Global Assessment of Agricultural System Redesign for Sustainable Intensification

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Abstract

The sustainable intensification (SI) of agricultural systems offers synergistic opportunities for the co-production of agricultural and natural capital outcomes. Efficiency and Substitution are steps towards SI, but system Redesign is essential to deliver optimum outcomes as ecological and economic conditions change. We show global progress towards SI by farms and hectares, using seven SI sub-types: integrated pest management, conservation agriculture, integrated crop and biodiversity, pasture and forage, trees, irrigation management, and small/patch systems. From 47 SI initiatives at scale (each >10^4 farms or hectares), we estimate 163M farms (29% of all worldwide) have crossed a redesign threshold, practising forms of SI on 453Mha of agricultural land (9% of worldwide total). Key challenges include investing to integrate more forms of SI in farming systems, creating agricultural knowledge economies, and establishing policy measures to scale SI further. We conclude that SI may be approaching a tipping point where it could be transformative.

Here we show that the sustainable intensification (SI) of agricultural systems offers synergistic opportunities for the co-production of agricultural and environmental outcomes. Efficiency and Substitution are steps towards SI, but system Redesign is essential to deliver optimum outcomes as ecological and economic conditions change. This global assessment of SI by farms and hectares categorises SI by seven sub-types: integrated pest management, conservation agriculture, integrated crop and biodiversity, pasture and forage, trees, irrigation management, and small and patch systems. From 47 SI initiatives at scale (each >10^4 farms or hectares), we estimate 163M farms (29% of all worldwide) have crossed a redesign threshold, practising forms of SI on 453 Mha of agricultural cropped and pasture land (9% of worldwide total). The key challenges centre now on creating agricultural knowledge economies and establishing policy measures to scale SI further. We conclude that SI may be at a tipping point where it could be transformative.

The past half century has seen substantial increases in global food production. World population has risen 2.5 fold since 1960 and yet per-capita food production has grown by 50% over the same period (1). At the same time, evidence shows that agriculture is the single largest cause of biodiversity loss, greenhouse gas emissions, consumptive use of freshwater, loading of nutrients into the biosphere (nitrogen and phosphorus), and a major cause of pollution due to pesticides (2). This is manifested in soil erosion and degradation, pollution of rivers and seas, depletion of aquifers, and climate forcing (3). As a consequence, efforts have advanced to develop production systems that at least reduce the damage footprint per unit produced (4).

This desire for agricultural systems to produce sufficient and nutritious food without environmental harm, and going further to produce positive contributions to natural, social and human capital, has been reflected in calls for a wide range of different types of more sustainable agriculture (5-7). The dominant paradigm for agricultural development centres on intensification (productivity enhancement) without integrating sustainability. When the environment is considered, the conventional focus is on reducing negative impacts rather than exploring synergies between intensification and sustainability. There is increasing evidence that sustainability frameworks can improve intensity through shifts in the factors of agricultural production: such as shifts from fertilizers to nitrogen-fixing legumes as part of rotations or intercropping, from pesticides to natural enemies, and from ploughing to reduced-intensity tillage.

Sustainable Intensification

Compatibility of *sustainability* and *intensification* was hinted at in the 1980s, then first used in conjunction with an examination of African agriculture (8). Intensification had previously become synonymous with types of agriculture that resulted in environmental harm (9). The combination of the two terms was an attempt to indicate that desirable outcomes, such as more food and better ecosystem services, need not be mutually exclusive. Both could be achieved by making better use of land, water, biodiversity, labour, knowledge and technologies. SI was further proposed in a number of key commissions, its adoption since increasing from about ten papers annually before 2010 to over 100 per year by 2015 (10). SI is now central to both the UN's Sustainable Development Goals and wider efforts to improve global food and nutritional security (11).

Sustainable intensification (SI) is defined as an agricultural process or system where valued outcomes are maintained or increased while at least maintaining and progressing to substantial enhancement of environmental outcomes. It incorporates the principles of doing this without the cultivation of more land (and thus loss of non-farmed habitats), in which increases in overall system performance incur no net environmental cost (12-15). The concept is open, emphasising outcomes rather than means, applying to any size of enterprise, and not predetermining technologies, production type, or particular design components. SI seeks synergies between agricultural and landscape-wide system components, and can 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 the concept of SI is an acceptance that there will be no perfect end point due to the multi-objective nature of sustainability. Thus, no designed system is expected to succeed forever, with no package of practices fitting the shifting dynamics of every location.

