-04-25 25-Apr-22	2022-04-26 26-Apr-22	2022-04-27 27-Apr-22	2022-04-28 28-Apr-22	2022-04-29 29-Apr-22	2022-04-30 30-Apr-22	2022-05-01 01-May-22	2022-05-02 02-May-22	2022-05-03 03-May-22	2022-05-04 04-May-22	2022-05-05 05-May-22	2022-05-06 06-May-22	2022-05-07 07-May-22
BSF1	33.63	24.5	31.62	20	24.5	20.87	33.88	21	26.75	20.12	22	29.37	31.62	27.5
BSF2	32.38	24.75	31.37	20.25	23.75	21	32.63	22	26.5	20	22.37	28.75	32.13	26.75
BSF3	32.38	24	29.5	20.37	24.25	21.12	32.25	21.12	26.12	20.12	21.75	28.37	30	27.5
BSF4	32	24.37	28.12	20.12	24	20.75	32.88	20.5	25.87	19.87	21.5	28.5	29.62	27.62
BSF5	30.87	23.5	28.37	19.87	23.25	20.25	30.12	20.62	25.5	19.37	21	26.5	29.5	26.37
BSF6	34	24.12	30.87	20.12	24.37	20.25	32.5	20.75	26.87	20.25	22	27	30.5	26.75
BSF7	32.5	23.75	29.37	20.12	24.5	20.62	29.62	20.5	26.37	20	21.5	26.37	29.75	26.62
BSF8	34.38	23.37	31.5	19.5	23.87	19.87	35.13	21.12	27.5	20.12	21.87	28.5	32.25	27.5
BSR1	34.75	26	34	21	25.37	22.37	38.25	24.37	29.5	21.37	24.62	33.13	37	29.25
BSR2	34.13	25.87	33.88	21.12	25.5	22.5	36.63	24	29.37	21.75	24.75	31.87	35.88	28.75
BSR3	34.75	25.75	33.5	20.87	24.75	21.75	36.25	22.25	28.25	21.12	23	31.5	33.5	28.62
BSR4	33.5	24.37	31.37	20.5	25.12	21.75	34.25	22.37	28.87	21.12	23.25	29.62	32.63	27.5
BSR5	33.88	24.87	32	20.5	24.87	21.75	35.5	23	28.75	20.75	23.25	30.25	34.25	27.87
BSR6	32.25	22.62	30.5	19.5	24	20.37	32.88	21	27.5	20.25	22.25	28	31.75	26.62
BSR7	32.63	24	28.87	20.62	24.62	21.12	35.25	23.12	28	20.37	22.62	29.25	32.38	27.37
BSR8	32.5	22.25	32.38	20	24.37	20.37	33.75	22.5	28.62	20.5	23.25	28.5	34.88	27.37
HDF1	33.13	25.25	31.25	20.25	23.75	20.87	32.75	21.37	26.37	20.12	21.87	28.37	31	27.12
HDF2	32.88	23.87	30.37	19.75	24.25	20.5	32.88	20.37	26	19.87	21.12	28.5	30.37	26.62
HDF3	33.5	24.75	30.62	20.5	23.87	21.12	33.63	22.25	26.87	20.25	22.62	29.12	31.25	27.25
HDF4	33.38	24.87	30.37	20.5	24.62	21.37	33.63	21.5	26.75	20.37	22	29.12	31	27.62
HDF5	31.25	23.5	28.37	20.25	23.37	20.37	31.5	21.62	26.12	19.62	21.75	27.12	31	26.12
HDF6	32.5	22.87	29.75	20.12	23.75	20.37	32.13	20.87	26.25	19.62	21.25	26.87	29.87	26.37
HDF7	34.25	23.75	29.5	20	24.12	20.12	32.63	20.62	26.62	20	21.5	27.25	28.62	26.87
HDF8	32.25	23.12	29.25	20.12	23.87	19.87	32.75	21.87	26.12	19.37	21.62	27	31.37	26.62
HDR1	35.38	26	34.88	21	25.62	22.37	37.75	24.12	29.62	21.37	24.75	32.5	36.63	28.75
HDR2	35.75	25.5	33.88	20.87	25.62	22	36.5	22.62	29.37	21.25	23.75	30.5	33.75	28.5
HDR3	34	25	32	20.75	25.12	22	35.88	23.5	29.25	21	23.75	30.62	34.88	27.75
HDR4	33.38	24.25	31	20.62	24.62	21.75	34.75	22.62	28.62	20.75	23	30	33.13	27.87
HDR5	32.5	24.62	31.75	20.62	25	21.75	33.5	22.25	28.12	20.87	22.75	28.75	32.25	27.62
HDR6	31.5	24.25	28.12	21.12	25	21.62	32.13	23.75	28.37	20.87	23.37	28	32.5	26.5
HDR7	33.13	23.25	29	20	24.12	20.5	33.88	21.62	27.62	20.25	22.12	28.25	30.25	27.12
HDR8	34.88	23.62	32.63	20.37	25.25	20.87	36.5	22.25	29.37	21	23.25	30	33.75	28.37
LDF1	34.13	25.25	32.38	20.62	24.75	21.37	34.5	22	27.37	20.5	22.75	30.12	32	27.87
LDF2	33.88	24.12	31.37	19.87	24.5	20.62	33	20.5	26.87	20	21.37	28	30.5	27.12
LDF3	34.63	25	31	20.37	24	21	34.38	21.87	27	20.25	22.25	29.37	31.87	27.75
LDF4	32	23.62	28.62	20.12	24	20.62	32.25	20.37	26.25	20	21.25	28	29	27
LDF5	31.25	22.75	28.25	19.87	23.25	20.12	31.75	21.37	26.12	19.5	21.62	26.87	30.25	26.12
LDF6	32.5	23.62	30.12	19.87	24.25	20.25	29.25	20.37	26.37	20	21.5	25.62	29.75	26.12
LDF7	34.38	22.75	31.87	19.87	23.87	19.62	33.5	21	26.75	19.62	21.37	27	31.75	27
LDF8	31.37	21.62	30.62	19.75	23.87	19.87	31.75	21.5	26.37	19.5	21.75	27	32.13	26.75
LDR1	33.5	25.5	33.25	21.12	25.37	22.5	36.63	24.37	29.5	21.62	24.75	31.75	35.75	28.37
LDR2	33.75	25.12	33.5	20.75	25.25	21.87	34.38	22.75	29.12	21.37	24.12	29.87	33.88	27.62
LDR3	33.13	24.25	31	20.75	24.75	21.75	34.88	23.37	28.75	20.75	23.5	30.5	34	27.75
LDR4	32.75	24	29.75	20.62	24.75	21.5	33.88	22.12	28	20.87	22.5	28.62	31.25	27.37
LDR5	33.63	23.75	32.38	20.25	24.87	21.12	33.25	21.75	28.87	20.87	23.12	28.5	32.75	27.37
LDR6	31.12	23.25	28.5	20.5	24.25	21.12	30.87	22.37	27.5	20.5	22.25	27	31.75	26.25
LDR7	34.63	24	32.38	20	24.5	20.5	35.75	21.62	28.37	20.62	23	29.37	33.13	27.75
LDR8	34.38	23.25	33.63	20.62	25.37	21.12	35	23	29.75	21.25	23.75	29.87	35.38	28.5

Average	2022-04-24 24-Apr-22	2022-04-25 25-Apr-22	2022-04-26 26-Apr-22	2022-04-27 27-Apr-22	2022-04-28 28-Apr-22	2022-04-29 29-Apr-22	2022-04-30 30-Apr-22	2022-05-01 01-May-22	2022-05-02 02-May-22	2022-05-03 03-May-22	2022-05-04 04-May-22	2022-05-05 05-May-22	2022-05-06 06-May-22	2022-05-07 07-May-22
BSF1	32.7675	24.045	30.09	20.04375	24.06125	20.59125	32.37625	20.95125	26.435	19.98125	21.74875	27.92	30.67125	27.07625
BSR1	33.54875	24.46625	32.0625	20.51375	24.825	21.4975	35.345	22.82625	28.6075	20.90375	23.37375	30.265	34.03375	27.91875
HDF	32.8925	23.9975	29.935	20.18625	23.95	20.57375	32.7375	21.30875	26.3875	19.9025	21.71625	27.91875	30.56	26.82375
HDR	33.815	24.56125	31.6575	20.66875	25.04375	21.6075	35.11125	22.84125	28.7925	20.92	23.3425	29.8275	33.3925	27.81
LDF1	33.0175	23.59125	30.52875	20.0425	24.06125	20.43375	32.5475	21.1225	26.6375	19.92125	21.7325	27.7475	30.90625	26.96625
LDR1	33.36125	24.14	31.79875	20.57625	24.88875	21.435	34.33	22.66875	28.7325	20.98125	23.37375	29.435	33.48625	27.6225

Standard Deviation	24-Apr-22	25-Apr-22	26-Apr-22	27-Apr-22	28-Apr-22	29-Apr-22	30-Apr-22	01-May-22	02-May-22	03-May-22	04-May-22	05-May-22	06-May-22	07-May-22
BSF1	1.1603294	0.48653292	1.428366	0.265703	0.432813	0.431523	1.807974	0.4952182	0.6237903	0.2716846	0.41598206	1.1296017	1.15425223	0.50059786
BSR1	0.9976177	1.44820024	1.786511	0.539072	0.503842	0.814384	1.722191	1.0595948	0.6751455	0.5245389	0.88348235	1.77286693	1.8195756	0.88007203
HDF	0.9079608	0.86705989	0.903865	0.250368	0.377397	0.508469	0.709703	0.6421268	0.3230988	0.3464823	0.47071185	0.96040821	0.9249556	0.49132292
HDR	1.4691494	0.92166677	2.280481	0.358905	0.499884	0.621145	1.87242	0.8605221	0.7167735	0.3395375	0.78242754	1.47703129	1.88966172	0.74726167
LDF1	1.3928158	1.2141127	1.47199	0.305041	0.45376	0.582947	1.711989	0.661983	0.4302408	0.3600174	0.51627097	1.45418362	1.18929676	0.64763167
LDR1	1.0915577	0.81043198	1.880224	0.338945	0.412603	0.609309	1.748501	0.9131333	0.7541078	0.3912777	0.83141768	1.43147277	1.59526923	0.694113

N														
BSF1	8	8	8	8	8	8	8	8	8	8	8	8	8	8
BSR1	8	8	8	8	8	8	8	8	8	8	8	8	8	8
HDF	8	8	8	8	8	8	8	8	8	8	8	8	8	8
HDR1	8	8	8	8	8	8	8	8	8	8	8	8	8	8
LDF1	8	8	8	8	8	8	8	8	8	8	8	8	8	8
LDR1	8	8	8	8	8	8	8	8	8	8	8	8	8	8

Confidence Limits														
BSF1	0.8040525	0.33714392	0.989789	0.18412	0.299918	0.299025	1.252839	0.3431624	0.4322567	0.1882643	0.28825556	0.78275966	0.79984129	0.34689024
BSR1	0.6913011	1.00353312	1.237966	0.373551	0.349139	0.564329	1.193396	0.7342482	0.4678434	0.3634802	0.61221079	1.22851153	1.26087839	0.6098476
HDF	0.6291732	0.60083081	0.626335	0.173493	0.261518	0.352345	0.49179	0.444963	0.223892	0.2400956	0.32618067	0.66551671	0.64094975	0.34046316
HDR1	1.0180499	0.63867075	1.580264	0.248704	0.346396	0.430424	1.297497	0.5963004	0.4966896	0.2352832	0.54218466	1.02351166	1.3094447	0.5178164
LDF1	0.9651543	0.84132172	1.020018	0.211379	0.314434	0.403954	1.186326	0.4587224	0.2981362	0.2494747	0.35775096	1.00767932	0.82412546	0.44877761
LDR1	0.756397	0.56159039	1.302905	0.234873	0.285914	0.422222	1.211627	0.6327575	0.5225604	0.2711366	0.57613247	0.99194179	1.10544487	0.48098693



HDFMAX	HDRMAX
33.13	35.38
32.88	35.75
33.5	34
33.38	33.38
31.25	32.5
32.5	31.5
34.25	33.13
32.25	34.88
25.25	26
23.87	25.5
24.75	25
24.87	24.25
23.5	24.62
22.87	24.25
23.75	23.25
23.12	23.62
31.25	34.88
30.37	33.88
30.62	32
30.37	31
28.37	31.75
29.75	28.12
29.5	29
29.25	32.63
20.25	21
19.75	20.87
20.5	20.75
20.5	20.62
20.25	20.62
20.12	21.12
20	20
20.12	20.37
23.75	25.62
24.25	25.62
23.87	25.12
24.62	24.62
23.37	25
23.75	25
24.12	24.12
23.87	25.25
20.87	22.37
20.5	22
21.12	22
21.37	21.75
20.37	21.75
20.37	21.62
20.12	20.5
19.87	20.87
32.75	37.75
32.88	36.5
33.63	35.88
33.63	34.75
31.5	33.5
32.13	32.13
32.63	33.88
32.75	36.5
21.37	24.12
20.37	22.62
22.25	23.5
21.5	22.62
21.62	22.25
20.87	23.75
20.62	21.62
21.87	22.25
26.37	29.62
26	29.37
26.87	29.25
26.75	28.62
26.12	28.12
26.25	28.37
26.62	27.62
26.12	29.37
20.12	21.37
19.87	21.25
20.25	21
20.37	20.75
19.62	20.87
19.62	20.87
20	20.25
19.37	21
21.87	24.75
21.12	23.75
22.62	23.75
22	23
21.75	22.75
21.25	23.37
21.5	22.12
21.62	23.25
28.37	32.5
28.5	30.5
29.12	30.62
29.12	30
27.12	28.75
26.87	28
27.25	28.25
27	30
31	36.63
30.37	33.75
31.25	34.88
31	33.13
31	32.25
29.87	32.5
28.62	30.25
31.37	33.75
27.12	28.75
26.62	28.5
27.25	27.75
27.62	27.87
26.12	27.62
26.37	26.5
26.87	27.12
26.62	28.37

Tests for equal means

HDFMAX		HDRMAX	
N:	112	N:	112
Mean:	25.635	Mean:	27.099
95% conf.	(24.784	2(95% conf.	(26.157 28.041)
Variance:	20.633	Variance:	25.317

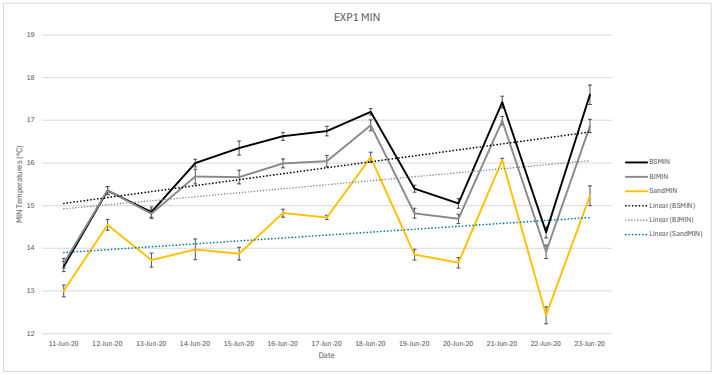
Difference 1.4644
95% conf. (0.2021 2.7266)
95% conf. (0.22661 2.733)

t :	2.2862	p (same n	0.02318	Critical t v	1.9707
Uneq. var.	2.2862	p (same n	0.02319		
Monte Cai	p (same n	0.0221			

Figure 19

Sensor	2020-06-11	2020-06-12	2020-06-13	2020-06-14	2020-06-15	2020-06-16	2020-06-17	2020-06-18	2020-06-19	2020-06-20	2020-06-21	2020-06-22	2020-06-23
BS1	13.5	15.3	14.8	16	16.4	16.5	16.7	17.1	15.4	15.2	17.4	14.4	17.6
BS2	13.5	15.3	14.7	16	16.4	16.7	16.7	17.1	15.4	14.9	17.5	14.4	17.7
BS3	13.7	15.4	15	16	16.4	16.7	16.8	17.4	15.4	15.1	17.4	14.4	17.4
BS4	13.6	15.4	14.9	16	16.2	16.6	16.8	17.2	15.4	15	17.4	14.3	17.7
TI1	13.5	15.3	14.8	15.9	15.4	16	16	16.7	14.6	14.8	16.7	13.7	16.5
TI2	14	15.7	15.3	16.2	16	16.2	16.1	17	14.9	15	17.1	13.9	16.7
TI3	13.7	15.4	15	15.8	15.5	16	15.8	16.7	14.7	14.7	16.7	13.5	16.4
TI4	13.8	15.5	15.1	16	15.8	16.3	16.1	16.9	14.8	15	17	13.9	16.7
TI5	13.5	15.4	14.9	15.9	15.9	16.1	16.1	16.8	14.7	14.9	17	13.8	16.7
TI6	13.6	15.4	14.9	16.1	16	16.4	16.4	17	15	15.3	17.4	14.2	16.9
TI7	13.5	15.4	14.9	16	16	16.2	16.1	16.8	14.7	14.8	16.9	13.8	16.6
TI8	13.9	15.7	15.3	16.1	15.9	16.3	16	16.9	14.8	14.9	17	13.7	16.7
TI9	13.8	15.6	15	16.2	16.2	16.3	16.3	16.9	14.9	14.9	17	13.6	15.7
BJ1	13.8	15.5	14.9	15.9	15.8	16.1	16.2	17.1	15	14.9	17.2	14.3	17
BJ2	13.4	15.1	14.6	15.3	15.4	15.8	15.7	16.6	14.6	14.5	16.8	13.6	16.5
BJ3	13.4	15.2	14.7	15.4	15.4	15.7	15.8	16.7	14.6	14.5	16.7	13.7	16.7
BJ4	13.8	15.5	15	16	16.1	16.2	16.4	17.1	15.1	14.8	17.1	14.1	17.3
BJ5	13.9	15.5	15.1	16	16	16.2	16.2	17.1	15	15	17.2	14.3	17.1
BJ6	13.6	15.4	14.7	15.5	15.5	15.9	15.9	16.7	14.6	14.5	16.9	13.7	16.7
BJ7	13.7	15.3	14.7	15.4	15.5	15.9	15.9	16.7	14.8	14.7	17.1	13.8	16.6
BJ8	13.6	15.3	14.7	15.7	15.6	16	16.1	16.9	14.9	14.6	16.9	13.8	16.9
BJ9	13.8	15.5	15	16	15.9	16.1	16.2	17.1	14.9	14.7	17	14.1	17.1
BJ10	13.5	15.3	14.7	15.6	15.5	16	16	16.8	14.7	14.7	17	13.8	16.8
Sand1	13.1	14.7	13.9	14.3	14	14.9	14.8	16.3	13.9	13.8	16.1	12.7	15.4
Sand2	13	14.5	13.7	13.9	14	14.8	14.7	16.125	13.8	13.65	16.05	12.425	15.225
Sand3	13.1	14.6	13.8	14	13.8	14.9	14.7	16.1	14	13.7	16.1	12.4	15.4
Sand4	12.8	14.4	13.5	13.7	13.7	14.7	14.7	16	13.7	13.5	16	12.2	14.9

Sensor	11-Jun-20	12-Jun-20	13-Jun-20	14-Jun-20	15-Jun-20	16-Jun-20	17-Jun-20	18-Jun-20	19-Jun-20	20-Jun-20	21-Jun-20	22-Jun-20	23-Jun-20	MEAN AV
BSMIN	13.575	15.35	14.85	16	16.35	16.625	16.75	17.2	15.4	15.05	17.425	14.375	17.6	15.8885
TIMIN	13.7	15.48888889	15.02222	16.02222	15.85556	16.2	16.1	16.85556	14.78889	14.92222	16.97778	13.78889	16.54444	15.559
BJMIN	13.65	15.36	14.81	15.68	15.67	15.99	16.04	16.88	14.82	14.69	16.99	13.92	16.87	15.49
SandMIN	13	14.55	13.725	13.975	13.875	14.825	14.725	16.13125	13.85	13.6625	16.0625	12.43125	15.23125	14.3111
Standard Deviation	0.09574271	0.057735027	0.129099	0	0.1	0.095743	0.057735	0.141421	0	0.129099	0.05	0.05	0.141421	
	0.18708287	0.145296631	0.17873	0.139443	0.255495	0.141421	0.173205	0.113039	0.12693	0.171594	0.210819	0.202759	0.346811	
	0.1779513	0.142984071	0.172884	0.278089	0.258414	0.166333	0.217051	0.204396	0.18738	0.172884	0.166333	0.257337	0.254078	
	0.14142136	0.129099445	0.170783	0.25	0.15	0.095743	0.05	0.124791	0.129099	0.125	0.047871	0.205523	0.235739	
N	4	4	4	4	4	4	4	4	4	4	4	4	4	
	9	9	9	9	9	9	9	9	9	9	9	9	9	
	10	10	10	10	10	10	10	10	10	10	10	10	10	
	4	4	4	4	4	4	4	4	4	4	4	4	4	
														CONF AV
Confidence Limits	0.09382613	0.056579287	0.126515	0	0.097998	0.093826	0.056579	0.13859	0	0.126515	0.048999	0.048999	0.13859	0.079
	0.12222523	0.094925388	0.116768	0.091101	0.16692	0.092394	0.113159	0.073851	0.082926	0.112106	0.137732	0.132467	0.226579	0.12024
	0.11029333	0.088620817	0.107153	0.172358	0.160164	0.103092	0.134527	0.126684	0.116137	0.107153	0.103092	0.159496	0.157476	0.12663
	0.13859038	0.126515131	0.167364	0.244995	0.146997	0.093826	0.048999	0.122293	0.126515	0.122498	0.046913	0.201409	0.23102	0.13984



