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Intensification for Redesigned and Sustainable Agricultural Systems

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Abstract

Redesign of agricultural systems is essential to deliver optimum outcomes as ecological and economic conditions change. The combination of agricultural processes in which production is maintained or increased, while environmental outcomes are enhanced, is currently known as sustainable intensification (SI). SI aims to avoid the cultivation of more land, and thus avoid the loss of unfarmed habitats, but also aims to increase overall system performance without net environmental cost. For instance, large changes are now beginning to occur to maximize biodiversity by means of integrated pest management (IPM), pasture and forage management, the incorporation of trees into agriculture, irrigation management, and by small and patch systems. SI is central to the United Nation's Sustainable Development Goals (SDG) and to wider efforts to improve global food and nutritional security.

Introduction

The mid-20th century brought agricultural transformation and the 'Green Revolution'. New crop varieties and livestock breeds, combined with increased use of inorganic fertilizers, manufactured pesticides and machinery, together with better water control and increased field size, led to sharp increases in food production from agriculture worldwide. As a result, aggregate world food production more than tripled during the past 50 years (1). The intensity of production on agricultural lands has also risen (2). The area under irrigation has doubled, and consumption of nitrogen fertilizers by sevenfold. At the same time, food production per person has grown, despite considerable population growth (Fig. 1). For each person today, there is 50% more food compared with each person in 1961 (1).

Yet this period of agricultural intensification was accompanied by considerable harm to the environment (3-5). This imposed costs on economies and made agricultural systems less efficient by degrading ecosystem goods and services, including through pollution of groundwater and losses of beneficial insects. Concern about these negative effects shifted ideas about how agricultural systems could be more effective at both food production and reductions in harm to the environment. The desire for agriculture to produce more food without environmental harm, and even to make positive contributions to natural and social capital, has been reflected in many calls for more sustainable agriculture. These have variously been evoked as a doubly green revolution (6), alternative agriculture (7-8), evergreen agriculture (9), agroecological intensification (10), save and grow (11-12), diversified agroecosystems (13), and sustainable intensification (14-16).

Sustainable Intensification comprises agricultural processes or systems where production is maintained or increased while progressing towards substantial enhancement of environmental outcomes. It incorporates these principles without the cultivation of more land and loss of unfarmed habitats, and with increases in system performance that incur no net environmental cost (17-19). However, some controversy surrounds the SI term (20). Does the term imply no more than businessas-usual; is it a vehicle to smuggle into agriculture potentially-harmful technologies; will it lead to losses of productivity as environmental goods are prioritised? At the same time, concepts of land-sparing and land-sharing have brought into sharp focus the need to improve the intensification of agricultural resources without expanding into non-agricultural and usually highly biodiverse habitats (21). SI seeks to make better use of natural and human resources (e.g., land, water, biodiversity, knowledge) and technologies.

In many farmed landscapes, the need for effective SI is urgent. Environmental degradation is reducing the asset base of existing agricultural lands (5, 22), expansion of urban and road infrastructure has removed agricultural land [in the current countries of the European Union, agricultural area fell by 31Mha over 50 years; in the USA and Canada, 0.5Mha are lost annually (23-24)], and climate change and extreme weather events create new stresses that test the resilience of agricultural systems. SI seeks to develop synergies between agricultural and landscape-wide system components, and is now a priority for the UN's Sustainable Development Goals (25). The concept is open, emphasising outcomes rather than means, can be applied to any size of enterprise, and does not predetermine technologies, production type, or design components. It can thus be distinguished from earlier manifestations of intensification because of the explicit emphasis on a wider set of environmental as well as socially-progressive outcomes. Central to SI is an acceptance that there will be no perfect end point. No designed system is expected to succeed forever, and no single package of practices is able to fit the dynamics of every ecosystem (26).

Redesign framework for sustainable intensification

Three non-linear stages in transitions towards sustainability have been proposed to occur: efficiency, substitution and redesign. While both efficiency and substitution are important, they are not sufficient for maximizing co-production of favourable agricultural and beneficial environmental outcomes without redesign (27-28).