SI is a necessary but not sufficient component of transformation in the wider food system. Changes in consumption behaviours (e.g., in animal products), as well as reductions in food waste, may make greater contributions to the overall sustainability of food and agriculture systems (7), as well as helping to address the challenge of over-consumption of calorie-dense food, which has become a global threat to health. System level changes will be necessary from production to consumption, and eating better is now a priority for affluent countries. At the farm and landscape level, the need for effective SI is nonetheless urgent. Pressure continues to grow on existing agricultural lands. Environmental degradation reduces the asset base (4, 16), expansion of urban and road infrastructure captures agricultural land (in the EU28, agricultural land area fell by 31Mha over 50 years from 1961; in the USA and Canada, 0.5Mha are lost annually (17-18)); and climate change and associated extreme weather create new stresses, testing the resilience of the global food system (19).

Attempts to implement SI can result in beneficial outcomes for both agricultural output and natural capital (14, 20-21). The largest increases in food productivity have occurred in less developed countries, mostly starting from a lower output base. In industrialised countries, systems have tended to see increases in efficiency (lower costs), minimizing harm to ecosystem services, and often some reductions in crop and livestock yields (22). However, the global challenge is significant: planetary boundaries are under threat or have been exceeded, world population will continue to grow from 7.6 billion (2018) to 10 billion by 2050 (23), and consumption patterns are converging on those typical in affluent countries for some sections of populations, yet still leaving some 800 million people hungry worldwide. One question centres on scale: can agriculture still provide sufficient nutritious food whilst improving natural capital and not compromising other aspects of well-being; and can this occur at a scale to benefit millions of lives, reverse biodiversity loss and environmental contamination, and limit greenhouse gas emissions? A further question centres on how much wider food system changes towards healthier diets could shape the requirements for agricultural production to focus on both food and environmental outcomes: healthier diets tend to be higher in fruit, pulse and nut content, therefore more dependent on pollination services (24). Healthier diets could also generate enhanced consumer demand for lower pesticide residues.

As SI is an umbrella term that includes a wide range of different agricultural practices and technologies, the precise extent of existing SI practice has been largely unknown. We use an analytical framework developed for this global assessment data sets of large-scale changes (by numbers of farms and hectares) that have been made towards SI in this millennium.

Beyond Improved Efficiency and Substitution to Redesign

Hill (25) proposed three non-linear stages in transitions towards sustainability: i) efficiency; ii) substitution; and iii) redesign. While both efficiency and substitution are valuable stages towards system sustainability, they are not sufficient for ensuring greatest co-production of both favourable agricultural and environmental outcomes at regional and continental scales (26).

The first stage: *Efficiency* focuses on making better use of on-farm and imported resources within existing system configurations. Many agricultural systems are wasteful, permitting natural capital degradation within the farm or the escape of inputs across system boundaries to cause external costs on-farm and beyond. Post-harvest losses reduce food availability: 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 (such as through deep-fertilizer placement: in Bangladesh used by 1M farmers on 2Mha (27), pesticide, and water to focus impact, reduce use, and cause less damage to natural capital and human health. Such precision farming can incorporate sensors, detailed soil mapping, GPS and drone mapping, scouting for pests, weather and satellite data, information technology, robotics, improved diagnostics and delivery systems to ensure inputs (e.g., pesticide, fertilizer, water) are applied at the rate and time to the right place, and only when needed (17, 28-29). Automatic control and satellite navigation of agricultural vehicles and machinery can enhance energy efficiency and limit soil compaction.

The second stage: *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 better at converting nutrients to biomass, tolerating 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 inputs); the use of RNA-based gene silencing pesticides; water-based architecture replacing the use of soil in hydroponics; and in no-tillage systems new forms of direct seeding and weed management replacing inversion tillage (14).