	BS	TI	BJ	Sand
	13.5	13.5	13.8	13.1
	13.5	14	13.4	13
	13.7	13.7	13.4	13.1
	13.6	13.8	13.8	12.8
	15.3	13.5	13.9	14.7
	15.3	13.6	13.6	14.5
	15.4	13.5	13.7	14.6
	15.4	13.9	13.6	14.4
	14.8	13.8	13.8	13.9
	14.7	15.3	13.5	13.7
	15	15.7	15.5	13.8
	14.9	15.4	15.1	13.5
	16	15.5	15.2	14.3
	16	15.4	15.5	13.9
	16	15.4	15.5	14
	16	15.4	15.4	13.7
	16.4	15.7	15.3	14
	16.4	15.6	15.3	14
	16.4	14.8	15.5	13.8
	16.2	15.3	15.3	13.7
	16.5	15	14.9	14.9
	16.7	15.1	14.6	14.8
	16.7	14.9	14.7	14.9
	16.6	14.9	15	14.7
	16.7	14.9	15.1	14.8
	16.7	15.3	14.7	14.7
	16.8	10	14.7	14.7
	16.8	15.9	14.7	14.7
	17.1	16.2	15	16.3
	17.1	15.8	14.7	16.125
	17.4	16	15.9	16.1
	17.2	15.9	15.3	16
	15.4	16.1	15.4	13.9
	15.4	16	16	13.8
	15.4	16.1	16	14
	15.4	16.2	15.5	13.7
	15.2	15.4	15.4	13.8
	14.9	16	15.7	13.65
	15.1	15.5	16	13.7
	15	15.8	15.6	13.5
	17.4	15.9	15.8	16.1
	17.5	16	15.4	16.05
	17.4	16	15.4	16.1
	17.4	15.9	16.1	16
	14.4	16.2	16	12.7
	14.4	16	15.5	12.425
	14.4	16.2	15.5	12.4
	14.3	16	15.6	12.2
	17.6	16.3	15.9	15.4
	17.7	16.1	15.5	15.225
	17.4	16.4	16.1	15.4
	17.7	16.2	15.8	14.9
		16.3	15.7	
		16.3	16.2	
		16	16.2	
		16.1	15.9	
		15.8	15.9	
		16.1	16	
		16.1	16.1	
		16.4	16	
		16.1	16.2	
		16	15.7	
		16.3	15.8	
		16.7	16.4	
		17	16.2	
		16.7	15.9	
		16.9	15.9	
		16.8	16.1	
		17	16.2	
		16.8	16	
		16.9	17.1	
		16.9	16.6	
		14.6	16.7	
		14.9	17.1	
		14.7	17.1	
		14.8	16.7	
		14.7	16.7	
		15	16.9	
		14.7	17.1	
		14.8	16.8	
		14.9	15	
		14.8	14.6	
		15	14.6	
		14.7	15.1	
		15	15	
		14.9	14.6	
		15.3	14.8	
		14.8	14.9	
		14.9	14.9	
		14.9	14.7	
		16.7	14.9	
		17.1	14.5	
		16.7	14.5	
		17	14.8	
		17	15	
		17.4	14.5	
		16.9	14.7	
		17	14.6	
		17	14.7	
		13.7	14.7	
		13.9	17.2	
		13.5	16.8	
		13.9	16.7	
		13.8	17.1	
		14.2	17.2	
		13.8	16.9	
		13.7	17.1	
		13.6	16.9	
		16.5	17	
		16.7	17	
		16.4	14.3	
		16.7	13.6	
		16.7	13.7	
		16.9	14.1	
		16.6	14.3	
		15.7	13.7	
			13.8	
			14.1	
			13.8	
			17	
			16.5	
			16.7	
			17.3	
			17.1	
			16.7	
			16.6	
			16.9	
			17.1	
			16.8	

Mann Whitney pariwise

	BS	TI	BJ	Sand
BS		0.1917	0.1339	2.30E-11
TI	2.822		0.9978	2.12E-09
BJ	3.068	0.2601		2.70E-09
Sand	10.16	9.136	9.078	

Figure 20

Sensor	2020-06-11	2020-06-12	2020-06-13	2020-06-14	2020-06-15	2020-06-16	2020-06-17	2020-06-18	2020-06-19	2020-06-20	2020-06-21	2020-06-22	2020-06-23
BS1	4.64591707	4.42152106	7.06083682	5.730282	8.057296	4.77239934	6.185721	3.823596	4.020101	2.60267563	3.925246	5.18184111	6.75666478
BS2	5.22391246	4.61761696	6.45931322	6.398523	8.667901	5.23654662	6.760354	5.170559	4.332799	3.83317111	4.581214	7.27233758	6.74854923
BS3	4.99319992	4.43826551	6.3094806	5.531783	8.088847	4.94404677	6.331325	5.038733	3.868403	3.80434112	4.551517	7.00384229	6.46573134
BS4	4.80527843	4.59254584	7.66970254	5.353058	8.777742	4.74305313	6.59877	4.664343	3.500279	2.84550416	4.142847	5.95616723	5.74358832
TI1	4.51023037	3.98191461	5.82008181	5.009289	7.638306	4.47325385	6.229608	3.731073	3.680749	2.79661253	4.457954	5.94452256	5.84371911
TI2	4.44077397	3.94845578	5.07530414	5.079243	7.682316	4.07749041	5.993744	4.712622	3.661292	2.97783796	4.198642	5.7362847	5.73132508
TI3	4.65160855	4.2029819	5.34060347	5.090601	7.950855	4.01019534	6.419476	4.836481	3.633965	3.41134749	3.937165	6.14327669	5.63823191
TI4	4.77971566	4.18561072	5.94945726	5.517119	8.202518	4.51382346	6.431957	4.97067	3.528214	3.68892949	3.858081	6.67982603	6.48095695
TI5	4.97330373	4.85699667	6.88887168	4.134468	9.082571	3.73891037	6.86126	4.681876	3.511502	2.65177185	3.872135	5.00334169	5.52499657
TI6	4.59856079	4.40983749	7.15599055	4.114063	8.449806	4.00570616	6.397025	3.719973	3.480824	2.41471577	3.856576	4.4119951	4.91750314
TI7	4.78550328	4.45210837	5.85436576	5.51476	8.684185	4.53719059	6.498371	4.835275	3.591288	2.88411927	4.496027	6.54224037	6.85175547
TI8	4.7021594	4.3403258	6.39880138	4.821692	8.173354	4.01586579	6.522707	4.45064	3.290068	2.94985875	4.321984	5.17013386	5.45596178
TI9	4.42928871	3.81488562	4.80977343	4.25367	7.055693	3.79998505	5.877061	4.16839	3.907147	3.74706703	3.491681	7.6689691	5.18178811
BJ1	4.27707286	4.2240944	5.6962358	4.925135	8.533037	4.21115492	6.559357	4.590271	3.516522	2.8628002	4.373448	6.04544031	6.68412865
BJ2	4.62326749	4.5422574	5.30483984	5.300795	8.825535	3.90773805	6.675146	4.866432	3.645891	2.99792858	4.601478	5.88758967	6.13095413
BJ3	4.30374	3.89960177	5.66684102	5.345157	7.738734	4.32991051	6.07202	4.511948	3.452505	3.43685187	4.354524	6.54940143	6.18652464
BJ4	4.12529843	3.75501937	5.10722157	5.097578	7.860623	3.86384024	5.770172	4.104781	3.388936	3.28528342	3.930731	5.98613455	5.19259197
BJ5	4.25177325	3.9954093	5.24253979	4.589625	7.664059	3.76395384	5.820166	3.618162	3.30927	2.96845473	3.807121	5.33212463	5.5295864
BJ6	4.36527057	4.60806071	6.09707611	3.562927	8.69925	3.0825941	6.905161	4.693609	3.39696	2.1023796	4.52022	5.02038081	5.25993108
BJ7	4.44643626	4.31309449	5.59499573	5.130453	8.339757	3.90783983	6.330779	3.537237	3.350492	2.59784657	3.384031	5.47976132	6.28819692
BJ8	4.46758739	4.09802475	6.80858554	3.597895	8.105281	4.02344926	6.137767	4.35525	3.068094	3.13318322	3.438637	5.89857616	5.69117139
BJ9	4.55924593	4.20078005	7.24632091	5.677588	8.6075	4.33425835	6.526181	4.730782	3.541523	3.11046011	4.555593	6.29210966	6.27098749
BJ10	4.9354028	4.54052043	5.47760592	3.62025	8.487251	3.95920485	6.540435	4.787349	3.083998	3.15248219	3.844841	6.22585488	5.37221563
Sand1	5.24616924	5.23795877	8.46472404	5.088586	9.575231	4.08557143	7.300601	6.044674	3.622886	2.85457501	4.913342	6.00543945	8.4276702
Sand2	5.36471532	5.41539787	7.99055195	4.295075	8.970245	3.90380666	7.524249	6.037016	3.471442	2.56936442	5.020479	5.44489809	6.11024613
Sand3	5.09851434	5.37690417	7.5638319	4.99629	9.206962	4.46031958	7.493876	5.651766	5.982481	4.00763003	4.847281	6.42085558	6.19638366
Sand4	5.1496212	5.74329814	8.13330112	3.721874	10.58801	3.32743702	8.420974	6.669767	6.635909	2.07727604	5.157152	5.10880108	6.66980561
S5 10	0	0	0	0	0	0	0	0	0	0	0	0	

Average	11-Jun-20	12-Jun-20	13-Jun-20	14-Jun-20	15-Jun-20	16-Jun-20	17-Jun-20	18-Jun-20	19-Jun-20	20-Jun-20	21-Jun-20	22-Jun-20	23-Jun-20
BSSTDEV	4.91707697	4.51748734	6.8748333	5.753412	8.397946	4.92401147	6.469043	4.674308	3.930395	3.27142301	4.300206	6.35354705	6.42863342
TISTDEV	4.65234939	4.24367966	5.92147217	4.837212	8.102178	4.130269	6.359023	4.456333	3.587228	3.05802891	4.054472	5.92228779	5.73624868
BJSTDEV	4.4355095	4.21768627	5.82422622	4.68474	8.286103	3.93839439	6.333719	4.379582	3.375419	2.96476705	4.081062	5.87173734	5.86062883
SandSTDEV	5.21475502	5.44338974	8.03810225	4.525457	9.585112	3.94428367	7.684925	6.100806	4.928179	2.87721138	4.984563	5.74499855	6.8510264
Standard Deviation	0.24897746	0.10189103	0.62147541	0.456839	0.378023	0.22643011	0.258798	0.606322	0.345841	0.63984179	0.320145	0.96572347	0.47631003
	0.17925424	0.31644903	0.78998338	0.551282	0.606771	0.30380795	0.293968	0.477019	0.16868	0.4600617	0.333839	0.98642094	0.60426466
	0.23069804	0.28874334	0.69935085	0.803478	0.417608	0.35936893	0.374465	0.47756	0.186075	0.38009875	0.459607	0.4684735	0.5156019
	0.1172309	0.21397103	0.37339093	0.642293	0.713432	0.47201464	0.500596	0.421337	1.617999	0.81915099	0.135395	0.5829293	1.07949976
N	4	4	4	4	4	4	4	4	4	4	4	4	4
	9	9	9	9	9	9	9	9	9	9	9	9	9
	10	10	10	10	10	10	10	10	10	10	10	10	10
	4	4	4	4	4	4	4	4	4	4	4	4	4
Confidence Limits	0.24399343	0.09985137	0.60903471	0.447694	0.370456	0.22189743	0.253617	0.594185	0.338918	0.62703343	0.313737	0.94639161	0.46677525
	0.11711062	0.2067429	0.51611299	0.360164	0.396417	0.19848421	0.192055	0.311647	0.110202	0.30056812	0.218104	0.64444984	0.39477899
	0.1429855	0.17896169	0.43345418	0.497991	0.258832	0.22273507	0.232092	0.29599	0.115329	0.23558332	0.284862	0.29035755	0.3195675
	0.11488417	0.20968776	0.36591639	0.629435	0.699151	0.46256585	0.490575	0.412902	1.58561	0.80275322	0.132685	0.57126021	1.05789032

BS	TI	BJ	Sand
4.64591707	4.51023	4.27707	5.24617
5.22391246	4.44077	4.62327	5.36472
4.99319992	4.65161	4.30374	5.09851
4.80527843	4.77972	4.1253	5.14962
4.42152106	4.9733	4.25177	5.23796
4.61761696	4.59856	4.36527	5.4154
4.43826551	4.7855	4.44644	5.3769
4.59254584	4.70216	4.46759	5.7433
7.06083682	4.42929	4.55925	8.46472
4.45931322	3.98191	4.9354	7.99055
6.3094806	3.94846	4.22409	7.56383
7.66970254	4.20298	4.54226	8.1333
5.7302824	4.18561	3.8996	5.08859
6.39852315	4.857	3.75502	4.29508
5.53178317	4.40984	3.99541	4.99629
5.35305775	4.45211	4.60806	3.72187
8.05729601	4.34033	4.31309	9.57523
8.66790055	3.81489	4.09802	8.97025
8.08884731	5.82008	4.20078	9.20696
8.77774174	5.0753	4.54052	10.588
4.77239934	5.3406	5.69624	4.08557
5.23654662	5.94946	5.30484	3.90381
4.94046677	6.88887	5.66684	4.46032
4.74305313	7.15599	5.10722	3.32744
6.18572097	5.85437	5.24254	7.3006
6.76035401	6.3988	6.09708	7.52425
6.33132544	4.80977	5.595	7.49388
6.59877026	5.00929	6.80859	8.42097
3.823596	5.07924	7.24632	6.04467
5.17055877	5.0906	5.47761	6.03702
5.03873255	5.51712	4.92513	5.65177
4.66434331	4.13447	5.3008	6.66977
4.02010101	4.11406	5.34516	3.62289
4.33279863	5.51476	5.09758	3.47144
3.86840348	4.82169	4.58963	5.98248
3.50027867	4.25367	3.56293	6.63591
2.60267563	7.63831	5.13045	2.85458
3.83317111	7.68232	3.5979	2.56936
3.80434112	7.95086	5.67759	4.00763
2.84550416	8.20252	3.62025	2.07728
3.92524608	9.08257	8.53304	4.91334
4.5812137	8.44981	8.82554	5.02048
4.55151698	8.68419	7.73873	4.84728
4.14284707	8.17335	7.86062	5.15715
5.18184111	7.05569	7.66406	6.00544
7.27233758	4.47325	8.69925	5.4449
7.00384229	4.07749	8.33976	6.42086
5.95616723	4.0102	8.10528	5.1088
6.75666478	4.51382	8.6075	8.42767
6.74854923	3.73891	8.48725	6.11025
6.46573134	4.00571	4.21115	6.19638
5.74358832	4.53719	3.90774	6.66981
	4.01587	4.32991	
	3.79999	3.86384	
	6.22961	3.76395	
	5.99374	3.08259	
	6.41948	3.90784	
	6.43196	4.02345	
	6.86126	4.33426	
	6.39703	3.9592	
	6.49837	6.55936	
	6.52271	6.67515	
	5.87706	6.07202	
	3.73107	5.77017	
	4.71262	5.82017	
	4.83648	6.90516	
	4.97067	6.33078	
	4.68188	6.13777	
	3.71997	6.52618	
	4.83528	6.54044	
	4.45064	4.59027	
	4.16839	4.86643	
	3.68075	4.51195	
	3.66129	4.10478	
	3.63396	3.61816	
	3.52821	4.69361	
	3.5115	3.53724	
	3.48082	4.35525	
	3.59129	4.73078	
	3.29007	4.78735	
	3.90715	3.51652	
	2.79661	3.64589	
	2.97784	3.45251	
	3.41135	3.38894	
	3.68893	3.30927	
	2.65177	3.39696	
	2.41472	3.35049	
	2.88412	3.06809	
	2.94986	3.54152	
	3.74707	3.084	
	4.45795	2.8628	
	4.19864	2.99793	
	3.93717	3.43685	
	3.85808	3.28528	
	3.87213	2.96845	
	3.85658	2.10238	
	4.49603	2.59785	
	4.32198	3.13318	
	3.49168	3.11046	
	5.94452	3.15248	
	5.73628	4.37345	
	6.14328	4.60148	
	6.67983	4.35452	
	5.00334	3.93073	
	4.412	3.80712	
	6.54224	4.52022	
	5.17013	3.38403	
	7.66897	3.43864	
	5.84372	4.55559	
	5.73133	3.84484	
	5.63823	6.04544	
	6.48096	5.88759	
	5.525	6.5494	
	4.9175	5.98613	
	6.85176	5.33212	
	5.45596	5.02038	
	5.18179	5.47976	
		5.89858	
		6.29211	
		6.22585	
		6.68413	
		6.13095	
		6.18652	
		5.19259	
		5.52959	
		5.25993	
		6.2882	
		5.69117	
		6.27099	
		5.37222	

Mann-Whitney Pairwise

	0 BS	TI	BJ	Sand
BS	0	0.03634	0.01545	0.2566
TI	0.218	0	0.6448	0.00234
BJ	0.09273	1	0	0.00197
Sand	1	0.01403	0.01184	0

Figure 21

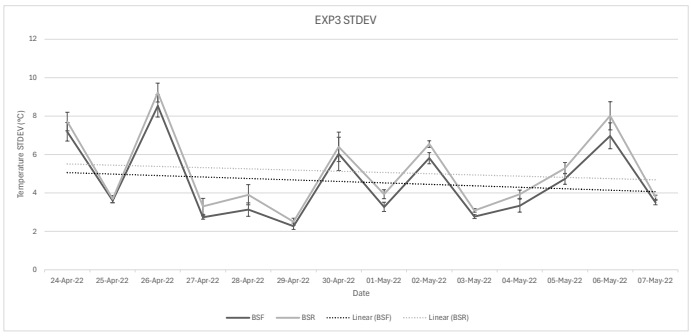
Sensor	2022-04-24	2022-04-25	2022-04-26	2022-04-27	2022-04-28	2022-04-29	2022-04-30	2022-05-01	2022-05-02	2022-05-03	2022-05-04	2022-05-05	2022-05-06	2022-05-07
CF1	7.95203949	3.790679	9.288893	2.835816	2.489578	2.403851	5.784145	3.2358957	5.9129863	2.775537	3.465366	4.847881	7.5087441	3.49127047
CF2	6.8538013	3.5379	8.981055	2.693699	3.586073	2.351365	5.63709	3.528803	5.7301302	2.7279095	3.5804231	4.8653417	7.5496189	3.38895611
CF3	7.1525953	3.752105	7.891346	2.919298	2.765625	2.503323	6.083782	3.1597313	5.589267	2.7189893	2.6928377	4.6007513	5.7689114	3.71242067
CF4	6.98660257	3.781718	7.110267	2.856371	2.983644	2.618909	6.804437	2.9350163	5.3829441	2.6330053	2.5514914	4.8279451	5.9658508	3.67536934
CF5	6.15048429	3.544167	7.864491	2.698204	3.274921	2.132008	5.413728	3.1159255	5.4889092	2.5908377	3.8468366	4.3792699	6.4437431	3.49103251
CF6	7.82834118	3.409295	9.362922	2.530743	3.403353	2.008633	5.056412	3.1935755	5.939355	2.8565416	3.3521956	4.2907038	6.8746424	3.238554
CF7	6.51751148	3.611418	8.521322	2.686151	2.666151	2.196283	4.799489	3.0571781	5.7328337	2.7835102	3.301472	4.5120873	6.8869856	3.66423674
CF8	8.03248727	3.37135	9.264405	2.646368	3.967213	1.976729	8.730201	4.0054861	6.7186304	3.0478575	3.9255539	5.5798429	8.7727308	3.38843524
CR1	8.51894507	4.197716	9.803722	3.86254	3.934089	2.746571	8.053529	4.4226939	6.8192727	3.1669061	4.3204816	5.9273914	9.3082678	3.67244719
CR2	8.00586778	3.85011	9.799363	3.854398	5.255397	2.757659	6.064058	4.2777149	6.7906761	3.2761882	4.3840236	5.7063465	8.9597062	3.97609219
CR3	7.80552756	3.705906	9.372053	2.668734	4.023841	2.471365	6.36443	3.7256824	6.3323969	3.0674887	3.8577339	5.4733978	7.8599611	3.94477747
CR4	7.03127305	3.660191	9.527693	3.841192	4.347703	2.659809	5.577715	3.93381	6.75409	3.2367494	3.8641747	5.1295962	7.9476259	3.75990397
CR5	8.16587812	3.771038	9.216641	3.904829	3.979462	2.74733	7.130283	4.1053228	6.7088315	3.1407564	4.1457916	5.4371545	8.4181098	3.92417806
CR6	7.47837068	3.511688	9.542742	2.785684	3.39642	2.306065	4.492074	3.5817713	6.4076473	3.0785231	3.6430277	4.5914433	8.0432819	3.66738861
CR7	6.42723791	3.387158	7.651508	2.967949	2.593761	2.100957	6.235609	3.9882196	6.2979791	2.8414576	3.8394012	4.9181363	5.7814538	3.62269851
CR8	8.29506757	3.446889	8.888847	2.61131	3.758944	2.229977	7.309413	3.47229	6.2446564	2.9664599	3.4964286	5.1722181	7.823415	3.66646055
HDF1	7.5375404	3.861285	8.326464	2.6721	3.615981	2.58334	6.754603	3.285503	5.6001032	2.6694781	4.0147609	4.8152751	6.9364702	3.66098179
HDF2	7.70916866	3.697334	8.845386	2.862694	2.619803	2.577737	5.837294	3.1221386	5.6473927	2.7941054	3.2707289	4.752787	7.0363093	3.32521123
HDF3	7.22404598	3.576698	8.212801	2.783903	3.480208	2.271343	6.205308	3.5081565	5.7860353	2.6964102	3.5476259	4.8686201	5.641549	3.31029183
HDF4	7.23080661	3.769305	7.917067	2.885251	2.909407	2.650155	6.430751	3.2626936	5.6688392	2.7575292	3.2488015	4.8773648	5.7796388	3.85364477
HDF5	6.26190368	3.553257	7.674489	2.654914	3.481873	2.33233	5.918743	3.4451297	5.5448551	2.5596692	3.1610021	4.8441372	6.8686342	3.51358548
HDF6	7.68112788	3.40243	8.331987	2.730096	3.682024	2.25821	6.422268	3.1839745	5.6512333	2.6213564	3.9021349	4.423676	6.9438307	3.58885
HDF7	7.28389791	3.678267	8.249622	2.670213	2.720437	2.070903	6.074252	3.1245469	5.8965586	2.8002717	3.3351346	4.463229	5.1272044	3.46021769
HDF8	7.01682098	3.176702	7.731623	2.76138	2.455119	1.967755	6.079057	3.4790738	5.5078778	2.4918245	2.9522249	4.5507068	6.8109331	3.29954448
HDR1	8.76375884	4.029375	10.40002	2.850351	3.702871	2.623528	6.501005	4.381314	6.9238289	3.2780815	4.4767518	5.721466	9.47809	4.01451224
HDR2	8.48015331	3.810767	10.38425	3.952901	3.743807	2.490108	5.801914	4.0564306	6.9676265	3.3089529	4.0450261	5.0783723	8.5726072	3.84591282
HDR3	8.26132433	3.655224	9.299505	3.940913	3.912688	2.507808	6.954706	4.2533032	6.8561466	3.1519151	4.2130244	5.5565029	8.4516395	3.89778458
HDR4	8.15644276	3.713432	9.082375	3.010179	4.47291	2.47203	6.609097	3.9996615	6.6891099	3.0983699	4.0277436	5.0424732	8.1733048	3.93351525
HDR5	8.08844887	3.790714	9.391901	3.010519	3.821336	2.524324	5.698699	3.7956799	6.4956957	3.1074892	3.8967751	4.7905106	7.9845022	3.70328105
HDR6	5.98986025	3.284795	7.503746	3.013798	3.787073	2.361691	5.558946	4.1116656	6.318291	2.877701	3.8855031	4.9725788	7.5183903	3.51884846
HDR7	6.8950605	3.53685	8.266027	2.811006	2.823969	2.079643	6.298807	3.6472331	6.4319864	3.0566903	3.8696037	4.6516855	6.1132277	3.60617896
HDR8	8.31809133	3.68409	9.543266	2.879998	4.230277	2.060492	6.932011	3.9278542	6.933562	3.2158436	4.1544977	5.1155786	8.4701291	4.06246238
LDF1	8.12734267	3.829411	9.167837	2.758796	2.673753	2.631417	6.394165	3.4798505	5.9480535	2.876894	3.6348459	4.8781861	7.3579816	3.64493773
LDF2	8.510515	3.865325	9.629325	2.789959	2.951141	2.408184	6.420245	3.1625343	6.0382151	2.8220836	3.3558804	5.0051726	7.5237158	3.55882748
LDF3	8.11141143	3.936333	8.41835	2.701095	3.696814	2.552132	6.976716	3.4826526	5.8566919	2.7305197	3.385596	4.9912291	7.2771246	3.80862593
LDF4	7.10759898	3.579969	7.307534	2.773032	3.011671	2.463283	6.542533	2.8403543	5.5285551	2.6683264	2.6380692	4.6528797	6.0748112	3.41935279
LDF5	6.91270468	3.179557	7.319172	2.480415	3.38731	2.02234	5.954843	3.2995688	5.5070917	2.5504118	3.0884462	4.6319212	5.6619894	3.46478759
LDF6	6.58195309	3.436931	9.240614	2.8721	3.537919	1.949817	4.183943	3.1807347	5.8862834	2.8473881	3.4686101	4.2214468	6.5909163	3.53258736
LDF7	8.27674231	3.361799	9.114605	2.109823	2.860213	2.001871	7.235278	3.3236581	5.8923729	2.7116843	3.4304849	4.7110556	7.5719379	3.43437191
LDF8	7.53736983	3.189833	8.322082	2.714914	2.768228	1.995022	7.330549	3.4913778	5.8149242	2.5724458	3.5833473	4.4634549	7.5589121	3.47639012
LDR1	8.32077275	4.026524	9.552418	3.868975	5.159033	4.096066	6.789233	4.4029688	6.8040175	3.2369343	4.3839765	5.7141058	8.9020293	3.59880925
LDR2	8.68080299	3.644571	10.06849	3.901456	5.490669	2.596044	4.91953	4.0213343	6.7613957	3.2825017	4.175268	5.1200513	8.7720425	3.76079449
LDR3	7.67411019	3.710527	8.763913	2.896414	4.084638	2.552036	6.817413	4.1279413	6.6162904	3.0299059	4.1236579	5.4600256	8.1888621	3.84058222
LDR4	7.22005532	3.68804	8.234587	2.90396	3.793704	2.512392	5.949078	3.733566	6.4319826	3.0763186	3.5807603	4.8610298	7.2945104	3.74565334
LDR5	8.47756636	3.261064	10.2941	3.827247	5.511079	2.313488	5.320027	3.761547	6.8451687	3.1935036	4.0021024	4.9810596	8.3186953	3.26673271
LDR6	6.10612593	3.285061	8.121932	2.762012	3.969732	2.249801	5.205121	3.7436266	6.1698085	2.9099957	3.6476757	4.7540415	7.564746	3.58541213
LDR7	8.10056979	3.404379	9.705587	2.765446	3.907364	1.994437	6.330632	3.6662063	6.6601891	3.1195153	3.8618897	5.1362904	8.4099959	3.91196758
LDR8	8.61459588	3.336546	9.84894	2.786718	5.397274	2.127418	7.037461	4.1145619	7.0588919	3.184671	4.0182439	5.4112684	9.0086317	4.12639834