Efficiency aims to make better use of on-farm and imported resources within existing farm configurations. Many agricultural systems are wasteful, permitting natural capital degradation within the farm or the escape of agrochemical inputs across system boundaries, which causes external costs on-farm and beyond. Post-harvest losses reduce food availability and tackling them contributes directly to efficiency gains and amplifies the benefits of yield increases generated by other means. On-farm efficiency gains can arise from targeting and rationalizing inputs of fertilizer, pesticide, and water to focus impact, reduce use, and cause less damage to natural capital and human health. Precision farming requires sensors, detailed soil mapping, drone mapping, scouting for pests, weather and satellite data, information technology, robotics, improved diagnostics and delivery systems to ensure targeted inputs (e.g., pesticide, fertilizer and water) are applied at an appropriate rate and time to the right place only when needed (10, 24, 29). Automatic control and satellite navigation of agricultural vehicles and machinery can enhance energy efficiency and limit soil compaction.

Substitution focuses on the replacement of technologies and practices. The development of new crop varieties and livestock breeds deploys substitution to replace less efficient system components with alternatives, such as plant varieties that are better at converting nutrients to biomass, that tolerate drought and/or increases in salinity, and with resistance to specific pests and diseases. Other forms of substitution include the release of biological control agents to substitute for agrochemical inputs, the use of RNA-based gene silencing pesticides, replacing the use of soil in hydroponics, and no-tillage systems that use new forms of direct seeding and weed management to replace inversion ploughing.

The third stage is fundamental for SI to achieve sustainability at scale. The redesign of agro-ecosystems is essential to harness ecological processes such as predation, parasitism, allelopathy, herbivory, nitrogen fixation, pollination, trophic dependencies and others (30-31). A prime aim is to modulate greenhouse gas emissions, provide clean water, maximize carbon sequestration, promote biodiversity, and disperse and ameliorate the effects of pests, pathogens and weeds. While efficiency and substitution tend to be additive and incremental within current production systems, redesign should be the most transformative.

Redesign presents social and institutional, as well as agricultural challenges (30-33). Unintended consequences must also be identified and mitigated as part of the redesign process.

SI impacts on productivity

The two key questions to ask of an SI system is first whether it actually generates more food, fibre and other valued products while simultaneously improving natural capital, and second, can this be done without harming key renewable capital assets? Farmers adopting various SI approaches can increase food outputs by multiplicative or by additive means (34). Multiplicative approaches improve yields per hectare by combining use of new and improved varieties with changes to agronomic-agroecological management. Additive methods require diversification of farms into a range of new crops, livestock or fish that add to the existing staples or vegetables already being cultivated. Additive components range from use of fish ponds or concrete tanks, raised beds and vegetable cultivation, rehabilitation of degraded land, fodder grasses and shrubs for livestock (and which can increase milk productivity), new crops or trees brought into rotations with staple crops such as clovers, soyabean, and indigenous trees, to the adoption of short-maturing varieties (e.g., sweet potato, cassava) that permit the cultivation of two crops per year instead of one.

An early large-scale assessment of SI was commissioned by the US National Research Council (NRC) (7). Partly driven by increased costs of fertilizer and pesticide inputs, plus growing scarcity of natural resources (such as groundwater for irrigation), and continued soil erosion, farmers had been adopting novel approaches in a wide variety of farm systems. The NRC noted that ‘alternative agriculture’ was not a single system of farming practices, but rather used a mix of crop rotations, IPM, soil- and water-conserving tillage, animal production systems that emphasised disease prevention without antibiotics, and genetic improvement of crops to resist pests and disease and to use nutrients more efficiently. Well-monitored alternative farming systems nearly always used less synthetic pesticide, fertilizer and antibiotics per unit of production than comparable conventional farms. They also required more information and management skills of farmers per unit of production. The NRC (8) conducted follow-up studies on ten of the original farms. These included integrated crop-livestock enterprises, fruit and vegetable farms, a beef cattle ranch and one rice farm. After 22 years, there were four common features of these farms: (i) Accumulation and maintenance of a natural resource base and maximization of internal resources. (ii) Environmental sustainability and closed nutrient cycles. (iii) Careful soil management, the use of crop rotations and cover crops, and, for livestock, management practices that did not use hormones or antibiotics. (iv) Taking advantage where possible of direct sales markets (via farmers markets and/or internet sales), with some sold at a premium with labelled traits and products (e.g., organic, naturally-raised livestock);