The third stage is a fundamental prerequisite for SI to achieve impact at scale. *Redesign* centres on the composition and structure of agro-ecosystems to deliver sustainability across all dimensions to facilitate food, fibre and fuel production at increased rates. Redesign harnesses predation, parasitism, allelopathy, herbivory, nitrogen fixation, pollination, trophic dependencies and other agro-ecological processes to develop components that deliver beneficial services for the production of crops and livestock (30-31). A prime aim is to influence the impacts of agroecosystem management on externalities (negative and positive), such as greenhouse gas emissions, clean water, carbon sequestration, biodiversity, and dispersal of pests, pathogens and weeds. While Efficiency and Substitution tend to be additive and incremental within current production systems, Redesign brings the most transformative changes across systems.

Redesign is, however, a social and institutional as well as agricultural challenge (31-32), as there is a need to create and make productive use of human capital in the form of knowledge and capacity to adapt and innovate, and social capital to promote common landscape-scale change, such as for positive biodiversity, water quantity and quality, pest management, and soil health outcomes (33-34). Negative unintended consequences for human, social and economic capital associated with the system must also be identified and mitigated as part of the redesign process.

Redesign is critical as ecological, economic, social and political conditions change across whole landscapes. The changing nature of pest, disease and weed threats illustrates the continuing challenge (35). New pests and diseases can suddenly emerge in different ways: development of resistance to pesticides; secondary pests outbreaks due to pesticide overuse; climate change facilitating new invasions; and accidental long-distance organism transfer. Recent appearances include wheat blast (*Mygnoporthe oryzae*) in Bangladesh (2016), and Fall Army Worm (*Spodoptera fruigiperda*) in sub-Saharan Africa (2017). The papaya mealybug (*Paraciccus marginatus*) is native to Mexico, but spread to the Caribbean in 1994 then to Pacific islands by 2002, was reported in Indonesia, India and Sri Lanka by 2008, then to West Africa; the preferred host is papaya, but it has now colonised mulberry, cassava, tomato and eggplant. Each geographic spread, each shift of host, requires redesigns of local agricultural systems, and rapid responses from research and extension. Such new pests and diseases may also impact crop pollinators, as illustrated by host shifts and the accidental anthropogenic spread of bee parasites (e.g., *Varroa* mites) and pathogens (e.g., *Nosema ceranae*) (36).

Redesign Typology and Methods

We analysed transitions towards redesign in agricultural systems worldwide. We reviewed literature on SI, including meta-analyses and practices, to produce a typology of seven system types that we classify as redesign: (i) integrated pest management, (ii) conservation agriculture, (iii) integrated crop and biodiversity, (iv) pasture and forage, (v) trees in agricultural systems, (vi) irrigation water management and (vii) intensive small and patch systems (Table 1). These seven systems and illustrative sub-types are discussed in more detail in Supplementary Section 1.

The seven system types span both industrialised and less-developed countries, and zones from temperate to tropical. Progress towards SI in developing countries is occurring in the context of the pressing need to implement sustainable development goals for poverty reduction, improved livelihoods and better nutrition by building more productive and sustainable systems of smallholder agriculture. There are some 570 million farms worldwide, 84% of which are landholdings of less than 2 ha (37). These small farms make up 12% of total agricultural area, yet produce 70% of food in Africa and Asia. Sustainable intensification will have to be effective worldwide, yet will have to reach larger numbers of farms in less developed countries: 74% of all farms 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. Owing to the average size of the 4% of farms in industrialised countries, the choices made by a single farmer can have landscape-wide consequences.

Table 1. Redesign typology and examples of sub-types of intervention

Redesign type	Illustrative redesign sub-types of intervention
1. Integrated pest management (IPM)	IPM through farmer field schools Integrated plant and pest management Push-pull systems
2. Conservation agriculture (CA)	Conservation agriculture practices Zero- and low-tillage Soil conservation and soil erosion prevention Enhancement of soil health
3. Integrated crop and biodiversity redesign	Organic agriculture Rice-fish systems Systems of crop and rice intensification (SCI, SRI) Zero-budget natural farming (ZBNF) Science and technology backyard platforms Farmer wisdom networks Landcare and watershed management groups
4. Pasture and forage redesign	Mixed forage-crop systems Management intensive rotational grazing systems (MIRGs) Agropastoral field schools
5. Trees in agricultural systems	Agroforestry Joint and collective forest management Leguminous fertilizer trees and shrubs
6. Irrigation water management	Water user associations Participatory irrigation management Watershed management Micro-irrigation technologies
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