Average	24-Apr-22	25-Apr-22	26-Apr-22	27-Apr-22	28-Apr-22	29-Apr-22	30-Apr-22	01-May-22	02-May-22	03-May-22	04-May-22	05-May-22	06-May-22	07-May-22
BSF	7.18423286	3.599829	8.535588	2.733331	3.14207	2.273888	6.038661	3.2789514	5.8118882	2.7667735	3.339522	4.7379779	6.9714034	3.50628438
BSR	7.71602097	3.691337	9.225321	3.312079	3.911202	2.502467	6.403389	3.9384381	6.5444437	3.0968162	3.9438829	5.2944605	8.0177277	3.77924332
HDF	7.24316401	3.58941	8.16118	2.752569	3.120607	2.338972	6.215285	3.3014021	5.6628619	2.6738306	3.4290517	4.6994745	6.9300712	3.50154091
HDR	7.86914252	3.688156	9.233887	3.183654	3.811866	2.389953	6.294398	4.0216428	6.7020309	3.1368805	4.0711157	5.116146	8.0952364	3.82281197
LDF1	7.64570475	3.547395	8.56494	2.650017	3.110881	2.253008	6.379784	3.2825914	5.8090235	2.7224692	3.32316	4.6944182	6.9521736	3.54248511
LDR1	7.8993249	3.544589	9.323746	3.214029	4.664187	2.55521	6.046062	3.946469	6.668468	3.1291683	3.9741968	5.1797341	8.3074392	3.72954376

Standard Deviation														
CF1	0.69553014	0.163999	0.834842	0.127537	0.504688	0.232806	1.250701	0.339682	0.4139375	0.141454	0.495043	0.4042125	0.9724701	0.16725634
CR1	0.7031252	0.260142	0.703863	0.601061	0.759614	0.263066	1.105305	0.3316049	0.2453658	0.1424252	0.3143561	0.4310466	1.0543962	0.14573667
HDF	0.46474426	0.217971	0.380994	0.087905	0.495527	0.249102	0.304606	0.1576278	0.1265365	0.1114196	0.3677176	0.1895269	0.7518212	0.1954281
HDR	0.93657495	0.216899	0.982802	0.477435	0.480382	0.21007	0.55066	0.2369043	0.2563522	0.1373001	0.2068978	0.3604669	0.9774019	0.19501003
LDF1	0.71365397	0.303021	0.883867	0.245899	0.37962	0.286786	1.001626	0.2219602	0.191575	0.1222399	0.3222529	0.2676324	0.7477605	0.13035556
LDR1	0.87851278	0.267543	0.837871	0.542838	0.786607	0.657585	0.82149	0.2603296	0.2720401	0.1213732	0.2692391	0.3263285	0.6168338	0.25534212

N														
CF1	8	8	8	8	8	8	8	8	8	8	8	8	8	8
CR1	8	8	8	8	8	8	8	8	8	8	8	8	8	8
HDF	8	8	8	8	8	8	8	8	8	8	8	8	8	8
HDR	8	8	8	8	8	8	8	8	8	8	8	8	8	8
LDF1	8	8	8	8	8	8	8	8	8	8	8	8	8	8
LDR1	8	8	8	8	8	8	8	8	8	8	8	8	8	8

Confidence Limits														
BSF	0.48196894	0.113643	0.578505	0.088377	0.349725	0.161323	0.866676	0.2353833	0.2868388	0.0980208	0.343041	0.2800998	0.673875	0.1159006
BSR	0.48723195	0.180266	0.487743	0.416506	0.526376	0.182292	0.765923	0.2297863	0.1700267	0.0986938	0.2178336	0.2986946	0.7306458	0.10098851
HDF	0.32204543	0.151043	0.264011	0.060914	0.343377	0.172616	0.211077	0.1092285	0.0876837	0.0772084	0.2548106	0.131333	0.520976	0.13542228
HDR	0.6490014	0.1503	0.681034	0.33084	0.332882	0.145569	0.381581	0.1641633	0.1776398	0.0951424	0.1433702	0.2497863	0.6772925	0.13513257
LDF1	0.49452788	0.209979	0.612477	0.170396	0.263058	0.198729	0.694078	0.1538077	0.1327522	0.0847064	0.2233058	0.1854564	0.5181621	0.09033013
LDR1	0.60876711	0.185394	0.580605	0.37616	0.545081	0.455675	0.569253	0.1803959	0.1885107	0.0841058	0.1865697	0.22613	0.4274362	0.17693981



	CFstd	CRstd
24-Apr	7.95204	8.51895
25-Apr	6.8538	8.00587
26-Apr	7.1526	7.80553
27-Apr	6.9866	7.03127
28-Apr	6.15048	8.16588
29-Apr	7.82834	7.47837
30-Apr	6.51751	6.42724
01-May	8.03249	8.29507
02-May	3.79068	4.19772
03-May	3.5379	3.85011
04-May	3.75211	3.70591
05-May	3.78172	3.66019
06-May	3.54417	3.77104
07-May	3.40929	3.51169
08-May	3.61142	3.38716
09-May	3.37135	3.44689
10-May	9.28889	9.80372
11-May	8.98106	9.79936
12-May	7.89135	9.37205
13-May	7.11027	9.52769
14-May	7.86449	9.21664
15-May	9.36292	9.54274
16-May	8.52132	7.65151
17-May	9.2644	8.88885
18-May	2.83582	3.86254
19-May	2.6937	3.8544
20-May	2.9193	2.66873
21-May	2.85637	3.84119
22-May	2.6982	3.90483
23-May	2.53074	2.78568
24-May	2.68615	2.96795
25-May	2.64637	2.61131
26-May	2.48958	3.93409
27-May	3.58607	5.2554
28-May	2.76563	4.02384
29-May	2.98364	4.3477
30-May	3.27492	3.97946
31-May	3.40335	3.39642
01-Jun	2.66615	2.59376
02-Jun	3.96721	3.75894
03-Jun	2.40385	2.74657
04-Jun	2.35137	2.75766
05-Jun	2.50332	2.47136
06-Jun	2.61891	2.65981
07-Jun	2.13201	2.74733
08-Jun	2.00863	2.30606
09-Jun	2.19628	2.10096
10-Jun	1.97673	2.22998
11-Jun	5.78414	8.05353
12-Jun	5.63709	6.06406
13-Jun	6.08378	6.36443
14-Jun	6.80444	5.57772
15-Jun	5.41373	7.13028
16-Jun	5.05641	4.49207
17-Jun	4.79949	6.23561
18-Jun	8.7302	7.30941
19-Jun	3.2359	4.42269
20-Jun	3.5288	4.27771
21-Jun	3.15973	3.72568
22-Jun	2.93502	3.93381
23-Jun	3.11593	4.10532
24-Jun	3.19358	3.58177
25-Jun	3.05718	3.98822
26-Jun	4.00549	3.47229
27-Jun	5.91299	6.81927
28-Jun	5.73013	6.79068
29-Jun	5.58927	6.3324
30-Jun	5.38299	6.75409
01-Jul	5.48891	6.70883
02-Jul	5.93935	6.40765
03-Jul	5.73283	6.29798
04-Jul	6.71863	6.24466
05-Jul	2.77554	3.16691
06-Jul	2.72791	3.27619
07-Jul	2.71899	3.06749
08-Jul	2.63301	3.23675
09-Jul	2.59084	3.14076
10-Jul	2.85654	3.07852
11-Jul	2.78351	2.84146
12-Jul	3.04786	2.96646
13-Jul	3.46537	4.32048
14-Jul	3.58042	4.38402
15-Jul	2.69284	3.85773
16-Jul	2.55149	3.86417
17-Jul	3.84684	4.14579
18-Jul	3.3522	3.64303
19-Jul	3.30147	3.8394
20-Jul	3.92555	3.49643
21-Jul	4.84788	5.92739
22-Jul	4.86534	5.70635
23-Jul	4.60075	5.4734
24-Jul	4.82795	5.1296
25-Jul	4.37927	5.43715
26-Jul	4.2907	4.59144
27-Jul	4.51209	4.91814
28-Jul	5.57984	5.17222
29-Jul	7.50874	9.30827
30-Jul	7.54962	8.95971
31-Jul	5.76891	7.85996
01-Aug	5.96585	7.94763
02-Aug	6.44374	8.41811
03-Aug	6.87464	8.04328
04-Aug	6.88699	5.78145
05-Aug	8.77273	7.82341
06-Aug	3.49127	3.67245
07-Aug	3.38896	3.97609
08-Aug	3.71242	3.94478
09-Aug	3.67537	3.7599
10-Aug	3.49103	3.92418
11-Aug	3.23855	3.66739
12-Aug	3.66424	3.6227
13-Aug	3.38844	3.66646

Tests for equal medians

CFstd		CRstd	
N:	112	N:	112
Mean rank	50.915	Mean rank	61.585
Mann-Wh	5077		
z :	2.463	p (same m	0.01378
Monte Car	p (same m	0.0133	

Figure 22

STDEV	2021-05-01	2021-05-02	2021-05-03	2021-05-04	2021-05-05	2021-05-06	2021-05-07	2021-05-08	2021-05-09	2021-05-10	2021-05-11	2021-05-12	2021-05-13	2021-05-14	2021-05-15	2021-05-16	2021-05-17	2021-05-18	2021-05-19	2021-05-20
C1	19.37	20.87	13.93	12.43	17.88	19.87	18.06	10.12	20.06	15.31	21.87	16.74	6	8.06	11.5	15.87	10.69	17.87	17.37	10.68
C2	17.93	18.44	13	10.37	15.19	15.75	15.44	9.25	17.56	12.87	19.06	14.74	5.43	6.93	9.75	14	8.19	14.75	12.62	9.5
C3	17.25	18.93	13.06	8.75	14.5	14.62	14.68	9.06	17.75	12.75	19.44	16.06	5.37	6.81	10.31	14.88	8.56	16.37	13.5	9.93
C4	17.37	18.74	12.93	10.31	15.37	15.99	14.56	9.18	17.38	12.31	18.44	13.93	5.31	6.81	9.5	13.31	8	14.68	13.75	9.25
C5	17.93	19.81	14	9.81	14.62	16.81	14.94	9.69	19.75	14.62	21.88	17.06	5.81	7.62	11.31	16.62	9.81	17.56	14.43	11.12
C6	14.94	16.06	11.93	8.75	13.06	13.93	13.63	8.75	16.31	11.75	17.68	14.06	5.12	6.31	9.31	13.62	8	15.62	11.87	8.68
C7	15.62	17.87	13.56	10.18	14.25	14.81	14.88	9.93	17.62	11.81	17.18	14.81	5.88	7.13	10.12	14.12	8.25	16.49	12.49	10.06
C8	15.69	17.06	13.25	8.25	12.31	13.37	12.56	9.43	17.18	11.56	17.31	14.31	5.37	6.56	9.62	13.75	6.87	12.94	10.56	9.93
L&M1	16.19	17.81	12.25	9.56	13.56	16.94	14.19	8.88	18	13.37	19.31	15.62	5.06	6.74	9.43	14.12	7.93	15.31	13.12	9.94
L&M2	17.18	17.5	12.63	9.81	13.74	16.13	14.24	9.06	17.12	12.37	18.13	15.43	5.31	7	9.5	13.75	7.62	15.06	12.25	9.87
L&M3	12	13	10.12	6.56	9.75	12.62	10.94	7.69	14.75	9.81	15.49	12.37	4.31	5.87	8.19	12.06	5.87	11.68	10.56	8.44
L&M4	16.06	16.62	12.12	9.12	13.5	15.44	13.69	9.13	17.12	11.88	18.31	14.18	5.31	7	9.75	13.68	8.5	15.12	14.94	9.75
L&M5	15.68	16.63	12.5	10.81	13.68	17.13	14.31	9.13	17.43	13.31	18.37	15.18	5.31	6.68	9.06	13.06	7.62	13.31	11.75	8.81
L&M6	15.62	17.69	12.74	9.12	14.25	14	14.37	9.12	16.74	12.12	17.37	14.56	5.31	6.38	8.68	12.62	7.18	13.94	11.56	9.12
L&M7	13.56	15.13	11.62	6.81	10.25	11.81	10.93	8.12	15.94	10.87	17.06	13.49	4.56	5.75	8.44	12.74	6	12.06	10.62	8.93
L+1	17.62	18.25	12.75	11.12	15.25	17.18	15.44	8.94	18	13.25	19.37	15.5	5.06	6.93	9.37	14.06	8.81	15.74	14.93	9.75
L+2	15.68	16.5	11.62	8.94	12.75	14.63	13.06	7.94	16.81	12.56	17.93	15.31	4.37	5.93	8.44	12.44	6.87	13.31	11.13	8.62
L+3	17.68	18.38	12.25	10.43	14.68	15.81	14.63	8.56	17.31	13.06	18.37	15.75	4.81	6.25	8.37	12.5	7.75	13	12.75	8.62
L+4	14.81	14.56	11.19	8.13	11.81	12.37	12.5	8.06	15.06	10	15.12	12.25	4.37	5.56	7.5	11	5.68	11.68	9.62	7.44
L+5	14.75	16	11.75	9.56	12.74	14.87	12.99	8.24	16.44	11.87	17.06	14.31	4.56	6	8.18	12.63	7.44	13.25	12.44	8.06
L+6	15.37	17.06	12.31	7.62	11.69	12.81	12.49	8.31	16.31	11.19	16.68	14.06	4.56	6.31	8.75	13.56	6.75	14.69	10.56	9.44
L+7	13.06	14	11.19	7.56	10.5	11.5	11.25	8.13	14.49	9.24	14.19	12.24	4.18	5.13	7.12	10.81	5.5	11.63	9	7.69
L+8	16.44	19.12	13.69	10.43	15.5	15.93	15.43	9.38	18.81	13.94	20.49	15.75	5.18	6.31	9.93	15.06	8.31	16.75	13.75	10
L1	17.19	18.56	12.37	9.87	15.31	15.31	15.87	8.5	16.62	11.87	16.81	15.19	4.87	6.62	8.81	13.13	8.31	15.63	13.56	9
L2	18.06	19.37	13.37	8.75	14.18	14.87	14.5	8.75	17.19	11.75	17.81	15.75	4.94	6.62	9.38	14.68	7.81	16.06	12.12	9.81
L3	15.06	14.43	11.19	8.56	10.93	13.99	12.43	7.99	15.81	11.06	16.68	13.19	4.31	5.81	7.75	11.37	6.25	12.06	10.63	7.94
L4	17.19	19.18	13.18	7.93	13.62	13.99	14.25	8.75	16.44	10.81	16.24	15.5	4.75	5.87	8.31	13.06	6.18	14.49	9.75	9.06
L5	15.87	18.81	13.56	9.38	14.74	15.13	14.94	9.12	18.87	13.87	20.31	16	5	6.18	9.5	14.68	7.62	15.93	13.12	9.69
M1	16.87	17.69	12.69	10.75	14	17.87	15.13	9.18	18.44	13.81	20.75	15.81	5.43	7.37	10.31	14.75	8.31	15.06	14.24	10.49
M2	18	19.62	13.19	10.75	16.38	17.75	17.31	9.56	18.69	14.06	19.69	16.87	5.56	7.37	10.25	14.19	9	15.43	14.38	9.56
M3	19.62	20.44	13.25	8.62	17.19	16.81	17.43	9.13	17.63	12.12	18.81	15.88	5.69	6.94	10.37	15	8.44	16.68	13.31	10.31
M4	16.31	16.81	12.13	8.94	13.62	14.63	14.12	8.81	16.75	11.93	18.19	14.06	5.18	6.75	9.37	13.56	8.12	14.87	13.62	9.56
M5	14.87	16.12	11.5	7.81	11.81	13.93	12.56	8.18	16.49	11.81	18	13.31	4.69	6.18	8.75	12.94	7	14.18	11.25	8.93
M6	14.75	16.31	12	8.5	12.93	13.44	13.24	8.74	16	11	16.12	13.37	4.94	6.06	8.56	12.31	6.62	14.49	11.62	8.49
M7	16.06	18.37	12.81	7.37	12.24	13.38	12.68	8.81	16.81	11.63	18.06	14.56	5	6.5	9.37	14.12	7	14.81	10.69	10.19
M8	14.5	16.38	12.68	8.94	11.37	14.37	12.31	8.31	17.25	12.24	18.74	13.75	4.94	5.93	9	13.56	6.63	13.06	11.31	9.56
Sh1	18.62	20.13	13.25	8.87	15.69	16.12	16.56	9.06	17.62	12.06	18.31	16.19	5.13	7.06	9.81	14.69	8.56	17	12.56	10.06
Sh2	13.06	13	10.06	8	9.87	13.75	11.5	7.75	15.06	10.56	16.06	12.63	4.31	5.68	7.75	11.56	6.18	10.93	11.12	8.06
Sh3	17.06	18.81	13.44	11.25	15.93	17.56	15.87	9.75	18.94	13.93	20.38	15.93	5.93	6.75	9.5	13.75	8.24	14.12	13.62	9
Sh4	12.31	13.12	10.62	7.37	10.56	11.62	10.93	8.12	14.81	9.94	15.75	12	4.56	5.5	7.38	11.06	5.87	11.62	9.43	7.93
Sh5	16.06	18.5	13.19	8.06	13.62	14.81	14.24	9.12	17.87	12.62	18.68	15.81	5.12	6.37	10	15.12	7.37	15.5	11.5	10.38
Sh6	13.93	15.5	11.94	8.94	12.25	13.87	12.75	9.06	16.5	11.37	17.06	13.31	5.06	5.93	8.38	12.24	6.68	13	10.24	9.37
Sub1	17.93	19.12	13.37	10.93	15.93	16.69	16.12	9.81	18.37	13.56	20.31	15.31	5.69	7.5	10.62	14.81	9.87	16.93	15.25	10.12
Sub2	19.62	21.12	14.62	9.88	15.81	17	16.43	10.37	19.62	14.13	21.31	17.5	6.37	7.87	12	16.56	10.12	18.31	15.31	11.68
Sub3	18.06	19.44	13.81	11.18	16.24	18.12	16.25	10.31	19.37	14.49	21.12	16.5	6.19	8	11.93	15.75	10.68	16.99	17	10.93
Sub4	17.31	18.5	14.31	10.74	14.62	16.69	15.25	10.37	19.5	14.44	21.37	15.43	5.87	7.06	11.31	15.25	8.93	15.38	12.87	10.87
Sub5	18.12	21.19	15.19	10.44	16.44	16.88	16.62	10.69	20.87	16.06	23.38	18.44	6.37	7.63	12.37	17.5	10.37	19.13	15.18	12.25

	01-May-21	02-May-21	03-May-21	04-May-21	05-May-21	06-May-21	07-May-21	08-May-21	09-May-21	10-May-21	11-May-21	12-May-21	13-May-21	14-May-21	15-May-21	16-May-21	17-May-21	18-May-21	19-May-21	20-May-21
BSDTR	17.0125	18.4725	13.2075	9.85625	14.6475	15.64375	14.84375	9.42625	17.95125	12.8725	19.1075	15.21375	5.53625	7.02875	10.1775	14.52125	8.54625	15.785	13.32375	9.89375
TI&BJMAX	15.1842857	16.34	11.9971429	8.82714286	12.6757143	14.8671429	13.2385714	8.73285714	16.7285714	11.9614286	17.72	14.4042857	5.02428571	6.48857143	9.00714286	13.1471429	7.24571429	13.7828571	12.1142857	9.26571429
TI+MAX	15.3985714	16.517143	12	8.95285714	12.81	13.9885714	13.1928571	8.37428571	16.4614286	11.6942857	17.12	14.2385714	4.57571429	5.92714286	8.32714286	12.5714286	6.9	13.4728571	11.3214286	8.55285714
TIMAX	16.674	18.07	12.734	8.898	13.756	14.658	14.398	8.622	16.986	11.872	17.57	15.126	4.774	6.22	8.75	13.384	7.234	14.834	11.836	9.1
BJMAX	16.3725	17.7175	12.53125	8.96	13.6925	15.2725	14.3475	8.84	17.2575	12.325	18.545	14.70125	5.17875	6.6375	9.4975	13.80375	7.64	14.8225	12.5525	9.63625
ShDTR	15.1733333	16.51	12.0833333	8.74833333	12.5866667	14.6216667	13.6416667	8.81	16.8	11.7466667	17.7066667	14.3116667	5.01833333	6.215	8.80333333	13.07	7.15	13.695	11.4116667	9.13333333
SubDTR	18.208	19.874	14.26	10.634	15.808	17.076	16.134	10.31	19.546	14.536	21.498	16.636	6.098	7.612	11.646	15.974	9.994	17.348	15.122	11.17
Ambient	11.6	12.1	11.7	12.7	11.8	10.7	12.8	15.6	18.6	15.6	15.6	14.6	12.6	12.7	13.4	14.4	15.5	15.4	15.6	12.8