Significant progress towards SI has also been made in developing countries over the past two decades. One study analysed 286 projects in 57 countries, and a later one assessed 40 projects in 20 African countries (35-36). In both, several million farmers on tens of Mha had adopted practices that had led to yield increases of 79% (study 1) and 113% (study 2). The timescale for these improvements varied from three to ten years. A further analysis of 85 IPM projects from 24 countries in Asia and Africa implemented over a 25-year period (1990-2014) further illustrated the potential for productivity improvement and substantial reductions in pesticide costs (37). Overall mean yields increased by 41%, and pesticide use declined to 31% of prior use (Figure 2). Compared with the benchmark pre-project point, a 30% of the crop combinations resulted in a transition to zero pesticide use.

While pesticide reductions with IPM should be expected, explanations for yield increases induced by IPM are more complex. IPM may, for example, reduce the incidence of severe-loss years, although yield increases in a normal year may not be evident, but mean production does increase across years. Many IPM projects involve interventions focused on more than just pest management. For example, they may involve a significant component of farmer training (e.g., through farmer field schools: FFS), in which case farmers' capabilities at innovating in several areas of their agroecosystems may also have increased, such as in soil and water management (38). Farmer training through FFS has resulted in greater and continuing innovation, with positive outcomes for both productivity and environmental services (33, 38).

Global extent of SI redesign

It is now clear that SI is spreading to increasing numbers of farmers and is being practised on a growing area of farmland. A recent global assessment screened 400 SI projects, programmes and initiatives worldwide (19). The intention was to assess where agricultural innovation had scaled to have potentially positive landscape-scale outcomes on ecosystem services (see Table 1).

There are some 570 million farms worldwide, 84% of which are landholdings of less than 2 ha (39). These small farms make up only 12% of total agricultural area. Of all farms, 74% are in Asia (of which 35% are in China and 24% in India), 9% in Sub-Saharan Africa, 7% in Central Europe and Central Asia, 3% in Latin America and the Caribbean, and 3% in Middle East and North Africa. Only 4% of farms are in industrialised countries. To be effective, sustainable intensification will have to encompass larger numbers of farms in less developed countries, and larger farms of smaller number in industrialised countries.

Table 1. Redesign for Sustainable Intensification: sub-types of SI, farm numbers and hectares (at 2018)

Redesign SI type	Illustrative redesign sub-types of SI intervention	Farm numbers (million)	Hectares under SI (million)
1. Integrated pest management (IPM)	IPM through farmer field schools; integrated plant and pest management; push-pull systems	20.03	17.41
2. Conservation agriculture (CA[b])	Conservation agriculture practices; zero- and low-tillage; soil conservation and soil erosion prevention; enhancement of soil health	17.10	181.03

3. Integrated crop and biodiversity redesign	Organic agriculture[a]; rice-fish systems; systems of crop and rice intensification (SCI, SRI); Zero-budget natural farming; science and technology backyard platforms; farmer wisdom networks; Landcare and watershed management groups	8.18	63.31
4. Pasture and forage redesign	Mixed forage-crop systems; management intensive rotational grazing systems (MIRGs); agropastoral field schools	1.43	81.85
5. Trees in agricultural systems	Agroforestry; joint and collective forest management; leguminous fertilizer trees and shrubs	30.00	61.21
6. Irrigation water management	Water user associations; participatory irrigation management; watershed management; micro-irrigation technologies	17.90	33.00
7. Intensive small and patch scale systems	Community farms, allotments, backyard gardens, raised beds; vertical farms; group purchasing associations and artisanal small producers (in Community Supported Agriculture, tekei groups, guilds); micro-credit groups for small-scale intensification; integrated aquaculture	68.41	15.52

Note: (a) Some sub-types span several types (e.g., organic agriculture also appears in elements of 4 and 7); (b) Community Supported Agriculture operations (CSAs) are group purchasing associations in North America and the UK, their equivalents are 'tekei' groups in Japan and 'guilds' in France, Belgium and Switzerland. Source (*19*).