Note: i) This is an illustrative list of sub-types; ii) Some sub-types span a number of types (e.g., organic agriculture also appears in elements of 4 and 7); iii) Community Supported Agriculture operations (CSAs) are group purchasing associations in North America and the UK, tekei groups are in Japan, guilds in France, Belgium and Switzerland.

We have screened 400 SI projects, programmes and initiatives worldwide (drawn from literature or existing data sets (20-21, 35) and selected those implemented to a scale greater than 10^4 farms or hectares. Our intention is not to map all innovation for SI worldwide, but to assess where innovation has scaled to have potentially positive outcomes on ecosystem services as well as agricultural objectives across landscapes.

Results

Forty-seven SI initiatives have exceeded the 10^4 scale, of which 17 exceed the 10^5 threshold, and 14 the 10^6 scale (Supplementary Table 1; Figures 1 and 2). Many SI initiatives worldwide show promise but remain limited in scale (either demonstrating locally-dependent conditioning, or the lack of attention to scalar mechanisms). We estimate from these projects-initiatives in some 100 countries that 163 million farms have crossed an important substitution-redesign threshold, and are using SI methods, in at least one farm enterprise, 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 comprises 29% of all farms worldwide; and 9% of agricultural land (total worldwide crop and pasture land is 4.9 x 10^9 hectares).

We note that this global assessment might imply numbers of farms and hectares are fixed: on the ground, there will be a flux in numbers as a result of both adoption and dis-adoption. This 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. We have also not included apparent adoption in this assessment: for example, EU regulations require all farms to use IPM, but this has not yet led to significant uptake of agricultural practices that significantly benefit ecosystem services (21).

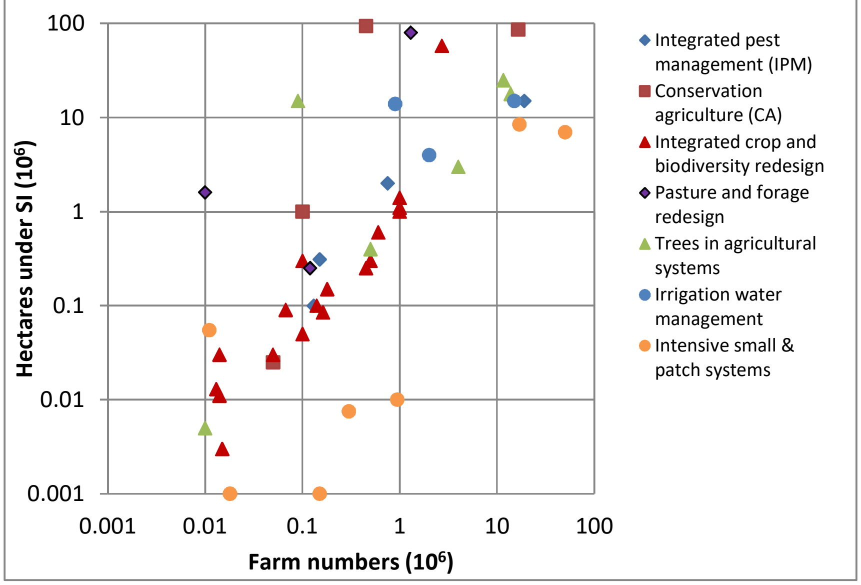

Figure 1. Farm numbers and hectares under seven types of Sustainable Intensification (47 initiatives)