STDEV

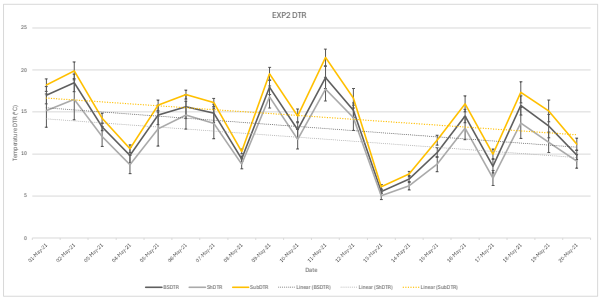
	1.48367064	1.5117232	0.66008116	1.32171898	1.66604536	2.04249803	1.58142736	0.46102177	1.28732766	1.38554528	1.88454428	1.23274302	0.31604419	0.56884438	0.82440888	1.17470285	1.18407212	1.63666036	2.02663646	0.77411586
	1.77833121	1.7373927	0.90830821	1.5713658	1.84954821	2.10110855	1.5891761	0.58554004	1.07638947	1.27940648	1.22495517	1.16765944	0.41904085	0.51037335	0.58775602	0.73339472	0.98067761	1.49386205	1.53314336	0.58846855
	1.4494531	1.8696677	0.86927173	1.23331145	1.74795118	1.75484499	1.40699105	0.48565616	1.42777716	1.67517021	2.09593257	1.51120734	0.33210727	0.44214305	0.90604846	1.4587715	1.03874925	1.78565314	1.73638925	0.92341241
	1.19424872	2.0990896	0.97495128	0.75004667	1.70056755	0.62953951	1.26153478	0.41685729	1.16255322	1.20354476	1.63583312	1.12308949	0.27555399	0.39121605	0.73426834	1.37703667	0.9640695	1.66967961	1.62074983	0.74320253
	1.77040552	1.63023	0.60736992	1.22979673	2.11065156	1.89804975	2.08038286	0.45456416	0.94243984	1.0639517	1.35331339	1.3291291	0.34942555	0.5656286	0.72755461	0.90014185	0.92956211	1.0356468	1.48705566	0.68864126
	2.46722446	3.0720286	1.46165203	1.35966785	2.55018954	2.06150835	2.30543199	0.73544544	1.64162115	1.44512514	1.75592331	1.87442169	0.55990773	0.61691977	1.11761651	1.69105884	1.0977067	2.31497516	1.52237205	1.00863604
	0.85250806	1.2174892	0.70562029	0.50077939	0.70927428	0.59835608	0.52889507	0.31685959	0.89085914	0.92888643	1.134447	1.34463006	0.30613722	0.36569098	0.68842574	1.07253438	0.66620567	1.43847836	1.4708399	0.81801589

N

BSDTR	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
TI&BJMAX	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7
TI+MAX	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7
TIMAX	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
BJMAX	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
ShDTR	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
SubDTR	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5

Confidence Limits

BSDTR	1.02811241	1.0475515	0.4574045	0.9158877	1.15448932	1.41535292	1.09585311	0.31946592	0.89205616	0.96011625	1.30589856	0.85423163	0.21900342	0.3941818	0.57127571	0.81401259	0.82090504	1.13412693	1.40436161	0.53642506
TI&BJMAX	1.31738199	1.2870549	0.67287178	1.16406268	1.37013931	1.5564944	1.17725656	0.43376616	0.79738582	0.94778017	0.90717613	0.8649832	0.31042411	0.37806292	0.43540775	0.5432742	0.72648279	1.10664815	1.13574763	0.43595559
TI+MAX	1.07375015	1.3850437	0.64395367	0.91363312	1.29487656	1.29998348	1.0422944	0.35977251	1.05769269	1.24096066	1.55266004	1.11949749	0.24602399	0.32753814	0.67119776	1.08065319	0.76950207	1.32280605	1.28631152	0.68406092
TIMAX	1.04678592	1.8048385	0.85456677	0.65743281	1.49058579	0.55180557	1.10576367	0.36538481	1.01900411	1.05493411	1.4338446	0.98441325	0.24152928	0.34209969	0.64360275	1.20700368	0.84502865	1.46351181	1.42062376	0.65143777
BJMAX	1.22680589	1.129671	0.42087814	0.85219	1.46258003	1.31525772	1.44165528	0.3149911	0.65306549	0.73729749	0.9377811	0.92102249	0.2421351	0.39195342	0.50416036	0.62375502	0.64414184	0.71765319	1.03046499	0.47719528
ShDTR	1.97415285	2.4580897	1.16954372	1.08794088	2.04053912	1.64951992	1.84469589	0.5884681	1.31354636	1.15631969	1.40500545	1.49982216	0.44801126	0.49362955	0.89426303	1.35310402	0.87833215	1.85233188	1.21812896	0.80706209
SubDTR	0.74724253	1.0671567	0.61849209	0.43894443	0.62169489	0.52447259	0.46358845	0.27773457	0.78085811	0.81418989	0.99436837	1.17859856	0.26833618	0.3204646	0.60342068	0.94010056	0.58394429	1.26085871	1.28922432	0.71700937



BJ	Sh	BS	Sub
16.87	18.62	19.37	17.93
18	13.06	17.93	19.62
19.62	17.06	17.25	18.06
16.31	12.31	17.37	17.31
14.87	16.06	17.93	18.12
14.75	13.93	14.94	19.12
16.06	20.13	15.62	21.12
14.5	13	15.69	19.44
17.69	18.81	20.87	18.5
19.62	13.12	18.44	21.19
20.44	18.5	18.93	13.37
16.81	15.5	18.74	14.62
16.12	13.25	19.81	13.81
16.31	10.06	16.06	14.31
18.37	13.44	17.87	15.19
16.38	10.62	17.06	10.93
12.69	13.19	13.93	9.88
13.19	11.94	13	11.18
13.25	8.87	13.06	10.74
12.13	8	12.93	10.44
11.5	11.25	14	15.93
12	7.37	11.56	15.81
12.81	8.06	13.56	16.24
12.68	8.94	13.25	14.62
10.75	15.69	12.43	16.44
10.75	9.87	10.37	16.69
8.62	15.93	8.75	17
8.94	10.56	10.31	18.12
12.93	11.5	13.06	10.31
12.24	15.87	14.25	10.37
11.37	10.93	12.31	10.69
17.87	14.24	19.87	18.37
17.75	12.75	15.75	19.62
16.81	9.06	14.62	19.37
14.63	7.75	15.99	19.5
13.93	9.75	16.81	20.87
13.44	8.12	13.93	13.56
13.38	9.12	14.81	14.13
14.37	9.06	13.37	14.49
15.13	17.62	18.06	14.44
17.31	15.06	15.44	16.06
17.43	18.94	14.68	20.31
14.12	14.81	14.56	21.31
12.56	17.87	14.94	21.12
13.24	16.5	13.63	21.37
12.68	12.06	14.88	23.38
12.31	10.56	12.56	15.31
9.18	13.93	10.12	17.5
9.56	9.94	9.25	16.5
9.13	12.62	9.06	15.43
8.81	11.37	9.18	18.44
8.18	18.31	9.69	5.69
8.74	16.06	8.75	6.37
8.81	20.38	9.93	6.19
8.31	15.75	9.43	5.87
18.44	18.68	20.06	6.37
18.69	17.06	17.56	7.5
17.63	16.19	17.75	7.87
16.75	12.63	17.38	8
16.49	15.93	19.75	7.06
16	12	16.31	7.63
16.81	15.81	17.62	10.62
17.25	13.31	17.18	12
13.81	5.13	15.31	11.93
14.06	4.31	12.87	11.31
12.12	5.93	12.75	12.37
11.93	4.56	12.31	14.81
11.81	5.12	14.62	16.56
11	5.06	11.75	15.75
11.63	7.06	11.81	15.25
12.24	5.68	11.56	17.5
20.75	6.75	21.87	9.87
19.69	5.5	19.06	10.12
18.81	6.37	19.44	10.68
18.19	5.93	18.44	8.93
18	9.81	21.88	10.37
16.12	7.75	17.68	16.93
18.06	9.5	17.18	18.31
18.74	7.38	17.31	16.99
15.81	10	16.74	15.38
16.87	8.38	14.74	19.13
15.88	14.69	16.06	15.25
14.06	11.56	13.93	15.31
13.31	13.75	17.06	17
13.37	11.06	14.06	12.87
14.56	15.12	14.81	15.18
13.75	12.24	14.31	10.12
5.43	8.56	6	11.68
5.56	6.18	5.43	10.93
5.69	8.24	5.37	10.87
5.18	5.87	5.31	12.25
4.69	7.37	5.81	
4.94	6.68	5.12	
5	17	5.88	
4.94	10.93	5.37	
7.37	14.12	8.06	
7.37	11.62	6.93	
6.94	15.5	6.81	
6.75	13	6.81	
6.18	12.56	7.62	
6.06	11.12	6.31	
6.5	13.62	7.13	
5.93	9.43	6.56	
10.31	11.5	11.5	
10.25	10.24	9.75	
10.37	10.06	10.31	
9.37	8.06	9.5	
8.75	9	11.31	
8.56	7.93	9.31	
9.37	10.38	10.12	
9	9.37	9.62	
14.75		15.87	
14.19		14	
15		14.88	
13.56		13.31	
12.94		16.62	
12.31		13.62	
14.12		14.12	
13.56		13.75	
8.31		10.69	
9		8.19	
8.44		8.56	
8.12		8	
7		9.81	
6.62		8	
7		8.25	
6.63		6.87	
15.06		17.87	
15.43		14.75	
16.68		16.37	
14.87		14.68	
14.18		17.56	
14.49		15.62	
14.81		16.49	
13.06		12.94	
14.24		17.37	
14.38		12.62	
13.31		13.5	
13.62		13.75	
11.25		14.43	
11.62		11.87	
10.69		12.49	
11.31		10.56	
10.49		10.68	
9.56		9.5	
10.31		9.93	
9.56		9.25	
8.93		11.12	
8.49		8.68	
10.19		10.06	
9.56		9.93	

Mann Whitney Pairwise

	BJ	Sh	BS	Sub
BJ		0.1627	0.1569	0.00023
Sh	0.1627		0.00948	8.67E-06
BS	0.1569	0.00948		0.00869
Sub	0.00023	8.67E-06	0.00869	

Figure 23

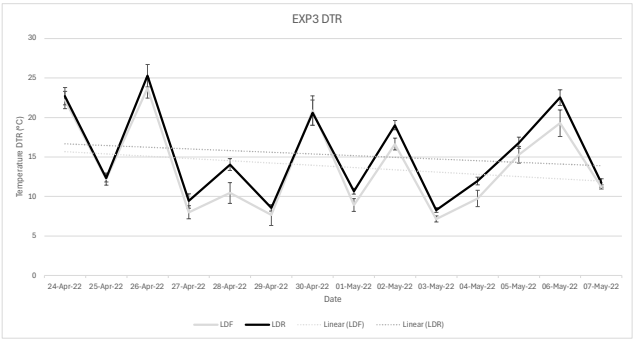
DTR	24-Apr-22	25-Apr-22	26-Apr-22	27-Apr-22	28-Apr-22	29-Apr-22	30-Apr-22	01-May-22	02-May-22	03-May-22	04-May-22	05-May-22	06-May-22	07-May-22
CF1	23	13.12	24.87	8.37	8.5	7.99	20.25	8.75	16.87	7.37	10.5	16.12	20.24	11.25
CF2	20.75	12.75	24.37	8.12	12.25	7.75	19.13	9.62	16.37	7.25	10.74	15.75	20.63	10.63
CF3	21.13	12.62	22.37	8.62	8.87	8.24	19.62	8.62	15.87	7.12	8.25	15.37	16.62	11.75
CF4	20.62	13.12	20.99	8.49	9.62	8.62	21.25	8	15.74	6.99	8	15.75	16.62	11.62
CF5	18.62	12.37	21.62	8.12	11	7.25	17.87	8.62	15.62	6.74	9.62	14.37	18.25	10.99
CF6	23.12	12.49	23.99	7.74	12.24	7	19.5	8.5	16.87	7.5	10.37	14.5	19	10.5
CF7	20.62	12.37	22.62	8.12	9	7.62	16.24	8.25	16.37	7.25	9.87	14.24	18.37	11.24
CF8	24.13	12.24	25.12	7.87	12.49	7.74	23.63	9.37	18	7.74	10.74	16.62	21.5	11.62
CR1	23.75	14.37	27	11	13.12	8.87	26.12	11.87	19.37	8.24	12.74	19.38	25.62	12
CR2	23.13	13.49	26.88	11.12	14.87	8.87	20.88	11.5	19.24	8.5	12.87	18.62	24.38	12.38
CR3	24.12	13.62	27.25	8.12	13.5	8.25	21.25	10.25	18.5	8.12	11.62	18.37	22.37	12.5
CR4	22.37	12.74	24.99	11.12	14.37	8.75	20.37	10.49	19.37	8.99	11.87	16.87	21.75	11.75
CR5	23.5	13.24	25.62	11.12	13.12	9	23.12	11.12	19.25	8.62	12.12	18	23.37	12.37
CR6	22.12	11.24	24.62	8.25	12.37	7.87	17.25	9.5	18.37	8	11.37	15.12	21.25	11.49
CR7	20.5	12.25	22.12	8.87	8.74	7.49	21.37	10.87	18.12	7.24	11.37	16.5	18	11.62
CR8	22.37	11.12	26.13	8	13.24	7.12	26.37	10.75	19.24	7.87	12.12	17.5	24.25	10.87
HDF1	21.75	13.62	24	8	11.87	8.37	21.25	8.87	16.12	7.12	9.99	15.62	19.25	11.37
HDF2	22.38	12.87	23.87	8.5	8.62	8.5	20.13	8.37	16.37	7.37	9.74	15.75	19.12	10.74
HDF3	21.87	12.62	23.37	8.37	11.62	7.62	20.88	9.62	16.49	7.12	10.74	15.99	16.62	10.63
HDF4	21.88	12.99	23.12	8.5	9.49	8.62	20.88	8.87	16.37	7.24	9	16.24	16.87	11.87
HDF5	19.37	12.25	21.37	8.12	11.62	7.87	19.75	9.37	15.99	6.74	9	15.24	19.75	10.87
HDF6	21.87	11.49	22.87	8.24	12.12	7.74	21	8.74	16.25	6.87	9.75	14.62	18.62	11.24
HDF7	22.62	12.62	22.62	8.12	9.12	7.24	21.13	8.49	16.62	7.25	10	14.75	14.87	10.87
HDF8	21.37	11.37	22.25	8.37	8.24	6.87	20.12	9.49	15.87	6.49	8.74	14.87	20.12	10.62
HDR1	24.75	14.12	28.13	8.5	13.37	8.62	22.75	11.87	19.74	8.49	13.12	18.87	25.38	12.75
HDR2	25.25	13.62	27.5	11.37	13.49	8.37	20.75	10.74	19.87	9.12	12.5	17	23	12.25
HDR3	23.62	13	25.5	11.25	13.24	8.37	22.75	11.5	19.62	8.12	12.5	18.12	24	12.12
HDR4	23	12.75	24.5	8.87	13.87	8.37	21.62	10.74	18.99	8	11.75	17.12	22.38	12.49
HDR5	22	13.12	25.25	8.87	13.25	8.5	19.87	10.25	18.37	8.12	11.37	15.87	21.37	11.74
HDR6	19	11.87	20.99	8.99	12.5	8.12	18.25	11.12	17.99	7.37	11.74	15.5	21.25	10.75
HDR7	21.75	12.37	22.87	8.5	9.62	7.37	21.88	9.99	18.24	7.87	11.12	15.62	17.87	11.62
HDR8	24.63	12.49	26.38	8.62	14.12	7.37	23.62	10.5	19.99	8.25	12.12	16.87	23.12	12.87
LDF1	23.25	13.5	25.25	8.24	8.87	8.49	21.25	9.5	17.12	7.5	10.87	16.37	20.25	11.62
LDF2	23.63	13.12	24.87	8.24	10.25	7.99	21.75	8.62	17.24	7.5	10.12	16.25	19.37	11.24
LDF3	23.75	13.5	23.87	8.12	12.12	8.37	22.5	9.37	16.75	7.25	9.37	16.49	20.12	12
LDF4	20.75	12.24	21.49	8.24	9.75	8.24	20.87	7.87	16	7	7.87	15.5	17.37	11
LDF5	20.37	10.87	21	7.62	11.25	6.99	19.75	8.99	15.74	6.62	8.74	14.99	16.5	10.74
LDF6	20.87	12.12	23.62	8.49	12.62	6.87	15	8.49	16.62	7.5	10.12	13.49	18.62	10.87
LDF7	24	11.62	25.37	6.99	9.74	7.12	23.25	9	17	7.12	10.24	14.87	20.75	11
LDF8	21.12	10.62	24.12	8.12	8.99	7.12	22.62	9.5	16.62	6.75	10.62	14.25	21.25	11.12
LDR1	22.62	13.5	26.25	11.12	14.74	12.62	22.63	11.87	19.37	8.37	12.87	18.37	24.25	11.37
LDR2	23.37	13.12	27	11.25	15	8.49	17.63	10.75	19.49	8.37	12.62	16.74	22.88	11.62
LDR3	22.38	12.75	24.25	8.62	13.25	8.5	22.38	11.24	18.87	8.25	12.12	18	23	12.12
LDR4	22.12	12.5	23.25	8.62	12.75	8.5	20.25	10.12	18.25	7.87	11	16.12	20.25	11.74
LDR5	23.5	11.5	26.25	11	14.99	7.87	19.5	10.12	19.49	8.24	11.99	16.25	22.12	10.75
LDR6	19.24	11.37	21.87	8.37	13	7.74	17.24	10.24	17.62	7.62	10.75	14.75	20.75	10.87
LDR7	24.25	12.5	26.13	8.25	13.37	7.12	22.75	9.87	18.99	8.49	11.87	16.87	22.38	12.25
LDR8	24	11.5	27.25	8.24	15.24	7.49	22.5	11	20.12	9	12.37	17.24	24.5	12.87

	24-Apr-22	25-Apr-22	26-Apr-22	27-Apr-22	28-Apr-22	29-Apr-22	30-Apr-22	01-May-22	02-May-22	03-May-22	04-May-22	05-May-22	06-May-22	07-May-22
BSF	21.49875	12.635	23.24375	8.18125	10.49625	7.77625	19.68625	8.71625	16.46375	7.245	9.76125	15.34	18.90375	11.2
BSR	22.7325	12.75875	25.57625	9.7	12.91625	8.2775	22.09125	10.79375	18.9325	8.1975	12.01	17.545	22.62375	11.8725
HDF	21.63875	12.47875	22.93375	8.2775	10.3375	7.85375	20.6425	8.9775	16.26	7.025	9.62	15.385	18.1525	11.02625
HDR	23	12.9175	25.14	9.37125	12.9325	8.13625	21.43625	10.83875	19.10125	8.1675	12.0275	16.87125	22.29625	12.07375
LDF	22.2175	12.19875	23.69875	8.0075	10.44875	7.64875	20.87375	8.9175	16.63625	7.155	9.74375	15.27625	19.27875	11.19875
LDR	22.685	12.3425	25.28125	9.43375	14.0425	8.54125	20.61	10.65125	19.025	8.27625	11.94875	16.7925	22.51625	11.69875

	24-Apr-22	25-Apr-22	26-Apr-22	27-Apr-22	28-Apr-22	29-Apr-22	30-Apr-22	01-May-22	02-May-22	03-May-22	04-May-22	05-May-22	06-May-22	07-May-22
CF1	1.786213	0.694991	1.991281	1.046859	1.69926	0.647235	3.17599	1.240345	1.29813	0.469222	1.509488	1.682904	2.984795	0.54584
CR1	1.154466	1.030312	1.663606	1.51148	1.891953	0.676166	2.569173	0.866066	1.084619	0.65152	0.835788	1.276826	2.289421	0.577159
HDF	0.993499	0.876363	2.034903	0.162744	1.887235	0.654261	0.923565	1.117762	1.248093	0.60095	1.414147	1.379953	3.15969	0.750589
HDR	2.060818	0.590448	2.035724	1.240235	1.997413	0.477164	1.671402	0.63333	1.017068	0.533745	0.606817	0.890929	1.946623	0.649874
LDF1	1.566349	1.12352	1.80964	1.207273	1.905449	1.896124	2.691749	1.191625	1.105761	0.548268	1.474972	1.513444	2.428359	0.390778
LDR1	1.585488	0.706416	2.048615	1.330911	1.081414	0.55484	2.320226	0.517968	0.83809	0.442482	0.692958	1.018982	1.431973	0.75637

N	24-Apr-22	25-Apr-22	26-Apr-22	27-Apr-22	28-Apr-22	29-Apr-22	30-Apr-22	01-May-22	02-May-22	03-May-22	04-May-22	05-May-22	06-May-22	07-May-22
CF1	8	8	8	8	8	8	8	8	8	8	8	8	8	8
CR1	8	8	8	8	8	8	8	8	8	8	8	8	8	8
HDF	8	8	8	8	8	8	8	8	8	8	8	8	8	8
HDR	8	8	8	8	8	8	8	8	8	8	8	8	8	8
LDF1	8	8	8	8	8	8	8	8	8	8	8	8	8	8
LDR1	8	8	8	8	8	8	8	8	8	8	8	8	8	8

Confidence Limits														
BSF	1.237759	0.481595	1.379862	0.725423	1.177505	0.448502	2.200809	0.859499	0.899542	0.325149	1.046003	1.166171	2.068319	0.378241
BSR	0.79999	0.713957	1.152799	1.047383	1.311032	0.46855	1.780313	0.600142	0.751589	0.451472	0.579161	0.884779	1.586459	0.399943
HDF	0.688447	0.607278	1.41009	0.112774	1.307763	0.453371	0.639986	0.774556	0.864868	0.41643	0.979936	0.956241	2.189513	0.520122
HDR	1.428048	0.409152	1.410659	0.859424	1.384111	0.330652	1.158201	0.438867	0.704779	0.36986	0.420495	0.617371	1.348916	0.450331
LDF1	1.085405	0.778546	1.253994	0.836582	1.320384	1.313923	1.865253	0.825739	0.766239	0.379924	1.022084	1.048744	1.682736	0.27079
LDR1	1.098667	0.489512	1.419592	0.922257	0.749368	0.384478	1.607805	0.358927	0.580756	0.306619	0.480186	0.706105	0.992289	0.524128