In the analysis summarized in Table 1, 47 of the SI initiatives exceeded the 10^4 scale for either hectares or farm numbers, of which 17 exceeded the 10^5 threshold, and 14 exceeded 10^6 (20). Many SI initiatives worldwide show promise but remain limited in scale. By 2018, it was estimated from these initiatives that in some 100 countries 163 million farms had crossed an important substitution-redesign threshold using SI methods in at least one farm enterprise, and on an area approaching 453 million ha of agricultural land (not counting the SI initiatives in home and urban gardens and on field boundaries). This is equivalent to 29% of all farms worldwide and 9% of agricultural land (total worldwide crop and pasture land is 4.9×10^9 hectares).

Such a global assessment might imply numbers of farms and hectares are fixed. Flux may arise from farmer choice and agency, but equally from the actions of vested interests, agricultural input companies, consolidation of small farms into larger operations, changes in agricultural policy or shifts in market demand, and discrepancies between on-paper claims and what farmers have implemented. Efficiency-substitution adoption was not included in this assessment. For example, European Union regulations require all farms to use IPM, but this has not yet led to significant redesign of agricultural practices that significantly benefit ecosystem services (24, 29).

Cost of pest management by pesticides

Pathogens, weeds and invertebrates cause significant crop losses worldwide. While the reporting of pesticide use and market data is patchy, the use of synthetic pesticides in agriculture has grown steadily to 3.5 billion kg of active ingredient (a.i.) per year (37). The value of the global market is now US $45 billion per year, with herbicides accounting for 42% of sales, insecticides 27%, fungicides 22%, and disinfectants and other agrochemicals 9%. China, USA and Argentina account for 70% of world pesticide use in agriculture (2.44 billion kg of a.i. annually) (37), and six countries each consume between 50-100 M kg (Brazil, Canada, France, Italy, Japan, Thailand) In the past 20 years, pesticide consumption in China has grown four fold, in Argentina 8-fold, Brazil 3-fold, Bangladesh 5-fold and Thailand 4-fold.

Pesticides are intended to be hazardous to life and there will be risks associated with their use; their full costs illustrate the often-hidden harm of non-sustainable deployment. The value of pesticides lies in their ability to kill unwanted organisms, but their toxicity can also cause unintended harm on and beyond the farm (external costs). The collateral effects of pesticide use show features commonly found across the agricultural sector. The costs of unintended harm are often neglected, in part because they may occur after a time lag and they may damage groups whose interests are not well-represented. Furthermore, it is not always clear where harmful compounds in the environment may have come from. In studies of pesticide externalities in China, Germany, Thailand, UK, and USA, costs have been calculated to range from $4-19 (€3-15) per kg active ingredient (40-44). These costs put annual pesticide externalities worldwide in the range of $10-60 billion (for use of 3.5 billion kg and for a market size of $45 billion).

Additional private costs are borne by farmers themselves and tend not to be included in calculations of damage, such as the costs of personal ill-health resulting from exposure to pesticides (45), or from increased pest, weed or fungal resistance. Worldwide, weed species have evolved resistance to every herbicide class, and more than 550 arthropod species have gained resistance to at least one insecticide (46). New research has also shown that residues of some classes of pesticide (e.g., neonicotinoid insecticides) are more ubiquitous than previously assumed, suggesting that external costs may be underestimated: 97% of neonicotinoids brought back in pollen by bees in arable landscapes originates from nearby wildflowers rather than from crops themselves (47). At the same time, it has been found that the total flying insect biomass in central Europe has declined by 75% over a 27-year period (22). The ecosystem services provided by wild insects have been estimated at $57 billion annually in the USA (48). Such private and external costs reveal that some forms of agriculture are less effective and efficient than might appear from productivity data alone, indicating the need for new metrics and system design (49).