	LDF	LDR
LDF1	23.25	22.62
LDF2	23.63	23.37
LDF3	23.75	22.38
LDF4	20.75	22.12
LDF5	20.37	23.5
LDF6	20.87	19.24
LDF7	24	24.25
LDF8	21.12	24
	13.5	13.5
	13.12	13.12
	13.5	12.75
	12.24	12.5
	10.87	11.5
	12.12	11.37
	11.62	12.5
	10.62	11.5
	25.25	26.25
	24.87	27
	23.87	24.25
	21.49	23.25
	21	26.25
	23.62	21.87
	25.37	26.13
	24.12	27.25
	8.24	11.12
	8.24	11.25
	8.12	8.62
	8.24	8.62
	7.62	11
	8.49	8.37
	6.99	8.25
	8.12	8.24
	8.87	14.74
	10.25	15
	12.12	13.25
	9.75	12.75
	11.25	14.99
	12.62	13
	9.74	13.37
	8.99	15.24
	8.49	12.62
	7.99	8.49
	8.37	8.5
	8.24	8.5
	6.99	7.87
	6.87	7.74
	7.12	7.12
	7.12	7.49
	21.25	22.63
	21.75	17.63
	22.5	22.38
	20.87	20.25
	19.75	19.5
	15	17.24
	23.25	22.75
	22.62	22.5
	9.5	11.87
	8.62	10.75
	9.37	11.24
	7.87	10.12
	8.99	10.12
	8.49	10.24
	9	9.87
	9.5	11
	17.12	19.37
	17.24	19.49
	16.75	18.87
	16	18.25
	15.74	19.49
	16.62	17.62
	17	18.99
	16.62	20.12
	7.5	8.37
	7.5	8.37
	7.25	8.25
	7	7.87
	6.62	8.24
	7.5	7.62
	7.12	8.49
	6.75	9
	10.87	12.87
	10.12	12.62
	9.37	12.12
	7.87	11
	8.74	11.99
	10.12	10.75
	10.24	11.87
	10.62	12.37
	16.37	18.37
	16.25	16.74
	16.49	18
	15.5	16.12
	14.99	16.25
	13.49	14.75
	14.87	16.87
	14.25	17.24
	20.25	24.25
	19.37	22.88
	20.12	23
	17.37	20.25
	16.5	22.12
	18.62	20.75
	20.75	22.38
	21.25	24.5
	11.62	11.37
	11.24	11.62
	12	12.12
	11	11.74
	10.74	10.75
	10.87	10.87
	11	12.25
	11.12	12.87

Tests for equal medians

LDF	LDR		
N:	112	N:	112
Mean rank	51.326	Mean rank	61.174
Mann-Wh	5169		
z :	2.2734	p (same m	0.023
Monte Car	p (same m	0.0222	

Figure 24

Coeff VAR	2021-05-01	2021-05-02	2021-05-03	2021-05-04	2021-05-05	2021-05-06	2021-05-07	2021-05-08	2021-05-09	2021-05-10	2021-05-11	2021-05-12	2021-05-13	2021-05-14	2021-05-15	2021-05-16	2021-05-17	2021-05-18	2021-05-19	2021-05-20
C1	48.738415	54.721661	37.179092	23.105659	44.103659	34.98518	42.274302	26.640184	31.517692	23.04598	38.283796	21.11024	15.056642	19.845101	23.36528	32.53667	22.301847	36.760583	32.573195	27.099101
C2	47.469482	51.075722	34.8734	25.227838	40.226494	36.922852	38.356493	24.795089	31.989482	22.507635	36.41251	29.661936	13.536498	17.345553	21.280331	31.140598	16.843125	33.025326	26.566667	24.851073
C3	46.444993	52.889876	36.765868	22.522182	40.695732	40.418537	38.989311	25.529367	31.508965	22.340689	37.763936	32.302338	14.057903	17.416086	22.381096	32.695828	16.437361	32.98023	29.244485	25.841163
C4	46.979387	51.993902	35.359416	24.257433	41.01643	35.484604	36.565262	24.792533	31.151469	20.777932	35.201032	20.656072	13.213119	17.22483	20.68073	29.355164	17.013475	30.212524	28.261822	24.143494
C5	48.263083	56.277676	38.933899	22.760162	41.086609	36.121263	41.36886	27.099471	31.805923	24.99945	39.079286	33.708138	12.410649	19.607126	24.9973	35.118175	18.838565	37.804349	30.405719	28.742172
C6	42.515346	46.72548	33.225886	21.825881	36.332743	34.656999	34.59199	23.977883	30.115255	21.160659	35.706253	28.051783	12.859424	16.209664	20.331472	30.599067	15.660642	33.510535	26.981788	22.981648
C7	45.679904	53.592204	37.542421	24.638678	41.945769	34.238301	39.930986	27.501815	31.676691	18.74632	36.408009	29.464152	15.003237	18.339044	23.007959	32.448811	16.318129	35.444098	28.021921	27.200811
C8	42.914343	50.845669	36.801223	21.559182	34.707775	40.629507	32.729625	25.977986	31.148185	21.423227	36.307252	30.81948	13.861169	16.808841	21.502517	31.498633	15.321444	29.315216	22.892353	26.154989
L&M1	44.524413	51.076829	34.247991	18.118858	39.497999	30.506028	26.246585	24.753215	26.466651	19.797695	35.627803	19.072123	10.746751	16.985181	20.814371	30.239049	17.222961	33.583688	26.440143	25.152146
L&M2	46.94473	50.77186	35.399006	22.885899	39.685052	28.358325	34.171677	24.991206	30.327896	19.294574	33.147647	21.662657	13.824287	17.547348	21.053874	31.556961	16.64129	33.640264	26.371292	25.625663
L&M3	24.406844	39.49807	30.200436	15.722342	29.032052	27.815329	26.370644	21.974329	28.12804	17.848841	32.298936	20.491445	10.956416	15.575722	18.221435	28.918844	13.421449	27.266929	22.67701	22.517491
L&M4	44.960968	48.59423	34.579432	22.784388	37.815132	33.5438	34.026513	25.573477	31.237752	20.125402	35.891665	20.932811	13.425594	18.061488	21.411505	30.173464	17.940158	32.802717	30.010989	25.750502
L&M5	45.169859	50.266864	35.396442	20.142255	38.796126	29.543313	30.395603	25.419861	29.609638	19.754649	31.216036	20.69535	13.468861	17.488926	20.489932	29.954809	17.146709	31.216768	24.648864	24.157575
L&M6	44.633733	49.636058	35.096886	17.681813	40.62659	23.582682	37.446102	24.582271	28.559574	17.448946	31.680573	18.013441	13.135788	16.091154	19.508328	28.964628	16.095651	30.590108	24.150993	23.700262
L&M7	40.327952	44.553968	32.705795	14.407937	29.752562	24.670066	26.4096	22.464238	26.462498	18.695764	33.783283	19.445423	11.644274	14.908679	19.154347	27.476352	13.163404	26.670549	22.309894	23.016475
L&M8	91.39799	90.049811	93.517839	93.357743	115.65959	103.26245	114.42748	113.19606	48.801946	63.940577	75.098259	80.927352	96.303068	44.125159	122.05148	32.447755	16.393867	36.245422	23.753851	130.49556
L+1	45.16982	47.974262	34.412893	25.078326	38.068059	31.711079	32.691416	24.155385	29.772606	20.419413	35.736537	20.247522	12.58559	17.044268	20.358724	29.865947	19.362095	32.288257	29.450248	24.736303
L+2	42.865145	45.09978	32.448741	19.066503	33.911864	27.510166	28.204328	21.917829	28.217787	19.553313	32.700752	22.202918	11.010016	15.259464	21.426312	27.882504	14.385079	29.388942	24.272583	22.440477
L+3	46.048556	49.237056	32.983323	20.114571	39.080648	35.795341	34.514705	23.290604	30.014277	19.418792	34.805014	20.867707	11.734467	15.770825	18.132726	27.702717	16.745616	29.150915	25.847859	22.427086
L+4	41.539845	42.04973	32.203629	19.874964	33.43021	33.470724	34.740409	23.084357	29.330328	19.039789	32.374652	21.555575	10.928354	14.784304	19.71699	26.42501	13.660543	27.809196	22.402256	20.362265
L+5	40.999843	45.134466	32.582603	19.075852	34.313973	27.666217	28.192853	22.939513	28.133927	18.101305	30.407113	20.247787	11.118731	15.749956	18.263214	28.154907	17.211637	29.694341	25.771738	21.9643
L+6	42.768553	49.655076	34.213781	15.272925	31.915105	36.401228	31.247227	23.407917	25.942513	18.097742	30.897006	17.850684	11.789058	16.553627	20.155449	30.449601	16.133686	34.016808	23.431964	24.236576
L+7	39.083499	42.624162	32.126907	20.230162	31.653644	34.384961	30.648831	23.196986	28.120511	17.399941	31.106832	19.990361	10.451889	13.567763	18.759125	25.827938	13.708109	28.006252	20.667496	20.788147
L+8	45.912763	53.132726	36.795762	25.066916	41.490605	35.10682	40.350115	25.796102	32.992964	24.064226	38.440397	31.682115	13.31122	16.274102	21.697462	32.984372	17.135564	37.313619	28.869825	26.264722
L1	44.029243	48.763562	32.230262	18.590637	39.82162	26.275644	37.330395	22.650996	26.9233	16.903783	27.271282	19.693068	11.641765	16.080267	18.987881	28.850749	17.864824	31.445784	27.333405	22.889501
L2	47.369293	54.115759	36.333308	22.143691	37.369986	42.030471	36.6147	24.377819	29.937816	21.792203	35.676353	31.579538	12.827187	16.879151	20.894978	31.544862	16.272496	35.304859	26.097464	24.807975
L3	42.056644	41.957358	31.814655	19.123465	31.027239	32.183262	30.879493	22.665151	28.499215	19.118636	33.347588	20.160875	10.734614	15.113875	20.1093	26.392602	15.08998	27.217172	23.531579	21.342573
L4	44.454859	51.931733	35.65022	20.806308	36.907475	39.66842	36.880083	24.221935	31.454564	21.629925	35.573672	28.834578	12.275336	15.38198	18.853717	29.983274	15.107433	32.953268	22.849324	23.344807
L5	44.272054	52.4121812	36.362846	23.08874	40.089349	31.748379	38.284869	25.053825	30.467728	21.733468	37.467405	31.917704	12.950645	15.818441	20.7619	31.164665	15.854235	33.497217	27.40405	25.196642
M1	44.949593	49.306745	34.585222	22.944855	37.580147	32.814548	27.757035	24.721933	29.801189	20.71043	36.439713	21.318047	11.475193	18.257389	22.162534	31.299773	17.173062	32.19491	27.05214	26.199508
M2	49.453579	54.770234	36.440392	19.100053	44.971924	33.440343	43.96753	25.785261	30.553429	19.439599	37.018814	20.875579	14.185379	18.764518	22.337824	31.108855	19.481846	34.193079	28.561992	25.865147
M3	49.688063	59.415345	37.684279	23.124836	46.823035	45.01534	44.434993	25.97904	30.672853	22.044301	36.72728	33.298163	12.228752	17.966462	23.193107	32.736483	16.801203	36.822564	28.442095	27.011836
M4	44.554013	48.713893	33.82059	22.090663	38.646145	34.736975	36.916519	24.33691	29.410098	20.373647	35.446222	28.309691	13.189774	17.011204	20.463003	29.319038	17.113124	30.819529	27.450367	24.408214
M5	44.524277	49.108271	33.574819	19.927518	34.994161	33.150489	30.921024	22.920052	29.974709	20.430191	35.232961	28.168258	12.138036	15.978809	19.511625	30.612169	15.207665	31.675555	25.109369	23.863854
M6	44.026607	50.001251	34.321225	22.392325	39.077795	25.748812	36.473843	24.617774	28.698708	16.57904	31.134951	18.626444	12.518143	15.697421	19.332915	28.688358	15.79933	32.363322	25.063262	22.832922
M7	45.563542	54.59187	36.684518	19.995569	35.764011	39.770633	34.571501	25.032275	29.780441	21.116093	36.497844	30.650392	11.168935	17.107863	21.228358	32.115656	14.6929	34.799295	24.18258	26.634764
M8	43.554057	50.739434	36.664112	21.684153	33.590831	32.295568	29.675273	23.614852	30.047047	20.79364	36.534981	21.203314	13.185041	15.780341	20.667455	30.98642	15.043823	30.87291	24.080003	25.631617
Sh1	48.044581	54.945864	36.51789	22.23849	40.239803	42.537195	40.548751	25.407954	28.968896	21.616064	36.28776	31.408509	10.703792	17.789988	22.017567	32.860959	18.25699	38.030387	27.774002	26.21204
Sh2	25.200461	31.306325	29.329003	17.430066	27.051919	27.942363	25.533079	22.255105	26.917016	18.038184	31.696837	19.407655	10.641067	14.802994	17.10761	26.562292	14.882288	25.628132	22.515297	21.476051
Sh3	45.952892	51.872741	35.754561	21.904061	41.220709	33.966431	40.024387	25.771917	31.241091	21.065838	37.130839	22.132699	14.575736	16.928398	20.474034	29.764124	17.389544	30.724805	26.686983	23.457873
Sh4	36.976178	40.168302	30.943727	19.828774	30.596457	32.093696	28.898951	23.31858	27.92304	18.09005	32.483605	19.616643	11.353143	14.720915	16.999075	26.046328	12.98835	26.872218	21.898455	21.475339
Sh5	45.477435	54.664579	36.939292	20.754714	37.076257	41.389917	37.316067	25.777477	32.402665	22.935716	37.916718	31.229471	13.701438	16.637084	22.296366	32.435961	14.362741	36.519448	25.162659	26.724358
Sh6	42.047925	48.110066	34.709506	22.954749	35.607531	31.928949	31.72225	25.914312	29.635224	20.481523	34.626159	19.943954	13.140458	15.929476	19.889136	29.282118	14.774973	31.625734	23.16898	26.041176
Sub1	48.888197	53.050922	36.523946	25.803408	41.633036	37.850052	39.424119	26.82258	32.991185	23.358164	38.250882	30.656827	14.535645	18.814903	22.62569	32.035832	18.949112	36.09858	31.702045	26.872027
Sub2	54.009485	59.999864	41.01373	23.130719	44.47222	48.927653	44.007365	29.060945	34.140188	24.408466	39.66934	35.407958	13.826471	20.120619	25.591501	34.745603	20.160545	40.217222	31.514056	30.159245
Sub3	49.135762	54.44854	38.651197	22.282295	42.219462	35.266829	42.057417	28.439053	33.127617	23.694178	40.056645	23.789208	15.770732	20.54036	25.071166	33.997138	20.931356	37.920063	33.199681	29.342133
Sub4	48.154674	53.965229	39.334844	25.162325	39.487055	35.416123	35.8902	28.200987	33.365891	24.611185	40.178879	30.632366	15.321185	18.066905	23.778801	32.731919	17.113129	34.3005	26.951539	28.673467
Sub5	55.07488	62.505877	42.453137	25.95904	45.540448	51.913494	45.668875	29.950529	35.061757	26.602939	42.229911	36.496206	14.57496	19.95235	26.788301	36.084769	20.777429	41.185138	31.545226	31.4258
Average	01-May-21	02-May-21	03-May-21	04-May-21	05-May-21	06-May-21	07-May-21	08-May-21	09-May-21	10-May-21	11-May-21	12-May-21	13-May-21	14-May-21	15-May-21	16-May-21	17-May-21	18-May-21	19-May-21	20-May-21
BSCoeffVAR	46.125619	52.265274	36.335768	23.237127	40.014402	36.682155	38.100849	25.789291	31.364208	21.825236	36.895259	27.096767	13.74983	17.849531	22.193336	31.924118	17.341824	33.631608	28.118494	25.876804
TI&BJCoeffVAR	41.566928	47.771125	33.94657	18.821927	36.457931	28.288506	30.723818	24.251228	28.684579	18.995124	33.377992	20.04475	12.457424	16.6655	20.093399	29.612015	15.947375	30.824432	25.229884	24.274302
TI+CoeffVAR	42.639323	45.96779	32.995983	19.815329	34.624786	32.419959	31.462824	23.141799	28.504479	18.861471	32.575415	20.422222	11.374015	15.532887	19.544649	28.044089	15.886681	30.050816	24.549163	22.422165
TICoeffVAR	44.76456	49.980227	34.564842	21.146204	37.323385	35.052883	36.410957	23.942401	29.961572	20.701755	34.061858	26.390035	12.158024	15.945875	20.108668	29.947172	16.294059	32.84694	25.736319	23.729916
BJCoeffVAR	45.878966	52.290053	35.434236	21.58307	39.743321	34.55319	36.665914	24.805884	29.919895	20.303346	35.745774	26.645535	12.481857	17.075388	21.123908	30.88075	16.515421	33.295684	26.658232	25.251611
ShCoeffVAR	40.867601	47.282874	34.358097	20.640043	34.962663	35.037528	33.666085	24.357648	29.583293	20.423249	35.34179	24.166382	12.360036	16.109953	19.927018	29.776012	15.487289	31.441317	24.686233	24.16288
SubCoeffVAR	48.447209	53.914924	38.046645	23.866699	40.683861	37.877921	38.62027	27.687576	32.652021	23.310703	38.556381	28.086063	14.518898	18.694452	23.391259	32.558522	18.385823	36.03242	29.30726	28.217609
Ambient	11.6	12.1	11.7	12.7	11.8	10.7	12.8	15.6	18.6	15.6	15.6	14.6	12.6	12.7	13.4	14.4	15.5	15.4	15.6	12.8
Standard Deviation	01-May-21	02-May-21	03-May-21	04-May-21	05-May-21	06-May-21	07-May-21	08-May-21	09-May-21	10-May-21	11-May-21	12-May-21	13-May-21	14-May-21	15-May-21	16-May-21	17-May-21	18-May-21	19-May-21	20-May-21
BSCoeffVAR	2.3169367	2.8903126	1.7755423	1.3379805	3.0432593	2.5157727	3.2911607	1.2386431	0.5831005	1.7360745	1.3391342	5.5223129	0.9491264	1.3046833	1.5583809	1.7154045	2.2669327	2.9668472	2.8632226	1.8506522
TI&BJCoeffVAR	7.8270569	4.2643839	1.8973376	3.2894903	4.9066085	3.4053076	4.5771275	1.4376367	1.8374408	1.031378	1.8401617	1.2556873	1.299326	1.1626532	1.1594057	1.2954649	1.9004826	2.8744888	2.6511507	1.2772112
TI+CoeffVAR	2.4025892	3.0629241	0.9437779	2.8784978	2.8842318	3.6381244	2.695229	0.6665441	1.3843615	1.0444644	2.0287576	1.3852845	0.7090717	1.1494031	1.2150997	1.6729874	2.1051312	2.2845126	2.8344052	1.6212405
TICoeffVAR	2.0045213	4.9167048	2.3609485	2.6031179	3.9819437	6.2303179	3.4358776	1.3231618	2.3868657	2.7517108	4.2037447	6.0117521	1.0104482	0.7083434	1.2220492	2.530542	1.2281884	3.8620401	2.5345409	1.8802572
BJCoeffVAR	2.3254613	3.7661256	1.5362973	1.6404473	4.1798128	5.7112045	5.7712508	0.9461904	0.6607534	1.7129756	2.0074898	5.5954131	0.9668523	1.1788904	1.3742421	1.3413788	1.4953665	1.9413849	1.6568953	1.4529136
ShCoeffVAR	8.5606328	9.5088688	3.3330106	1.8010108	5.5678393	5.7318577	6.4174669	1.4947447	2.0569482	1.970673	2.5924667	5.6319959	1.679354	1.2260874	2.3389568	2.9084683	1.9678319	4.9941889	2.3072269	2.3603549
SubCoeffVAR	4.2615694	4.2354649	2.4639217	1.525872	3.3470936	6.526214	4.9121509	1.2852172	1.7440282	1.6620697	2.3271199	6.1534445	1.0712824	1.8367598	2.2729004	2.1148899	2.4801544	3.2976722	4.152824	1.7168112
COUNT																				
BSCoeffVAR	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
TI&BJCoeffVAR	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7
TI+CoeffVAR	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7
TICoeffVAR	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
BJCoeffVAR	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
ShCoeffVAR	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6
SubCoeffVAR	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5
Confidence Limits																				
BSCoeffVAR	1.6055257	2.0028476	1.2303654	0.9271561	2.1088323	1.7432783	2.2806161	0.8583201	0.4040606	1.2030161	0.9279556	3.8266973	0.657699	0.9040826	1.079883	1.1886928	1.5708753	2.0558825	1.9840756	1.282413
TI&BJCoeffVAR	5.7982584	3.1590418	1.4055415	2.4368438	3.6347997	2.5226408	3.3907212	1.0649966	1.3611701	0.7640415	1.3631858	0.9302091	0.9625365	0.8612897	0.858884	0.9596762	1.4078713	2.1293972	1.9639638	0.9461539
TI+CoeffVAR	1.7798303	2.2690042	0.6991476	2.1323818	2.1366296	2.6951107	1.9966169	0.4937737	1.0255305	0.7737359	1.502897	1.0262142	0.525278	0.8514741	0.9001419	1.2393436	1.5594744	1.6923595	2.0997182	1.2010097
TICoeffVAR	1.7570081	4.3702304	2.0894246	2.2816915	3.4902634	5.4610141	3.0116242	1.1597812	2.0921416	2.4119366	3.684677	5.2694362	0.8856806	0.620879	1.0711537	2.2180771	1.0765348	3.3851652	2.2215822	1.6480878
BJCoeffVAR	1.6114328	2.609744	1.0645802	1.1367511	2.8964093	3.9575901	3.9991993	0.6556644	0.4578703	1.1870097	1.3910939	3.8773522	0.6699821	0.8169144	0.9522837	0.929511	1.0362171	1.3452863	1.1481487	1.0067993
ShCoeffVAR	6.849967	7.6085399	2.6669149	1.4410823	4.4551174	4.5863571	5.1349486	1.1960229	1.6458711	1.5768379	2.0743672	4.5064525	1.3437384	0.9810562	1.8715208	2.3272166	1.5745646	3.9961084	1.8461321	1.8886426
SubCoeffVAR	3.7353616	3.7124805	2.1596829	1.3374612	2.9338629	5.7203737	4.305611	1.1265218	1.52868	1.4568415	2.039773	5.3936328	0.9390032	1.6099613	1.9922484	1.8537486	2.1739112	2.890484	3.6400438	1.5048238

Coeff VAR	BS	TI	Sub
C1	48.7384	44.0292	48.8882
C2	47.4695	47.3693	54.0095
C3	46.445	42.0566	49.1358
C4	46.9794	44.4549	48.1547
C5	48.2631	44.2721	55.0749
C6	42.5153	48.7636	53.0509
C7	45.6799	54.1158	59.9999
C8	42.9143	41.9574	54.4485
	54.7217	51.9317	53.9652
	51.0757	52.4128	62.5059
	52.8899	32.2303	36.5239
	51.9939	36.3333	41.0137
	56.2777	31.8147	38.6512
	46.7255	35.6502	39.3348
	53.5922	36.3628	42.4531
	50.8457	18.5906	25.8034
	37.1791	22.1437	23.1307
	34.8783	19.1235	22.2823
	36.7659	20.8063	25.1623
	35.3594	23.0887	25.959
	38.9339	39.8216	41.633
	33.2259	37.37	44.4722
	37.5424	31.0272	42.2195
	36.8012	36.9075	39.4871
	23.1057	40.0893	45.5404
	25.2278	26.2756	37.8501
	22.5222	42.0305	48.9277
	24.2574	32.1833	35.2668
	22.7602	39.6684	35.4161
	21.8259	31.7484	51.9135
	24.6387	37.3304	39.4241
	21.5592	36.6147	44.0074
	44.1037	30.8795	42.0574
	40.2265	36.8801	35.8902
	40.6957	38.2849	45.6689
	41.0164	22.651	26.8226
	41.0896	24.3778	29.0609
	36.3327	26.6652	28.4391
	41.9458	24.2219	28.201
	34.7078	25.0538	29.9505
	34.9852	26.9233	32.9912
	36.9229	29.9378	34.1402
	40.4185	28.4992	33.1276
	35.4846	31.4546	33.3659
	36.1213	30.4677	35.0618
	34.657	16.9038	23.3582
	34.2383	21.7922	24.4085
	40.6295	19.1186	23.6942
	42.2743	21.6299	24.6112
	38.3565	21.7335	26.6029
	38.9893	27.2713	38.2509
	36.5653	35.6764	39.6693
	41.3689	33.3476	40.0566
	34.592	35.5737	40.1789
	39.931	37.4674	42.2299
	32.7296	19.6931	30.6568
	26.6402	31.5795	35.408
	24.7951	20.1609	23.7892
	25.5294	28.8346	30.6324
	24.7925	31.9177	36.4962
	27.0995	11.6418	14.5356
	23.9779	12.8272	13.8265
	27.5018	10.7346	15.7707
	25.978	12.2753	15.3212
	31.5177	12.9506	14.575
	11.9895	16.0803	18.8149
	31.509	16.8792	20.1206
	31.1515	15.1139	20.5404
	31.8059	15.382	18.0669
	30.1153	15.8184	19.9523
	31.6767	18.9879	22.6257
	31.1482	20.895	25.5915
	23.046	20.1093	25.0712
	22.5076	18.8537	23.7788
	22.3407	20.7619	26.7883
	20.7779	28.8507	32.0358
	24.5995	31.5449	34.7456
	21.1607	26.3926	33.9971
	18.7463	29.9633	32.7319
	21.4232	31.1647	36.0848
	38.2838	17.8648	18.9491
	36.4125	16.2725	20.1605
	37.7639	15.09	20.9314
	35.201	15.1074	17.1131
	39.0793	15.8542	20.7774
	35.7063	31.4458	36.0986
	36.408	35.3049	40.2172
	36.3073	27.2172	37.9201
	21.1102	32.9533	34.3005
	29.6619	33.4972	41.1851
	32.3023	27.3334	31.702
	20.6561	26.0975	31.5141
	33.7081	23.5316	33.1997
	28.0518	22.8493	26.9515
	20.4642	27.404	31.5452
	30.8195	22.8895	26.872
	15.0566	24.808	30.1592
	13.5365	21.3426	29.3421
	14.0579	23.3448	28.6735
	13.2131	25.1966	31.4258
	12.4106		
	12.8594		
	15.0032		
	13.8612		
	19.8451		
	17.3456		
	17.4161		
	17.2248		
	19.6071		
	16.2097		
	18.339		
	16.8088		
	23.3653		
	21.2803		
	22.3811		
	20.6807		
	24.9973		
	20.3315		
	23.008		
	21.5025		
	32.5367		
	31.1406		
	32.6958		
	29.3552		
	35.1182		
	30.5991		
	32.4488		
	31.4986		
	22.3018		
	16.8431		
	16.4374		
	17.0135		
	18.8386		
	15.6606		
	16.3181		
	15.3214		
	36.7606		
	33.0253		
	32.9802		
	30.2125		
	37.8043		
	33.5105		
	35.4441		
	29.3152		
	32.5732		
	26.5667		
	29.2445		
	28.2618		
	30.4057		
	26.9818		
	28.0219		
	22.8924		
	27.0991		
	24.8511		
	25.8412		
	24.1435		
	28.7422		
	22.9816		
	27.2008		
	26.155		

Mann-Whitney Pariwise

	BS	TI	Sub
BS		0.1057	0.03623
TI	0.1057		0.0012
Sub	0.03623	0.0012	

Appendix B - Summary data and statistical analysis for 'Correlations between variability indices'

Table 5

EXP1	LoMIN	MEANMIN	HiMAX	MEANMA	MEANME	MEANSTD	MEANDTP	MEANCoeffVAR
LoMIN		3.36E-05	0.00745	0.026841	0.97436	0.007885	1.17E-03	0.006564
MEANMIN	0.70992		0.53672	0.48264	0.24206	0.12891	5.89E-02	0.041476
HiMAX	-0.50328	-0.12431		3.05E-10	8.43E-02	1.67E-06	3.50E-08	2.61E-05
MEANMA	-0.42569	-0.14111	0.89487		1.12E-02	1.26E-11	1.59E-13	8.41E-09
MEANME	0.00649	0.23305	0.33833	0.48046		0.005951	3.04E-02	1.33E-01
MEANSTD	-0.50019	-0.29963	0.77934	0.91941	0.51526		5.61E-14	1.38E-13
MEANDTP	-0.59111	-0.36801	0.84271	0.94382	0.4171	0.9484		4.20E-12
MEANCoe	-0.51009	-0.39493	0.71669	0.86081	0.2967	0.94444	0.92641	

EXP2	LoMIIN	MEANMIN	HiMAX	MEANMA	MEANME	MEANSTD	MEANDTP	MEANCoeffVAR
LoMIIN		1.48E-12	0.02553	0.02613	0.65621	0.000267	0.001281	2.45E-06
MEANMIN	0.8216		0.80045	0.4623	0.02557	0.011806	0.053547	0.000119
HiMAX	-0.32559	-0.03788		1.29E-14	5.14E-10	7.43E-11	1.15E-12	8.38E-08
MEANMA	-0.32435	-0.10985	0.85807		9.92E-13	2.00E-22	5.49E-32	1.38E-13
MEANME	0.06666	0.32551	0.7615	0.82505		6.22E-07	6.20E-09	0.000886
MEANSTD	-0.50803	-0.36436	0.78359	0.9386	0.65391		9.62E-32	1.40E-28
MEANDTP	-0.45586	-0.28342	0.82378	0.97734	0.72907	0.97676		6.98E-20
MEANCoe	-0.62662	-0.53203	0.68939	0.841	0.46889	0.96774	0.91963	

EXP3	LoMIIN	MEANMIN	HiMAX	MEANMA	MEANME	MEANSTD	MEANDTP	MEANCoeffVAR
LoMIIN		1.15E-09	0.02088	0.056236	0.66025	0.001509	0.001513	7.39E-05
MEANMIN	0.74615		0.23211	0.3625	0.18379	0.000879	0.006535	3.68E-07
HiMAX	-0.33265	-0.17576		4.66E-17	1.96E-07	4.63E-12	1.92E-16	2.03E-08
MEANMA	-0.27745	-0.13438	0.88716		1.24E-14	2.35E-18	2.99E-24	4.81E-10
MEANME	-0.06509	0.19514	0.66947	0.85377		4.88E-07	1.69E-08	0.004184
MEANSTD	-0.44548	-0.46459	0.80632	0.90159	0.65306		3.75E-33	1.58E-24
MEANDTP	-0.44538	-0.38731	0.87955	0.94661	0.70909	0.97842		4.49E-18
MEANCoe	-0.54024	-0.65827	0.70636	0.75699	0.4061	0.94811	0.89863	

Figure 28

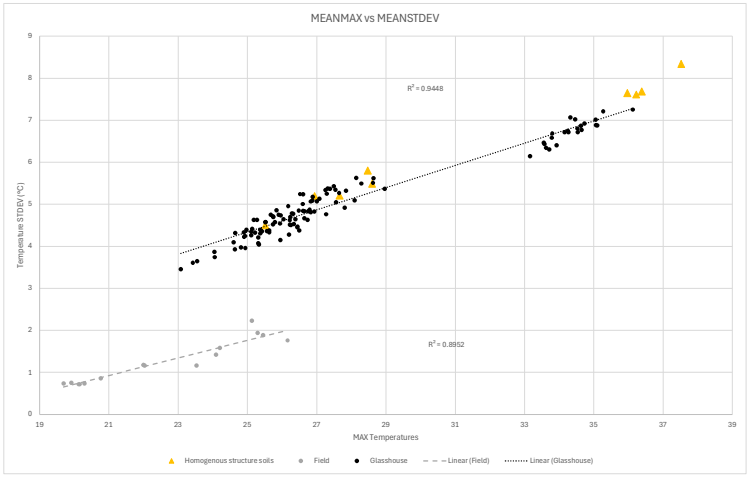
			MEANMAX	MEANSTD	MAX/STDEV	STDEV/MAX
EXP1	BS1	EXP1BS1	34.64615385	6.771273009	5.116638157	0.195440828
EXP1	BS2	EXP1BS2	36.12307692	7.256321609	4.978152688	0.200877728
EXP1	BS3	EXP1BS3	35.1	6.88079842	5.1011522	0.196034143
EXP1	BS4	EXP1BS4	35.05384615	7.014536992	4.99731432	0.200107485
EXP1	TI1	EXP1TI1	33.78461538	6.585477144	5.130169712	0.194925325
EXP1	TI2	EXP1TI2	33.92307692	6.405533896	5.295901555	0.188825262
EXP1	TI3	EXP1TI3	34.26923077	6.720810103	5.098973225	0.196117915
EXP1	TI4	EXP1TI4	34.53846154	6.720638679	5.139163581	0.194584193
EXP1	TI5	EXP1TI5	35.26923077	7.213732269	4.889179339	0.204533303
EXP1	TI6	EXP1TI6	34.24615385	6.74815977	5.074887824	0.19704869
EXP1	TI7	EXP1TI7	34.73076923	6.925389541	5.014991435	0.199402135
EXP1	TI8	EXP1TI8	34.15384615	6.71467299	5.086449661	0.196600786
EXP1	TI9	EXP1TI9	33.71538462	6.304413531	5.347901823	0.186989222
EXP1	BJ1	EXP1BJ1	34.63076923	6.872263684	5.03920845	0.198443865
EXP1	BJ2	EXP1BJ2	34.46153846	7.025085701	4.905497232	0.203852933
EXP1	BJ3	EXP1BJ3	33.57692308	6.438248185	5.215226582	0.191746223
EXP1	BJ4	EXP1BJ4	33.16153846	6.14505195	5.396461857	0.1853066
EXP1	BJ5	EXP1BJ5	33.62307692	6.347149458	5.297350747	0.188773605
EXP1	BJ6	EXP1BJ6	34.32307692	7.066348112	4.857258145	0.205877466
EXP1	BJ7	EXP1BJ7	33.8	6.684368896	5.056573108	0.197762393
EXP1	BJ8	EXP1BJ8	33.55384615	6.466118714	5.189178801	0.192708719
EXP1	BJ9	EXP1BJ9	34.52307692	6.80551836	5.072806375	0.197129543
EXP1	BJ10	EXP1BJ10	35.06153846	6.886060133	5.091668935	0.196399258
EXP1	Sand1	EXP1Sand1	35.96923077	7.650569066	4.701510497	0.2126976
EXP1	Sand2	EXP1Sand2	36.38076923	7.683764077	4.734758754	0.211204003
EXP1	Sand3	EXP1Sand3	36.22307692	7.613621245	4.757667312	0.210187038
EXP1	Sand4	EXP1Sand4	37.52307692	8.340512578	4.498893392	0.222276883
EXP2	BS1	EXP2BS1	28.96515152	5.370933485	5.39294549	0.185427426
EXP2	BS2	EXP2BS2	26.38621212	4.647335501	5.677707605	0.176127421
EXP2	BS3	EXP2BS3	27.00651515	5.071544842	5.325106253	0.18778968
EXP2	BS4	EXP2BS4	26.44030303	4.456655544	5.932767917	0.168555388
EXP2	BS5	EXP2BS5	27.31439394	5.376537053	5.080294931	0.196838966
EXP2	BS6	EXP2BS6	25.31075758	4.211757402	6.009547835	0.16640187
EXP2	BS7	EXP2BS7	26.64181818	4.838306005	5.506435135	0.181605699
EXP2	BS8	EXP2BS8	25.36666667	4.397601844	5.76829544	0.173361439
EXP2	TI+BJ1	EXP2TI+BJ1	26.64545455	4.668935312	5.706965885	0.175224457
EXP2	TI+BJ2	EXP2TI+BJ2	26.79545455	4.876828545	5.494442608	0.182002083
EXP2	TI+BJ3	EXP2TI+BJ3	24.63863636	3.926493484	6.274971922	0.159363263
EXP2	TI+BJ4	EXP2TI+BJ4	26.73909091	4.630203386	5.774927941	0.173162334
EXP2	TI+BJ5	EXP2TI+BJ5	25.63030303	4.335917382	5.911160378	0.169171522
EXP2	TI+BJ6	EXP2TI+BJ6	25.94818182	4.153950714	6.246627273	0.160086388
EXP2	TI+BJ7	EXP2TI+BJ7	25.30969697	4.072859815	6.214232289	0.160920924
EXP2	TI+1	EXP2TI+1	26.33939394	4.530889985	5.813293641	0.172019523
EXP2	TI+2	EXP2TI+2	24.81787879	3.977301307	6.239878972	0.160259519
EXP2	TI+3	EXP2TI+3	26.20060606	4.282449362	6.118135638	0.163448485
EXP2	TI+4	EXP2TI+4	23.4230303	3.610323	6.487793558	0.154135607
EXP2	TI+5	EXP2TI+5	25.32863636	4.045935534	6.260266915	0.159737598
EXP2	TI+6	EXP2TI+6	24.60151515	4.096660858	6.005260383	0.166520673
EXP2	TI+7	EXP2TI+7	23.07787879	3.453231013	6.682981446	0.149633814
EXP2	TI+8	EXP2TI+8	25.93909091	4.543003926	5.709678294	0.175141216
EXP2	TI1	EXP2TI1	26.49348485	4.378909047	6.050247805	0.165282486
EXP2	TI2	EXP2TI2	26.32242424	4.777560899	5.509594707	0.181501554
EXP2	TI3	EXP2TI3	24.05772727	3.743510022	6.426516059	0.155605306
EXP2	TI4	EXP2TI4	25.10954545	4.264113359	5.888573623	0.169820412
EXP2	TI5	EXP2TI5	26.75212121	4.83799912	5.529583728	0.18084544
EXP2	BJ1	EXP2BJ1	27.805	4.92380421	5.647056385	0.17708341
EXP2	BJ2	EXP2BJ2	28.09424242	5.095266369	5.513792683	0.181363366
EXP2	BJ3	EXP2BJ3	27.64621212	5.272937439	5.243038144	0.19072911
EXP2	BJ4	EXP2BJ4	26.93348485	4.832994235	5.572836121	0.179441846
EXP2	BJ5	EXP2BJ5	24.90151515	4.228591546	5.88884381	0.169812621
EXP2	BJ6	EXP2BJ6	25.55651515	4.361055805	5.860166963	0.170643602
EXP2	BJ7	EXP2BJ7	25.89893939	4.753776486	5.448076802	0.18355101
EXP2	BJ8	EXP2BJ8	24.89863636	4.331409026	5.748391855	0.173961697
EXP2	Sh1	EXP2Sh1	26.60227273	4.848229039	5.487008248	0.182248678
EXP2	Sh2	EXP2Sh2	24.93818182	3.962180515	6.294054933	0.158880088
EXP2	Sh3	EXP2Sh3	27.27393939	4.765323243	5.723418539	0.174720754
EXP2	Sh4	EXP2Sh4	23.54757576	3.646614693	6.457379718	0.154861576
EXP2	Sh5	EXP2Sh5	25.74575758	4.700211889	5.477573816	0.182562579
EXP2	Sh6	EXP2Sh6	24.04590909	3.865635917	6.220427791	0.160760648
EXP2	Sub1	EXP2Sub1	27.65954545	5.207260697	5.311726657	0.1882627
EXP2	Sub2	EXP2Sub2	28.47363636	5.802654194	4.907002108	0.203790416
EXP2	Sub3	EXP2Sub3	28.59727273	5.492730428	5.206385623	0.192071827
EXP2	Sub4	EXP2Sub4	25.51939394	4.501383733	5.669233164	0.176390699
EXP2	Sub5	EXP2Sub5	26.93732084	5.198317484	5.181930677	0.192978267
EXP3	BSF1	EXP3BSF1	26.24	4.698763077	5.584448412	0.179068715
EXP3	BSF2	EXP3BSF2	26.045	4.643726129	5.60864256	0.178296261
EXP3	BSF3	EXP3BSF3	25.63214286	4.37935592	5.852948087	0.17085407
EXP3	BSF4	EXP3BSF4	25.40857143	4.365258682	5.820633616	0.171802602
EXP3	BSF5	EXP3BSF5	24.64928571	4.316754091	5.710143593	0.175126944
EXP3	BSF6	EXP3BSF6	25.73928571	4.524661941	5.688664932	0.17578817
EXP3	BSF7	EXP3BSF7	25.11357143	4.352616396	5.769764469	0.1733173
EXP3	BSF8	EXP3BSF8	26.17714286	4.955883949	5.28203306	0.189321041
EXP3	BSR1	EXP3BSR1	28.64142857	5.625326594	5.091513905	0.196405238
EXP3	BSR2	EXP3BSR2	28.28571429	5.496971415	5.145690627	0.194337373
EXP3	BSR3	EXP3BSR3	27.56142857	5.048092444	5.459770968	0.183157866
EXP3	BSR4	EXP3BSR4	26.87285714	5.090823276	5.278685919	0.189441087
EXP3	BSR5	EXP3BSR5	27.24928571	5.342543276	5.100433315	0.196061773
EXP3	BSR6	EXP3BSR6	25.67785714	4.751866189	5.40374163	0.18505696
EXP3	BSR7	EXP3BSR7	26.44428571	4.475251762	5.909005151	0.169233225
EXP3	BSR8	EXP3BSR8	26.51714286	5.24480647	5.055885857	0.197789275
EXP3	HDF1	EXP3HDF1	25.96214286	4.738134689	5.479401613	0.18250168
EXP3	HDF2	EXP3HDF2	25.525	4.57843499	5.575049129	0.179370617
EXP3	HDF3	EXP3HDF3	26.25714286	4.508071118	5.824473964	0.171689324
EXP3	HDF4	EXP3HDF4	26.22142857	4.517232472	5.804755176	0.172272554
EXP3	HDF5	EXP3HDF5	25.14	4.415323099	5.69380755	0.175629399
EXP3	HDF6	EXP3HDF6	25.185	4.630228364	5.439256559	0.183848655
EXP3	HDF7	EXP3HDF7	25.41785714	4.353911018	5.83793675	0.171293394
EXP3	HDF8	EXP3HDF8	25.37142857	4.305760189	5.89243884	0.169709016
EXP3	HDR1	EXP3HDR1	28.62428571	5.510353823	5.194636612	0.192506247
EXP3	HDR2	EXP3HDR2	27.84714286	5.324202338	5.230293871	0.191193846
EXP3	HDR3	EXP3HDR3	27.53571429	5.350860693	5.146034604	0.194324383
EXP3	HDR4	EXP3HDR4	26.88285714	5.177188894	5.192558682	0.192583283
EXP3	HDR5	EXP3HDR5	26.59642857	5.007134053	5.311706915	0.188263399
EXP3	HDR6	EXP3HDR6	26.22142857	4.621634836	5.673626217	0.176254121
EXP3	HDR7	EXP3HDR7	25.79357143	4.57771195	5.634599055	0.177474917
EXP3	HDR8	EXP3HDR8	27.29357143	5.252010888	5.196785005	0.192426664
EXP3	LDF1	EXP3LDF1	26.82928571	4.81453366	5.572561666	0.179450684
EXP3	LDF2	EXP3LDF2	25.83714286	4.860080218	5.316196791	0.188104399
EXP3	LDF3	EXP3LDF3	26.48142857	4.851806491	5.45805539	0.183215436
EXP3	LDF4	EXP3LDF4	25.22142857	4.329140607	5.825966598	0.171645337
EXP3	LDF5	EXP3LDF5	24.935	4.247182785	5.870950525	0.17033017
EXP3	LDF6	EXP3LDF6	24.97071429	4.395088886	5.681503818	0.176009738
EXP3	LDF7	EXP3LDF7	25.73928571	4.716849757	5.456880553	0.183254882
EXP3	LDF8	EXP3LDF8	25.275	4.629917813	5.459060186	0.183181714
EXP3	LDR1	EXP3LDR1	28.14142857	5.632561695	4.996204231	0.200151946
EXP3	LDR2	EXP3LDR2	27.38214286	5.371068066	5.098081522	0.196152218
EXP3	LDR3	EXP3LDR3	27.08071429	5.134736885	5.274021803	0.189608621
EXP3	LDR4	EXP3LDR4	26.28428571	4.787545557	5.490137985	0.182144784
EXP3	LDR5	EXP3LDR5	26.60571429	5.240955798	5.076500416	0.196986096
EXP3	LDR6	EXP3LDR6	25.51642857	4.576792141	5.575177502	0.179366486
EXP3	LDR7	EXP3LDR7	26.83	5.069604966	5.292325572	0.18895285
EXP3	LDR8	EXP3LDR8	27.49071429	5.433687104	5.059311248	0.197655363
EXP4	Meadow1	EXP4Meadow1	22	1.177272246	18.68726633	0.053512375
EXP4	Meadow2	EXP4Meadow2	20.29333333	0.738020082	27.4969934	0.036367612
EXP4	Meadow3	EXP4Meadow3	20.76666667	0.862017389	24.09077464	0.041509666
EXP4	Meadow4	EXP4Meadow4	20.15833333	0.719872381	28.00264862	0.035710908
EXP4	Meadow5	EXP4Meadow5	19.91666667	0.752814198	26.45628459	0.037798202
EXP4	Meadow6	EXP4Meadow6	20.125	0.71968099	27.96377879	0.035760546
EXP4	Meadow7	EXP4Meadow7	19.69166667	0.737719294	26.69262797	0.037463527
EXP4	Meadow8	EXP4Meadow8	22.03333333	1.161788069	18.96501945	0.052728657
EXP4	Disturbed	EXP4Disturbed1	25.12666667	2.23316952	11.25157156	0.088876473
EXP4	Disturbed	EXP4Disturbed2	23.53333333	1.163519795	20.22598845	0.049441351
EXP4	Disturbed	EXP4Disturbed3	24.2	1.584271792	15.27515677	0.065465777
EXP4	Disturbed	EXP4Disturbed4	26.15833333	1.763348127	14.83446912	0.067410569
EXP4	Disturbed	EXP4Disturbed5	24.09166667	1.421126463	16.95251428	0.0589883
EXP4	Disturbed	EXP4Disturbed6	25.29166667	1.938477522	13.04718078	0.07664491
EXP4	Disturbed	EXP4Disturbed7	25.45	1.890813303	13.45981645	0.074295218