Redesign for SI-integrated pest management and ecosystem services

Redesign is critical as ecological, economic, social and political conditions change across whole landscapes. The rapidly changing nature of pest, disease and weed threats illustrates the continuing challenge to respond with agility. New pests and diseases can suddenly emerge because of resistance to pesticides, which can then lead to secondary pest outbreaks owing to pesticide overuse. Climate change has facilitated invasions of pests and pathogens, the accidental long-distance transfer of organisms as well as long-distance trade (e.g., of bees, pets, plants). For example, wheat blast fungus (*Magnaporthe oryzae*) has recently emerged as crop pathogen in Bangladesh (2016), and the Fall Army Worm (*Spodoptera frugiperda*) is spreading across sub-Saharan Africa (2017). The papaya mealybug (*Paracoccus marginatus*) is native to Mexico but spread to the Caribbean in 1994, then to

Pacific islands by 2002, Indonesia, India and Sri Lanka by 2008, and is currently found in West Africa. Although the mealybug's preferred host is papaya, it has now adapted to mulberry, cassava, tomato and eggplant (50). Each geographic spread, each shift of host, requires redesign of local agricultural systems, and rapid responses from research and extension services. Such new pests and diseases may also impact crop pollinators, as illustrated by host shifts and the anthropogenic spread of bee parasites (e.g., *Varroa* mites) and pathogens (e.g., *Nosema ceranae*) (4).

A further example is the cassava pink mealybug: first reported in the greater Mekong region of Thailand in 2008, causing an immediate 27% drop in cassava production (51). An IPM programme was developed with multiple tactics involving ploughing and drying soil, soaking stalk cuttings in insecticide, burning of infested plants, banning transport of infested plant materials, and the release of *Anagyrus lopezi*. parasitoids. In 2010-11, six million pairs of *Anagyrus* were released in Thailand, which brought the pest completely under control, and enabling a lasting recovery of fresh root yields. This further underlies how important are ecologically-based tactics to the sustainable intensification of agriculture.

Old pests can return. The brown planthopper (BPH) has been called the "ghost of green revolutions past" (52). It was the primary threat to rice in the 1960s, yet it has resurfaced as a major pest threat in the 2000s owing to resistance to insecticides coupled with the heavy use of nitrogen fertilizers. BPH outbreaks are often triggered by overuse of insecticides, which reinforces farmers' fears of insect pests, provoking in them the wish to apply more. In China, between 6-9 Mha were infested with BPH in 2005-07, up from 2 Mha in the 1990s (50). Farmers in China apply on average 180 kg N/ha to rice as fertilizer, and N-enriched plants are known to enhance size, performance and abundance of herbivorous pests.

IPM consists of a toolbox of interventions combining the use of targeted compounds with agronomic and biological techniques to control different classes of crop pests. Complementary and alternative modes of pest control exploiting specificities in pest ecologies, have been gaining increasing attention. The use of on- and off-farm biodiversity is key in IPM as biodiverse agroecosystems experience less pest damage and have more natural pest enemies than non-biodiverse ones (26, 53). At the same time, both social and human capital are important for successful outcomes (32). IPM is knowledge-intensive. For successful IPM farmers need to monitor pests and natural enemies, understand thresholds for decisions, and be competent in the deployment of a range of different methods.

IPM approaches span the efficiency-substitution-redesign ESR framework (Table 2). These range from targeted use of pesticide compounds to habitat and agroecological design. In only rare cases, such as the aerial release of the parasitic wasp, *Epidinocarsis lopezi*, to control cassava mealybug in West and Central Africa (54), can IPM be implemented without farmer engagement. Recent years have seen a substantial increase in understanding how to increase farmers' knowledge so that they are able to husband crops and livestock while reducing or eliminating pesticides.

Table 2. ESR options for integrated pest management and sustainable intensification.