	STDEV/MAX
EXP1TI1	0.19493
EXP1TI2	0.18883
EXP1TI3	0.19612
EXP1TI4	0.19458
EXP1TI5	0.20453
EXP1TI6	0.19705
EXP1TI7	0.1994
EXP1TI8	0.1966
EXP1TI9	0.18699
EXP1BJ1	0.19844
EXP1BJ2	0.20385
EXP1BJ3	0.19175
EXP1BJ4	0.18531
EXP1BJ5	0.18877
EXP1BJ6	0.20588
EXP1BJ7	0.19776
EXP1BJ8	0.19271
EXP1BJ9	0.19713
EXP1BJ10	0.1964
EXP2TI+BJ1	0.17522
EXP2TI+BJ2	0.182
EXP2TI+BJ3	0.15936
EXP2TI+BJ4	0.17316
EXP2TI+BJ5	0.16917
EXP2TI+BJ6	0.16009
EXP2TI+BJ7	0.16092
EXP2TI+1	0.17202
EXP2TI+2	0.16026
EXP2TI+3	0.16345
EXP2TI+4	0.15414
EXP2TI+5	0.15974
EXP2TI+6	0.16652
EXP2TI+7	0.14963
EXP2TI+8	0.17514
EXP2TI1	0.16528
EXP2TI2	0.1815
EXP2TI3	0.15561
EXP2TI4	0.16982
EXP2TI5	0.18085
EXP2BJ1	0.17708
EXP2BJ2	0.18136
EXP2BJ3	0.19073
EXP2BJ4	0.17944
EXP2BJ5	0.16981
EXP2BJ6	0.17064
EXP2BJ7	0.18355
EXP2BJ8	0.17396
EXP4Meadow1	0.1825
EXP4Meadow2	0.17937
EXP4Meadow3	0.17169
EXP4Meadow4	0.17227
EXP4Meadow5	0.17563
EXP4Meadow6	0.18385
EXP4Meadow7	0.17129
EXP4Meadow8	0.16971

	STDEV/MAX
EXP1Sand1	0.2127
EXP1Sand2	0.2112
EXP1Sand3	0.21019
EXP1Sand4	0.22228
EXP2Sub1	0.18826
EXP2Sub2	0.20379
EXP2Sub3	0.19207
EXP2Sub4	0.17639
EXP2Sub5	0.19298

Tests for equal means

STDEV/MAX	0.19493				
N:	9	N:	54		
Mean:	0.2011	Mean:	0.17942		
95% conf.:	(0.1899 0.	95% conf.	(0.1755 0.18334)		
Variance:	0.00021	Variance:	0.000206		
Difference between means:	0.02167				
95% conf. interval (parametric):	(0.011311 0.032032)				
95% conf. interval (bootstrap):	(0.011945 0.031664)				
t :	4.1828	p (same m	9.37E-05	Critical t v	1.9996
Uneq. var. t :	4.1402	p (same m	0.001722		
Monte Carlo permutation:	p (same m	0.0001			



Appendix C - Summary data for 'Temperature rate of change'

Average Temperature rate

Bare Soil	Temperature Average	Total	>17°C	>17<24	>24°C
N	1343	1343	237	613	613
Min	13.575	0	0	0.003333333	0.003333333
Max	42.65	0.08166667	0.04666667	0.08166667	0.08166667
Sum	32858.6	33.68	2.42	19.30778	19.30778
Mean	24.46657	0.02507818	0.01021097	0.03149719	0.03149719
Std. error	0.2042342	0.000470543	0.00050348	0.00060718	0.00060718
Variance	56.01867	0.000297355	6.01E-05	0.000225994	0.000225994
Stand. de	7.484562	0.01724398	0.007750981	0.01503308	0.01503308
Median	22.775	0.02166667	0.006666667	0.03166667	0.03166667
25 prcntil	17.925	0.01166667	0.006666667	0.01833333	0.01833333
75 prcntil	30.175	0.03666667	0.01333333	0.04166667	0.04166667
Skewness	0.5240536	0.7125758	1.293152	0.3486383	0.3486383
Kurtosis	-5.74309	-6.717797	3.019281	-0.2994104	-0.2994104
Geom. me	23.37355	0	0	0.02737985	0.02737985
Coeff. var	30.59098	68.76088	75.90837	47.72832	47.72832

Average Temperature rate

Trifolium Incarnatum	Temperature Average	Total	>17°C	>17<24	>24°C
N	1343	1343	237	613	613
Min	13.7	0	0	0.005185	0.005185185
Max	41.34444	0.1325926	0.04667	0.128889	0.1288889
Sum	32112.57	34.13481	2.42	18.99084	18.99084
Mean	23.91107	0.02541684	0.01021	0.03098	0.03098016
Std. error	0.1950138	0.000490919	0.0005	0.000477	0.00047703
Variance	51.07481	0.000323665	6.01E-05	0.000139	0.000139493
Stand. dev	7.146664	0.0179907	0.00775	0.011811	0.0118107
Median	22.38889	0.02148148	0.00667	0.02963	0.02962963
25 prcntil	17.57778	0.01111111	0.00667	0.023333	0.02333333
75 prcntil	29.45556	0.03777778	0.01333	0.03709	0.03708995
Skewness	0.5182533	0.8751027	1.29315	1.941191	1.941191
Kurtosis	-5.722242	-7.806571	3.01928	11.86894	11.86894
Geom. mean	22.89103	0	0	0.028929	0.02892934
Coeff. var	29.88852	70.78259	75.9084	38.12344	38.12344

Disturbed	Temperature Average	Average Temperature rate
N	1248	1248
Min	17.65	0
Max	35.63333	0.1777778
Sum	27285.83	11.005
Mean	21.86364	0.008818109
Std. error	0.06862754	0.000293326
Variance	5.877755	0.000107378
Stand. dev	2.424408	0.01036235
Median	21.425	0.006666667
25 prcntil	19.975	0.003333333
75 prcntil	23.75	0.01166667
Skewness	0.721638	9.12835
Kurtosis	1.223394	120.7295
Geom. mea	21.73408	0
Coeff. var	11.08877	117.5122

Average Temperature rate

Brassica Juncea	Temperature Average	Total	>17°C	>17<24	>24°C
N	1343	1343	237	609	609
Min	13.65	0	0	0.008	0.008
Max	40.78	0.08133333	0.04666667	0.06066667	0.06066667
Sum	31860.27	32.56267	2.42	18.78777	18.78777
Mean	23.72321	0.02424621	0.01021097	0.0308502	0.0308502
Std. error	0.1940249	0.0004671	0.00050348	0.000404926	0.000404926
Variance	50.55812	0.000293018	6.01E-05	9.99E-05	9.99E-05
Stand. de	7.110423	0.01711778	0.007750981	0.009992737	0.009992737
Median	22.05	0.02	0.006666667	0.03066667	0.03066667
25 prcntil	17.47	0.01066667	0.006666667	0.02333333	0.02333333
75 prcntil	29.28	0.036	0.01333333	0.03866667	0.03866667
Skewness	0.5276929	0.7939777	1.293152	0.2928044	0.2928044
Kurtosis	-5.714182	-6.816833	3.019281	-0.2248469	-0.2248469
Geom. me	22.70801	0	0	0.02913117	0.02913117
Coeff. var	29.97244	70.59979	75.90837	32.39116	32.39116

Average Temperature rate

Sand	Temperature Average	Total	>17°C	>17<24	>24°C
N	1343	1343	237	584	584
Min	12.43125	0	0	0.003333	0.003333333
Max	43.79375	0.1595833	0.04667	0.126667	0.1266667
Sum	31819.07	40.74833	2.42	25.6725	25.6725
Mean	23.69253	0.03034128	0.01021	0.04396	0.04395976
Std. error	0.2209398	0.000668188	0.0005	0.000709	0.000709254
Variance	65.55773	0.000599616	6.01E-05	0.000294	0.000293776
Stand. dev	8.096773	0.02448706	0.00775	0.01714	0.01713989
Median	21.30625	0.02333333	0.00667	0.042361	0.04236111
25 prcntil	16.5	0.01083333	0.00667	0.031667	0.03166667
75 prcntil	30.425	0.04666667	0.01333	0.055	0.055
Skewness	0.5300299	1.035324	1.29315	0.627843	0.6278427
Kurtosis	-5.645964	-7.968243	3.01928	0.877135	0.8771349
Geom. mean	22.3769	0	0	0.040405	0.04040522
Coeff. var	34.17437	80.70545	75.9084	38.98995	38.98995

Meadow	Temperature Average	Average Temperature rate
N	1248	1248
Min	16.12	0
Max	35.54	0.1746667
Sum	23640.22	5.809333
Mean	18.94248	0.004654915
Std. error	0.04441969	0.000278419
Variance	2.46244	9.67E-05
Stand. dev	1.569216	0.00983571
Median	18.86	0.004
25 prcntil	18.165	0.001333333
75 prcntil	19.66	0.005333333
Skewness	4.239768	13.60202
Kurtosis	39.25288	209.0766
Geom. mea	18.887	0
Coeff. var	8.28411	211.2973

Appendix D - Summary data for 'Difference between bare soil and treatment'

Figure 30

EXP1BS-Sand	EXP2BS-Sub	EXP2BS-BJ	EXP3BS-TI	EXP2BS-TI	EXP2BS-TI	EXP1BS-TI	EXP2BS-S	EXP1BS-E	EXP2BS-TI	EXP5D-M
-0.297678054	-0.40044027	0.293625898	0.30303	0.54568	0.3868	0.26473	0.82051	0.48157	0.19828	1.20249
-0.925902397	0.016934664	0.2411593	0.31131	0.30913	1.04594	0.27381	1.01127	0.2998	0.98647	1.14435
-1.163268955	-0.2167376	0.212047968	0.09705	0.16055	0.39041	0.95336	0.35811	1.05061	0.30968	0.78817
1.227955063	-0.0820489	0.439190685	0.59586	0.51533	0.62484	0.9162	0.50576	1.06867	0.41595	0.71493
-1.187165189	0.134982779	0.333033814	0.6056	0.62901	0.62332	0.29577	1.06516	0.11184	0.87664	0.39797
0.979727792	0.342207237	0.740862659	0.35257	1.01158	1.13095	0.79374	1.01907	0.98562	0.9359	1.02861
-1.215882355	-0.33542663	0.256686234	0.18321	0.20929	0.5045	0.11002	0.52642	0.13532	0.5066	0.90432
-1.426498375	-0.26147414	0.204832414	0.18961	0.27283	0.20566	0.21797	0.16328	0.29473	0.32216	0.11507
-0.997783896	-0.39497062	0.3612897	0.18522	0.32623	0.6704	0.34317	0.48097	0.55498	0.63485	0.45236
-0.684357478	-0.44563064	0.340786478		0.2774	0.60093	0.21339	0.38344	0.30666	0.53653	0.81067
0.608548501	-0.4725443	0.237680005		0.44114	0.67823	0.24573	0.50596	0.21914	0.76995	0.7316
-0.422392979	-0.51042426	0.323014663		0.14682	1.04042	0.43126	0.69062	0.48181	0.82013	1.33599
	-0.04202102	0.26094274		0.2695	0.24045	0.69238	0.26757	0.568	0.36043	0.73208
	-0.13932333	0.139571253		0.27915	0.16515		0.27706		0.31659	0.35142
	-0.23579129	0.207647595		0.3392	0.35166		0.42026		0.32288	0.19712
	-0.30210979	0.242113462		0.40796	0.51267		0.56412		0.74494	0.77495
	-0.19726315	0.144607954		0.07165	0.1493		0.30278		0.09639	1.03813
	-0.62448278	0.083999156		0.20808	0.5435		0.37517		0.50588	1.07087
	-0.33593666	0.428043944		0.58614	0.63704		0.826		0.68729	1.17281
	-0.36538475	0.106859471		0.33173	0.24448		0.27705		0.4464	0.98636
	-0.24426023	0.068497844		0.2736	0.21879		0.2216		0.39809	0.88257
	-0.13818797	0.186608611		0.29368	0.25464		0.25379		0.35002	0.96138
	-0.60542951	-0.058416475		-0.00913	0.39252		-0.01884		0.51256	1.05969
	-0.63658561	0.187209486		0.28018	0.65237		0.40252		0.85768	1.0806
	-0.24359495	0.159912306		0.33963	0.25369		0.30091		0.40324	1.04256
	-0.40823496	0.206537561		0.28298	0.38325		0.3398		0.47051	0.95375
	-0.41786721	0.22308398		0.3102	0.59618		0.68973		0.92352	
	-0.74109781	0.117493681		0.12314	0.58828		0.41615		0.71877	
	-0.70942717	0.053016655		0.19232	0.23918		0.77439		0.51014	
	-0.67425692	0.011350739		-0.07558	0.33488		0.90492		0.79001	
	-0.8090806	-0.160514222		-0.15497	0.39024		0.76922		0.80901	
	-0.90798247	-0.500826228		-0.40546	0.14008		0.87664		0.74522	
	-0.80306615	-0.468731447		-0.11074	0.17356		0.66245		0.92308	
	-0.42533317	-0.002832981		0.42992	0.17194		0.54857		0.82336	
	-0.27712609	0.026947932		0.56047	0.24686		0.74488		1.02983	
	-0.4636213	-0.211106154		0.18256	0.22878		0.38645		0.5363	
	-0.70927661	-0.353007599		0.05131	0.5129		0.44532		0.98348	
	-0.46864614	-0.181302067		0.35206	0.56637		1.00035		0.9452	
	-0.22137924	-0.264732946		1.02614	0.54206		1.11662		1.05982	
	-0.43513899	-0.187007814		0.35131	0.09456		0.44084		0.54557	
	-0.41858745	-0.238092729		0.35186	0.05115		0.38694		0.56387	
	-0.29391186	-0.174144794		0.65802	0.02818		0.58291		0.69683	
	-0.33202357	-0.191260083		0.82254	0.22177		0.88856		0.88399	
	-0.741712	-0.610010599		0.12027	0.01592		0.40315		0.57526	
	-0.57833212	-0.410581606		0.38742	-0.03714		0.60414		0.70774	
	-0.66095119	-0.408100037		0.86154	0.3866		1.08797		1.78303	
	-0.27252422	-0.090667472		0.1671	-0.01773		0.13413		0.25605	
	-0.18601497	-0.053790832		0.12366	0.08952		0.08218		0.29166	
	-0.22174224	-0.02020981		0.13148	0.16042		0.06052		0.32008	
	-0.18780529	0.117924849		0.40915	0.24914		0.21173		0.54712	
	-0.02464683	0.038299537		0.49236	0.33443		0.41207		0.79421	
	-0.38653835	0.203250539		1.16254	0.81335		0.95478		1.61379	
	-0.57223138	0.089826993		0.6803	0.68575		0.64342		1.18689	
	-0.22450375	0.173670721		0.68764	0.40678		0.37709		0.84006	
	-0.74502027	0.080891275		0.75875	0.83999		0.60522		1.49693	
	-0.29773726	0.045195055		0.32498	0.18071		0.18749		0.54317	
	-0.20053956	0.131822122		0.36624	0.2638		0.15138		0.48053	
	-0.08728195	0.095812413		0.35464	0.25072		0.17825		0.43672	
	-0.01296963	-0.015270618		0.29714	0.14766		0.14313		0.29062	
	0.528793116	0.183025934		0.9272	0.74773		0.73284		1.34898	
	-0.24485093	0.001654322		0.53404	0.72982		0.33583		1.31252	
	0.318230576	0.362208129		0.67966	0.47897		0.33894		0.86197	
	0.528149498	0.297425159		0.85149	0.62484		0.42194		1.37656	
	0.246609682	-0.020627607		0.44882	0.60028		0.17927		1.05887	
	-0.19882783	0.128464989		0.58026	0.36653		0.29127		0.74899	
	-0.17146722	0.29506704		0.68518	0.44811		0.34156		0.93834	
	-0.42934241	0.130591439		0.75256	0.73074		0.37959		1.19583	
	-0.23749536	0.172935006		0.57461	0.46654		0.29613		0.84424	

	EXP1BS-Sand	EXP2BS-Sub	EXP2BS-BJ	EXP3BS-TI	EXP2BS-TI	EXP2BS-TI	EXP1BS-TI	EXP2BS-S	EXP1BS-E	EXP2BS-TI	EXP5D-M
Mean	-0.45872486	-0.31342284	0.07008067	0.31372	0.39446	0.41165	0.44243	0.49308	0.50452	0.72241	0.84349
Standard deviation	0.913385014	0.913385014	0.300367484	0.24522	0.18108	0.29328	0.26207	0.29082	0.28257	0.33573	0.35182
N	12	12	68	68	9	68	68	13	68	13	68
Confidence limits	0.516786726	0.516786726	0.071391507	0.05828	0.1183	0.06971	0.06229	0.15809	0.06716	0.1825	0.08362

Mann-Whitney Pairwise

	EXP1BS-Sand	EXP2BS-Sub	EXP2BS-BJ	EXP3BS-TI	EXP2BS-TI	EXP2BS-TI	EXP1BS-TI	EXP2BS-S	EXP1BS-E	EXP2BS-TI	EXP5D-M
EXP1BS-Sand		0.06392	0.008433	0.05966	0.00297	0.00272	0.02079	0.00199	0.0155	0.00045	0.00052
EXP2BS-Sub	0.06392		4.87E-12	1.35E-05	2.03E-19	1.97E-20	1.95E-07	4.68E-21	1.37E-07	1.47E-22	2.40E-13
EXP2BS-BJ	0.008433	4.87E-12		0.00514	1.69E-10	2.34E-11	3.73E-05	4.80E-15	2.24E-05	1.31E-20	5.80E-12
EXP3BS-TI	0.05966	1.35E-05	0.005135		0.3875	0.299	0.3165	0.06473	0.3165	0.0005	0.00027
EXP2BS-TI	0.002968	2.03E-19	1.69E-10	0.3875		0.8635	0.9027	0.05689	0.4288	8.74E-08	2.06E-07
EXP2BS-TI&BJ	0.002717	1.97E-20	2.34E-11	0.299	0.8635		0.7526	0.1013	0.5159	1.19E-07	2.25E-07
EXP1BS-TI	0.02079	1.95E-07	3.73E-05	0.3165	0.9027	0.7526		0.3712	0.4418	0.00437	0.00111
EXP2BS-Sh	0.001986	4.68E-21	4.80E-15	0.06473	0.05689	0.1013	0.3712		0.9333	0.00011	1.37E-05
EXP1BS-BJ	0.0155	1.37E-07	2.24E-05	0.3165	0.4288	0.5159	0.4418	0.9333		0.04827	0.01086
EXP2BS-TI+	0.0004481	1.47E-22	1.31E-20	0.0005	8.74E-08	1.19E-07	0.00437	0.00011	0.04827		0.03957
EXP5D-M	0.0005202	2.40E-13	5.80E-12	0.00027	2.06E-07	2.25E-07	0.00111	1.37E-05	0.01086	0.03957	

Figure 31

	BS-TI	BS-BJ	BS-Sand
N	1388	1388	1388
Min	-1.125	-1.31	-10.53
Max	3.30278	2.485	12.865
Sum	813.033	1057.31	-601.385
Mean	0.58576	0.76175	-0.43327
Std. error	0.01796	0.01764	0.13613
Variance	0.44767	0.43198	25.7229
Stand. de	0.66908	0.65725	5.07177
Median	0.58056	0.765	-1.2475
25 prcntil	0.08889	0.195	-4.18
75 prcntil	1.04375	1.24	3.1925
Skewness	0.34229	0.24469	0.41411
Kurtosis	-8.50815	-6.85895	-6.99501
Geom. me	0	0	0
Coeff. var	114.224	86.2814	-1170.57

Appendix E - Data and summary statistics for 'Changes in STDEV at temperature bands'

Figure 33 and 34

EXP1

BSstd25-;	Tlstd25-3	BJstd25-;	Sstd25-30
4.14285	3.63396	3.64589	5.23796
4.61762	3.85808	3.30927	5.24617
4.43827	3.87213	4.35525	5.36472
5.22391	4.16839	3.38894	5.09851
4.59255	3.93717	4.52022	
4.9932	4.32198	4.10478	
4.42152	4.857	3.93073	
4.80528	3.49168	3.43864	
4.64592	4.45211	3.35049	
	4.9733	4.54052	
	4.40984	4.54226	
	4.34033	4.60806	
	4.18561	4.9354	
	4.77972	4.31309	
	4.20298	4.20078	
	4.7855	4.22409	
	4.70216	4.55925	
	4.59856	3.99541	
	4.65161	4.09802	
	3.94846	4.62327	
	4.44077	4.27707	
	4.42929	4.36527	
	4.51023	4.46759	
	3.98191	4.25177	
	3.81489	4.44644	
		3.8996	
		4.30374	
		3.75502	
		4.1253	

BSstd30-;	Tlstd30-25	BJstd30-;	Sstd30-35
3.80434	6.229607641	3.13318	2.85458
5.17056	3.411347485	3.90774	2.56936
4.58121	3.688929487	3.90784	4.00763
3.92525	4.077490408	4.33426	6.03702
4.3328	2.884119266	6.33078	6.04467
5.03873	2.949858754	2.99793	6.63591
4.55152	4.473253849	2.10238	3.62289
3.8236	2.977837964	2.96845	5.65177
3.8684	3.747067035	3.76395	4.84728
4.0201	3.799985048	6.13777	3.47144
3.50028	2.796612534	3.11046	5.02048
4.66434	5.877061212	4.32991	4.91334
	2.414715775	6.07202	5.15715
	5.993743582	5.82017	5.98248
	3.856576437	3.43685	5.7433
	4.970669655	3.86384	5.4154
	4.836481472	4.02345	5.14962
	3.661291687	5.77017	5.3769
	3.511501664	4.37345	
	4.457953821	3.28528	
	4.712622075	3.80712	
	4.835275211	4.55559	
	3.680749471	4.59027	
	4.496027287	4.78735	
	4.681875919	3.51652	
	3.528214202	3.84484	
	3.480824093	4.86643	
	3.591287859	4.73078	
	3.907146715	3.54152	
	3.73107345	3.084	
	4.450640488	3.38403	
	3.71997322	4.69361	
	4.198642457	3.53724	
	3.290067698	4.60148	
		4.35452	
		3.39696	
		3.61816	
		3.45251	
		4.51195	
		3.06809	

BSstd35-;	Tlstd35-40	BJstd35-4	Sstd35-40
8.08885	5.944522562	6.2882	8.08885
5.18184	4.411995099	8.82554	5.18184
6.45931	5.170133856	8.69925	6.45931
8.0573	8.449806121	5.19259	8.0573
5.35306	5.736284697	5.3008	5.35306
5.73028	5.51475981	8.48725	5.73028
5.53178	4.821691832	5.33212	5.53178
7.6697	8.202518322	8.6075	7.6697
6.30948	5.517118676	5.98613	6.30948
5.23655	8.173353787	5.67759	5.23655
6.76035	7.950855205	8.33976	6.76035
7.06084	5.090601486	8.53304	7.06084
3.83317	5.079243263	5.47976	3.83317
4.7724	4.253670429	3.62025	4.7724
4.94405	6.88887168	5.47761	4.94405
4.74305	7.682315633	3.56293	4.74305
6.59877	5.854365763	7.86062	6.59877
6.33133	4.114062635	5.09758	6.33133
2.8455	7.638305579	7.66406	2.8455
2.60268	5.949457258	8.10528	2.60268
6.18572	7.055692952	4.92513	6.18572
3.80434	7.15599055	5.34516	3.80434
	5.340603473	5.13045	
	6.398801379	5.30484	
	6.861260375	7.24632	
	5.00928872	7.73873	
	3.73891037	3.5979	
	5.82008181	4.58963	
	4.809773431	5.69624	
	5.075304141	5.595	
	2.651771849	6.09708	
	4.537190594	6.90516	
	6.419476461	3.15248	
	6.522706552	5.66684	
	4.015865788	5.10722	
	6.431957382	4.21115	
	6.498371008	6.52618	
	4.513823465	3.9592	
	4.005706157	6.54044	
	4.01019534	3.08259	
	6.397025232	6.67515	
		5.24254	
		6.80859	
		6.55936	
		2.8628	
		2.59785	

EXP1	BSstd25-;	Tlstd25-3	BJstd25-;	Sstd25-30	BSstd30-;	Tlstd30-2	BJstd30-35	Sstd30-35	BSstd35-;	Tlstd35-4	BJstd35-4	Sstd35-40
N	9	25	29	4	12	34	40	18	22	41	46	22
BJin	4.14285	3.49168	3.30927	5.09851	3.50028	2.41472	2.10238	2.56936	2.60268	2.65177	2.59785	2.60268
BJax	5.22391	4.9733	4.9354	5.36472	5.17056	6.22961	6.330779	6.63591	8.08885	8.44981	8.82554	8.08885
SuBJ	41.8811	107.348	120.576	20.9474	51.2811	136.921	163.6129	88.5012	124.1	235.714	269.302	124.1
BJean	4.65346	4.29391	4.1578	5.23684	4.27343	4.02707	4.090322	4.91673	5.64093	5.74912	5.85439	5.64093
Std. error	0.10735	0.07987	0.0785	0.05445	0.15296	0.15335	0.1525754	0.27286	0.32311	0.21698	0.2503	0.32311
VarianBSe	0.10372	0.1595	0.17869	0.01186	0.28078	0.79954	0.9311698	1.34013	2.29684	1.93024	2.88193	2.29684
Stand. dev	0.32206	0.39937	0.42272	0.1089	0.52988	0.89417	0.9649714	1.15764	1.51553	1.38933	1.69763	1.51553
BJedian	4.61762	4.34033	4.25177	5.24206	4.17645	3.77353	3.885789	5.15339	5.63103	5.73629	5.63092	5.63103
25 prBSntiTl	4.42989	3.94281	3.91517	5.13338	3.8348	3.50383	3.406933	3.91144	4.76506	4.67348	5.05447	4.76506
75 prBSntiTl	4.89924	4.62509	4.4939	5.33508	4.64356	4.54249	4.598676	5.80309	6.63917	6.69198	6.99045	6.63917
Skewness	0.34887	-0.2157	-0.6241	-0.2864	0.36632	0.72774	0.6720307	-0.7378	-0.3053	0.12453	0.03715	-0.3053
Kurtosis	0.2285	-0.7874	-0.2675	1.51752	-0.9921	0.48808	0.216292	-0.3274	-0.3055	-0.5581	-0.7064	-0.3055
GeoBJ. BJean	4.64363	4.27573	4.136	5.23599	4.24379	3.93512	3.983542	4.7656	5.41869	5.57844	5.5947	5.41869
BSoeff. var	6.92083	9.30089	10.1668	2.0794	12.3995	22.204	23.59158	23.5449	26.8667	24.166	28.9975	26.8667

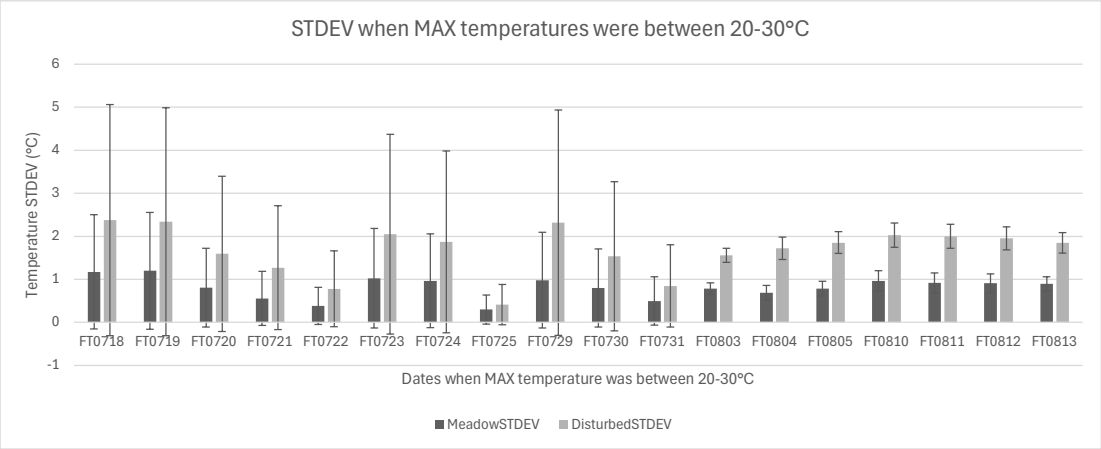
Mann-Whitney pairwise	BSstd25-;	Tlstd25-3	BJstd25-;	Sstd25-30
BSstd25-30		0.03855	0.00252	0.0109
Tlstd25-30	0.03855		0.3143	0.00174
BJstd25-30	0.00252	0.3143		0.00152
Sstd25-30	0.0109	0.00174	0.00152	

	BSstd30-;	Tlstd30-2	BJstd30-;	Sstd30-35
BSstd30-35		0.1302	0.2542	0.05408
Tlstd30-25	0.1302		0.841	0.00578
BJstd30-35	0.2542	0.841		0.00853
Sstd30-35	0.05408	0.00578	0.00853	

	BSstd35-;	Tlstd35-4	BJstd35-4	Sstd35-40
BSstd35-40		0.8911	0.6797	0.9906
Tlstd35-40	0.8911		0.6676	0.8911
BJstd35-40	0.6797	0.6676		0.6797
Sstd35-40	0.9906	0.8911	0.6797	

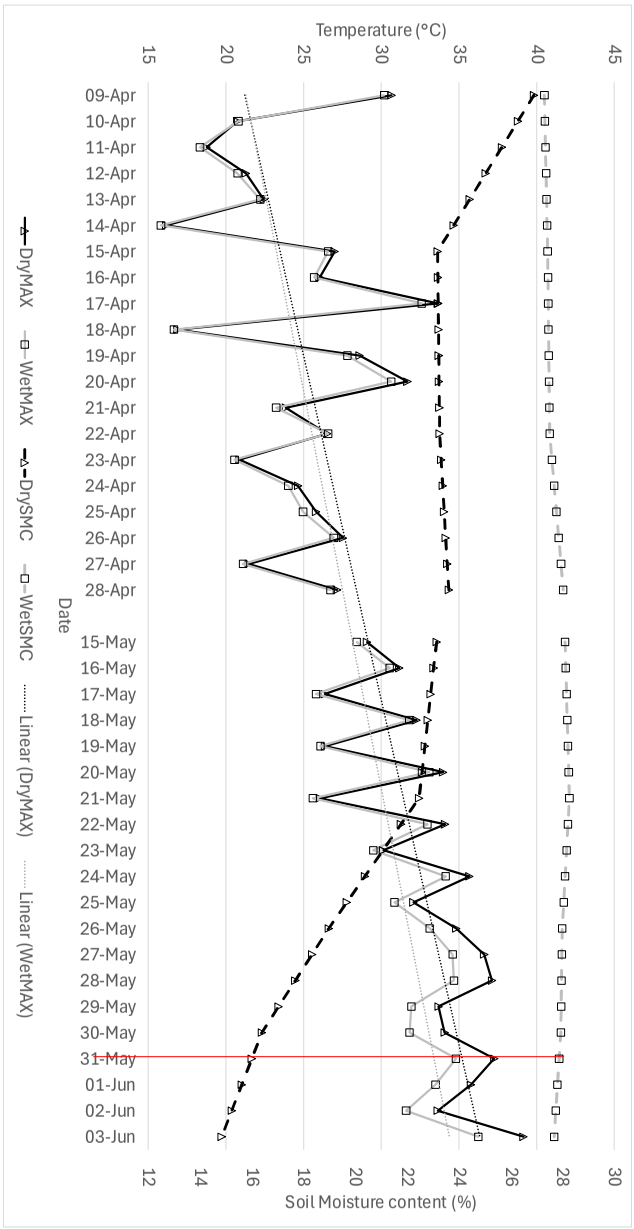
Figure 35

	Average				Standard Deviation		N		Confidence Limits	
	MeadowSTDEV	MeadowMAX	DisturbedSTDEV	DisturbedMAX	MeadowSTDEV	DisturbedSTDEV			Mconf	Dconf
FT0718	1.173034295	21.5	2.375526465	26.53333333	0.41080462	1.036510772	3	3	1.32738887	2.68811186
FT0719	1.197508827	22.46666667	2.341861808	28.13333333	0.432093884	1.025361312	3	3	1.35508391	2.65001741
FT0720	0.806393901	21.76666667	1.594560679	25.96666667	0.315719086	0.697488707	3	3	0.91250383	1.80438212
FT0721	0.557013465	20.53333333	1.271945542	23.86666667	0.187011545	0.51443444	3	3	0.63030849	1.43931543
FT0722	0.382863039	20.1	0.780837088	22.3	0.123478523	0.21416419	3	3	0.43324235	0.88358411
FT0723	1.022811126	20.8	2.051421064	24.73333333	0.365977471	0.910865514	3	3	1.15739848	2.32135881
FT0724	0.964855438	21.33333333	1.869172013	25.33333333	0.342605201	0.827581155	3	3	1.09181665	2.11512838
FT0725	0.298856899	20.03333333	0.413923743	21.9	0.054219089	0.130408529	3	3	0.3381822	0.4683902
FT0729	0.982046793	20.23333333	2.318039749	24.73333333	0.347031797	1.053075263	3	3	1.11127014	2.62306071
FT0730	0.800981393	20.13333333	1.533057139	23.53333333	0.16526274	0.422207316	3	3	0.90637912	1.73478559
FT0731	0.495924114	20.1	0.847344805	22.6	0.084834333	0.16516963	3	3	0.56118065	0.95884329
FT0803	0.782983866	20.76	1.557936812	24.2	0.154695665	0.163845561	5	4	0.13559424	0.1605657
FT0804	0.684200315	20.8	1.722325967	25.6	0.196653601	0.263234271	5	4	0.17237131	0.25796485
FT0805	0.783797626	20.08	1.854669359	24.975	0.194388344	0.257226011	5	4	0.17038576	0.25207686
FT0810	0.966874194	20.54	2.026566512	26.025	0.269940835	0.288495206	5	4	0.23660923	0.28272011
FT0811	0.917832963	21.02	1.998435541	26.75	0.267687031	0.284169197	5	4	0.23463372	0.2784807
FT0812	0.909208489	21.28	1.951772215	27	0.251940762	0.274133149	5	4	0.22083176	0.26864555
FT0813	0.894909894	21.52	1.848662464	27.125	0.18562163	0.243576907	5	4	0.16270154	0.23870098



Appendix F - Summary data and statistics for Chapter 5

Figure 38



Date	WetMAX	DryMAX	WetSTDEV	DrySTDEV	WetSMC	DrySMC	Ambient Hi
09-Apr	30.185	30.665	8.78094899	9.03542825	27.3002163	26.8965079	15
10-Apr	20.81	20.7391667	3.36036557	3.39109953	27.3211533	26.2767967	15
11-Apr	18.3316667	18.7683333	4.83463496	5.06111713	27.3420903	25.6570855	12
12-Apr	20.7475	21.29	5.7973734	6.24761046	27.3630274	25.0373743	10
13-Apr	22.215	22.4358333	5.41274356	6.14834033	27.3839644	24.4176631	12
14-Apr	15.825	16.1575	3.27722057	3.37986885	27.4049014	23.7979519	9
15-Apr	26.5816667	27.0075	6.8108042	7.08384451	27.4258385	23.1782407	15
16-Apr	25.685	26.0391667	5.55422186	5.86200399	27.437014	23.1894163	15
17-Apr	32.6058333	33.6375	7.90799612	8.55713054	27.4481896	23.2005918	16
18-Apr	16.6666667	16.895	1.58413929	2.12304754	27.4593651	23.2117674	10
19-Apr	27.82	28.6116667	5.96974742	6.54988169	27.4705407	23.2229429	
20-Apr	30.635	31.6875	9.11730021	9.57966756	27.4817162	23.2341185	
21-Apr	23.2358333	23.8633333	6.26354786	6.56581768	27.4928918	23.245294	
22-Apr	26.5808333	26.5191667	5.19452897	5.87799744	27.5040674	23.2564696	
23-Apr	20.56	20.8725	2.94926116	2.97801291	27.5916536	23.3149167	
24-Apr	24.0183333	24.6441667	6.00832762	6.23725105	27.6792398	23.3733638	
25-Apr	24.9675	25.8091667	7.57751932	7.97675812	27.766826	23.4318109	
26-Apr	26.9458333	27.54	7.10574572	7.33448572	27.8544123	23.490258	
27-Apr	21.1008333	21.4766667	5.64424213	5.85662175	27.9419985	23.5487052	
28-Apr	26.7375	27.1525	4.45943497	4.54578292	28.0295847	23.6071523	
15-May	28.4241667	29.0808333	6.29807479	6.61638339	28.0979815	23.1360821	
16-May	30.5508333	31.1675	7.32239246	7.57284143	28.1261432	23.0237984	
17-May	25.7991667	26.3725	7.05526707	7.40646692	28.1543049	22.9115146	
18-May	31.8008333	32.2816667	6.5987886	7.07281994	28.1824666	22.7992309	
19-May	26.0916667	26.3825	3.92428556	4.48712463	28.2106283	22.6869472	
20-May	33.0841667	33.98	7.43875889	8.26239266	28.23879	22.5746635	
21-May	25.6008333	26.0591667	4.77524492	4.99949721	28.2669518	22.4623798	
22-May	32.98	34.1058333	7.55695808	8.28137136	28.2116106	21.7651225	
23-May	29.4875	30.135	4.98679498	5.46691326	28.1562694	21.0678652	
24-May	34.1483333	35.67	8.8219175	9.51130723	28.1009282	20.3706079	
25-May	30.8516667	32.0741667	5.41552713	6.01995921	28.0455871	19.6733506	
26-May	33.1166667	34.8258333	7.42472767	8.71757508	27.9902459	18.9760933	
27-May	34.5958333	36.6275	7.60200472	8.94210392	27.975589	18.3301034	
28-May	34.6783333	37.1283333	8.14570683	9.49767474	27.9609321	17.6841135	
29-May	31.9375	33.6875	6.03864253	7.12368281	27.9462752	17.0381237	
30-May	31.8225	34.085	7.45815921	8.30391936	27.9333012	16.3921338	
31-May	34.8041667	37.2725	6.72371968	8.01399948	27.8699473	16.0045002	
01-Jun	33.5008333	35.7833333	6.70597106	7.82977804	27.8065934	15.6168667	
02-Jun	31.605	33.6358333	6.61579638	7.43301851	27.7432395	15.2292332	
03-Jun	36.2516667	39.1575	8.28688647	9.48424139	27.6798856	14.8415997	

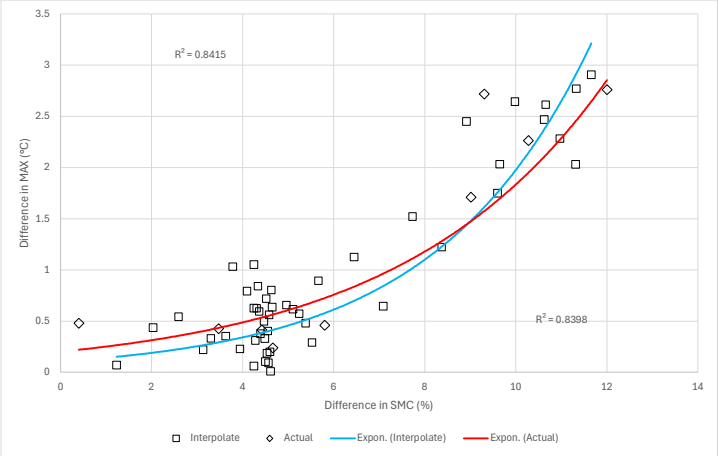
Appendix F - Summary data and statistics for Chapter 5

Figure 39

		SMC Diff+	MAX DIFF+	Aggregation
Interpolated data	10/04/2023	1.2311128	0.0708333	2023-04-10
	11/04/2023	2.034336	0.4366667	2023-04-11
	12/04/2023	2.5905176	0.5425	2023-04-12
	13/04/2023	3.1353791	0.2208333	2023-04-13
	14/04/2023	3.3039078	0.3325	2023-04-14
	16/04/2023	3.6285142	0.3541667	2023-04-16
	17/04/2023	3.7846027	1.0316667	2023-04-17
	18/04/2023	3.9398093	0.2283333	2023-04-18
	19/04/2023	4.0941392	0.7916667	2023-04-19
	20/04/2023	4.2475978	1.0525	2023-04-20
	21/04/2023	4.2475978	0.6275	2023-04-21
	22/04/2023	4.2475978	0.0616667	2023-04-22
	23/04/2023	4.2767369	0.3125	2023-04-23
	24/04/2023	4.305876	0.6258333	2023-04-24
	25/04/2023	4.3350151	0.8416667	2023-04-25
	26/04/2023	4.3641542	0.5941667	2023-04-26
	27/04/2023	4.3932933	0.3758333	2023-04-27
	30/04/2023	4.4679599	0.5	2023-04-30
	01/05/2023	4.4843483	0.3308333	2023-05-1
	02/05/2023	4.5007366	0.105	2023-05-2
	03/05/2023	4.517125	0.7183333	2023-05-3
	04/05/2023	4.5335134	0.1875	2023-05-4
	05/05/2023	4.5499017	0.405	2023-05-5
	06/05/2023	4.5662901	0.0925	2023-05-6
	07/05/2023	4.5826784	0.5616667	2023-05-7
	08/05/2023	4.5990668	0.2	2023-05-8
	09/05/2023	4.6154551	0.0108333	2023-05-9
	10/05/2023	4.6318435	0.8033333	2023-05-10
	11/05/2023	4.6482318	0.6358333	2023-05-11
	15/05/2023	4.9618994	0.6566667	2023-05-15
	16/05/2023	5.1023448	0.6166667	2023-05-16
	17/05/2023	5.2427902	0.5733333	2023-05-17
	18/05/2023	5.3832357	0.4808333	2023-05-18
	19/05/2023	5.5236811	0.2908333	2023-05-19
	20/05/2023	5.6641265	0.8958333	2023-05-20
	22/05/2023	6.4464881	1.1258333	2023-05-22
	23/05/2023	7.0884042	0.6475	2023-05-23
	24/05/2023	7.7303203	1.5216667	2023-05-24
	25/05/2023	8.3722365	1.2225	2023-05-25
	27/05/2023	9.6454856	2.0316667	2023-05-27
	28/05/2023	8.9165021	2.45	2023-05-28
	29/05/2023	9.5975266	1.75	2023-05-29
	31/05/2023	10.623224	2.4683333	2023-05-31
	01/06/2023	10.967898	2.2825	2023-06-01
	02/06/2023	11.312571	2.0308333	2023-06-02
	03/06/2023	11.657244	2.9058333	2023-06-03
	05/06/2023	11.327681	2.7691667	2023-06-05
	06/06/2023	10.653444	2.6141667	2023-06-06
	07/06/2023	9.9792072	2.6441667	2023-06-07
Actual Data	09/04/2023	0.4037084	0.48	2023-04-09
	15/04/2023	3.4715381	0.4258333	2023-04-15
	28/04/2023	4.4224325	0.415	2023-04-28
	12/05/2023	4.6646202	0.2383333	2023-05-12
	21/05/2023	5.8045719	0.4583333	2023-05-21
	26/05/2023	9.0141526	1.7091667	2023-05-26
	30/05/2023	10.278551	2.2625	2023-05-30
	04/06/2023	12.001918	2.7591667	2023-06-04
	08/06/2023	9.3049704	2.7183333	2023-06-08

	MAXDiff	SMCDiff
	0.9740805	5.903795
Standard deviation	0.8724643	2.8652282
N	58	58
	MAXConfinde	SMCCONf
Confidence limmits	0.2245338	0.7373833

Spearmans Rank	SMC Diff+	MAX DIFF+
SMC Diff+		2.25E-09
MAX DIFF+	0.68893	



Appendix F - Summary data and statistics for Chapter 5

Figure 40

Sensor	2023-06-04	2023-06-05	2023-06-06	2023-06-07	2023-06-08	2023-06-09	2023-07-02	2023-07-03	2023-07-04	2023-07-05	2023-07-06	2023-07-07	2023-07-08	2023-07-09	2023-07-10	2023-07-11	2023-07-12	2023-07-13	2023-07-14
DryMAX	39.78333333	39.31416667	38.6375	40.52167	40.94	35.98166667	32.335	31.76083333	27.66333	31.10417	34.6575	41.40833333	30.54	27.65333	36.27417	32.19917	30.455	32.66667	24.1525
WetMAX	37.02416667	36.545	36.02333	37.8775	38.22167	33.79416667	32.11416667	31.385	27.52917	30.58083	34.46083	40.9925	30.6125	27.82917	35.63667	31.91667	30.27833	32.45917	24.13333
DryMAX STDEV	1.927284162	1.996034516	2.016356	2.065918	1.952346	1.213461115	1.024557184	0.694135608	1.088522	2.200967	2.237209	0.648312495	1.169253	1.523772	0.945193	0.861336	1.394244	0.388239	
Wet MAX STDEV	1.435450251	1.359508601	1.446622	1.430315	1.471584	1.545094633	0.873774466	0.82568383	0.870501	1.914193	1.704343	0.669642035	1.292506	1.107169	0.900094	0.960169	1.145897	0.503051	
DryMAX N	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	
Wet MAX N	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	
DryMAX Confidenc Li	1.090443632	1.129342091	1.14084	1.168881	1.104623	0.686567644	0.579687147	0.392736976	0.615878	1.245292	1.265797	0.366810585	0.661555	0.862139	0.534784	0.487338	0.788853	0.219663	
Wet MAX Confidenc L	0.812167513	0.769200269	0.818488	0.809262	0.832612	0.874203522	0.494375361	0.467166022	0.492523	1.083037	0.964305	0.378878687	0.731291	0.626429	0.509267	0.543257	0.648341	0.284623