IPM SI Type	**Examples of application**
Efficiency	
1. Management of application of pesticides	• Targeted spraying • Threshold spraying prompted by decision-making

	derived from observation/data on pest, disease or weed incidence
Substitution	
2a. Substitution of pesticidal products with other compounds	• Synthetic pesticide with high toxicity substituted by another product with low toxicity • Use of agrobiologicals or biopesticides (e.g. derived from neem)
2b. Releases of antagonists, predators or parasites to disrupt or reduce pest populations	• Sterile breeding of male pest insects to disrupt mating success at population level • Identification and deliberate release of parasitoids or predators to control pest populations
2c. Deployment of pheromone compounds to move or trap pests	• Sticky and pheromone traps for pest capture
2d. Crop and livestock breeding	• Deliberate introduction of resistance or other traits into new varieties or breeds (e.g. recent use of genetic modification for insect resistance and/or herbicide tolerance)
Redesign	
3. Agroecological system and habitat redesign	• Seed and seed bed preparation • Deliberate use of domesticated or wild crops/plants to push-pull pests, predators and parasites • Use of crop rotations and multiple-cropping to limit pest, disease and weed carryover across seasons or viability within seasons • Adding host-free periods into rotations • Adding stakes to fields for bird perches

Source: adapted from (37).

Social capital matters greatly. IPM strategies have now transitioned from individual field-based practice to coordinated, community-scale decision-making covering wider landscapes. While this improves the effectiveness of pest control, it presents a significant obstacle to wider adoption by presenting a collective-action dilemma: how can farmers as individual businesses be persuaded to work together for personal as well as wider landscape benefits (32). Farmer Field Schools (FFS), which were started in the 1980s (55-56), are among the most significant mechanism for the development and spread of IPM. FFS are not an extension method: they increase knowledge of agroecology, problem-solving skills, group building and political strength. They can be particularly effective where there are simple messages (e.g., do not use insecticides in the first 40 days of rice cultivation as herbivore-damaged plants recover with no yield loss: 57). FFS have been used in 90 countries (33, 58-59), with 19 million farmer graduates and now some 20,000 FFS graduates are now running FFS for other farmers.

One of the most effective IPM-redesign systems is the ‘push-pull’ system (where pests and beneficial insects are pushed and pulled into and away from valued crops), which is yielding notable successes in monocropped cereal systems (15). This method has been deployed with great effect against *Striga* weed and stemborer infestations in maize, millet and sorghum (60-61) and involves the use of interplanted ‘decoy’ crops. Across Kenya, Uganda, Tanzania and Ethiopia, push-pull systems are used on about 130,000 small farms. Interplanting of the leguminous forage crop *Desmodium* suppresses *Striga* and repels stemborer moths while attracting their natural enemies; planting *Napier* grass as a border crop attracts stemborer moths out of the crop. The interplanted fodder crop not only fixes nitrogen but has also provided an additional resource that has enabled farmers to diversify into dairy and poultry production, which in turn provides animal manure for application on fields. As a result, yields of maize and sorghum have increased significantly, with up to three-fold increase over control plots. Better quality of fodder for dairy animals has increased milk yields by at least 2 litres daily and ultimately gives significantly higher economic returns to the farmer than monocropping.

This kind of redesign has been deployed in many agroecosystems, resulting in increased rotational diversity, use of wildflowers for pollinators and other beneficial insects, and deployment of conservation headlands and trap crops (62-63), often with large reductions in input use without yield compromise (64). In tropical systems, fish, crab and duck reintroduced into rice systems reduce pest and weed incidence, often eliminate the need for pesticides, and increase gross productivity through provision of animal protein outputs (65).

Towards collective action and landscape-scale change

Pest management exemplifies the need for continuing active intervention for SI: the job is never done. Ecological and economic conditions will change, and appropriate responses will be needed. Agro-ecosystems will have to be adaptable consistently to deliver a range of ecosystem services, including food production, but also water and soil conservation, soil carbon storage, nutrient recycling and pest control.

Cooperation, or at least individual actions that collectively result in additive or synergistic benefits, is needed for SI to have a transformative impact across landscapes. Farmers will have to be given the confidence to innovate in a flexible way as conditions change. Every example of successful redesign for SI at scale has involved the prior building of social capital (19). Such initiatives require relations of trust, reciprocity and exchange, common rules, norms and sanctions, and connectedness in groups. As social capital reduces the costs of working together, it facilitates co-operation, which gives people the confidence to invest in collective activities, knowing that others will do so too. Individuals are then less likely to get away with free-rider actions that cause resource degradation.

Widespread adoption of IPM needs new knowledge economies for agriculture (66). Technologies and practices are growing, but new knowledge needs to be collectively created and deployed, and to give equal emphasis to ecological and technological innovations. Extension systems and farmer field schools must give equal consideration to environmental as well as agronomic skills (33). For example, the Landcare movement in Australia consists of 6000 groups of farmer-led watershed councils. The agroecosystem research network in the USA, the French network of agroecology farms, and the Farmer Cluster Initiatives in the UK (67-68) are all important examples from industrialised countries that are delivering practices to address locally specific problems of erosion, nutrient loss, pathogen escape and waterlogging. In Cuba, the *Campesino-a-Campesino* movement has built agroecological methods with knowledge and technologies spread through exchange and cooperatives. As a result the productivity of 100,000 farmers has increased by 150% over ten years, and pesticide use has fallen to 15% of former levels (69). In Bangladesh, innovation platforms have driven adoption of direct seeding and use of early-maturing rice (70). In China, Science and Technology Backyard (STB) platforms operate in 21 provinces covering many cereal, root and fruit crops (71). STB platforms bring agricultural scientists to live in villages and use field demonstrations and farm schools for developing innovations. They are successful because they centre on in-person communication, socio-cultural bonding, and trust developed among farmer groups of 30-40 individuals.

Concluding comments

In general, policy makers and regulators find it easier to seek to prevent practices or problems, such as the regulation of certain pesticide compounds, or the establishment of safe drinking water limits for certain compounds. It has been harder to encourage positive practices. In most contexts, state policies for SI remain poorly developed or counter-productive. In the EU, farm subsidies have increasingly been shifting towards targeted environmental outcomes rather than payments for production (72), but this seldom guarantees synergistic benefits across whole landscapes. Ethical and sustainable sourcing by food manufacturers, processors and retailers would help drive up demand, particularly if producers connect directly with consumers (73). There are some regional scale exemplars of positive policy practice. For instance, India's state of Andhra Pradesh, where the state government has made explicit its support to zero-budget natural farming (a local form of uncertified organic farming that does not require the expenditure of farmer income on inputs), aiming to reach 6 million farmers by 2027 (74). The greening of the Sahel through agroforestry began when national tree ownership regulations were changed to favour local people (17); and in China, where the 2016 No. 1 Central Document emphasises innovation, coordination, greening and sharing as key parts of a new strategy for SI (75).

There are arguments from some quarters that we would not need to increase agricultural production if less food were wasted, and less energetically-inefficient meat consumed by the affluent. These would help, but there is no magic wand of redistribution. Most if not all farmers need to raise yields while improving environmental services. As the evidence shows, redesign of agro-ecosystems around SI can achieve both yield increases and resilience. The evidence from farms of redesign and transformations towards SI offers scope for optimism. A full transition from increased efficiency through substitution to redesign will be essential. The concept and practice embodied in the SI model of agriculture will be a process of adaptation, driven by a wide range of actors cooperating in new agricultural knowledge economies.

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Terminology: in this paper, the term pesticide incorporates all synthesised pest, disease, weed, fungal and other control compounds. There is also no single accepted terminology for grouping of types of countries. Terms relate to past stages of development (developed, developing, less developed), state of economy or wealth (industrialised, affluent), geographic location (global south or north), or membership (OECD, non-OECD). None are perfect. Here I have simply used *industrialised* and *less-developed*, and acknowledge the shortcomings.

Figure legends (captions)

Figure 1. Global per capita agricultural production (1961=100). Source data (1)

Figure 2. Impacts of SI-IPM projects and programmes in Asia and Africa on pesticide use and crop yields (85 projects, 24 countries). Source data (37)