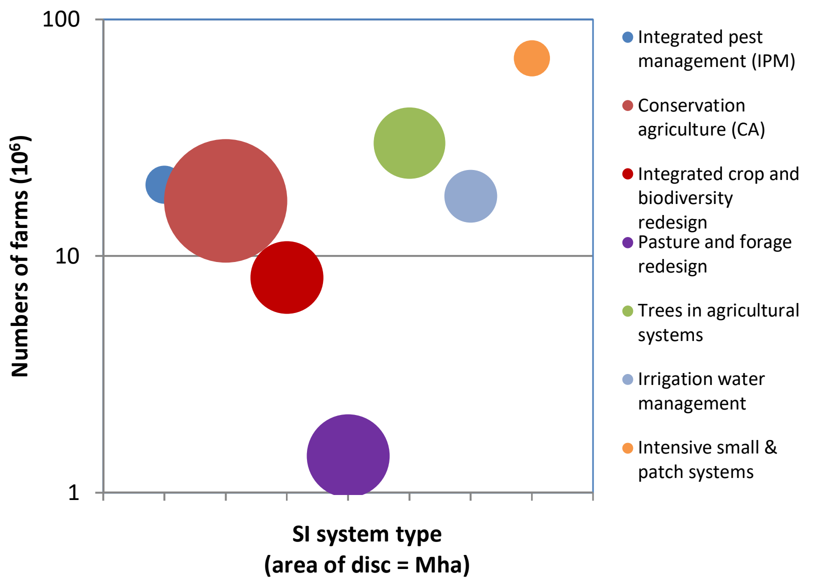

Figure 2: Seven types of sustainable intensification (47 initiatives): disc area (Mha)

The Co-creation of Agricultural Knowledge Economies

For SI to have a transformative impact on whole landscapes, it requires cooperation, or at least individual actions that collectively result in additive or synergistic benefits. For farmers to be able to adapt their agroecosystems in the face of stresses, they will need to have the confidence to innovate. As ecological, climatic, and economic conditions change, and as knowledge evolves, so must the capacity of farmers and communities to allow them to drive transitions through processes of collective social learning. This suggests a valued property of intrinsic adaptability, whereby interventions that can be adapted by users to evolve with changing environmental, economic and social conditions are likely to be more sustainable than those requiring a rigid set of conditions to function. Every example of successful redesign for SI at scale has involved the prior building of social capital (32), in which emphasis is paid to: i) relations of trust, ii) reciprocity and exchange, iii) common rules, norms and sanctions, and iv) connectedness in groups. As social capital lowers the costs of working together, it facilitates co-operation, and people have the confidence to invest in collective activities, knowing that others will do so too. They are also less likely to engage in free-rider actions that result in resource degradation.

This suggests the need for new knowledge economies for agriculture (38). The technologies and practices increasingly exist to provide both positive food and ecosystem outcomes: new knowledge needs to be co-created and deployed in an interconnected fashion, with an emphasis on ecological as well as technological innovation. This includes the need to rebuild extension systems and extend them to environmental as well as agronomic skills, with farmer field schools already dense enough in some locations that they have transformed knowledge co-creation and behavioural change (34). Important examples in industrialised countries include the Landcare movement in Australia with

6000 groups, farmer-led watershed councils and the long-term agroecosystem research network in the USA, the French network of agroecology farms, and the 49 Farmer Cluster Initiatives in the UK (39-40). These have created platforms for creation of practices to address locally specific problems of erosion, nutrient loss, pathogen escape and waterlogging. In Cuba, the *Campesino-a-Campesino* movement integrates agroecology into redesign, with knowledge and technologies spread through exchange and cooperatives: productivity of 100,000 farmers increased by 150% over ten years, and pesticide use fell to 15% of former levels (41). In West Africa, innovation platforms have increased yield in maize and cassava systems (42), and in Bangladesh have resulted in the development and spread of direct seeded and early-maturing rice (43). In China, Science and Technology Backyard (STB) platforms operate in 21 provinces covering many crops: wheat, maize, rice, soybean, potato, mango and lychee (44). STB platforms bring agricultural scientists to live in villages, and use field demonstrations and farm schools to engage farmers in developing innovations: reasons for success centre on in-person communication, socio-cultural bonding, and the trust developed among farmer groups of 30-40 individuals.

Next Steps: A Tipping Point

This analysis shows that the expansion of SI has begun to occur at scale across a wide range of agroecosystems. The benefits of both scientific and farmer input into technologies and practices that combine crops and animals with appropriate agro-ecological and agronomic management are increasingly evident. The associated creation of novel social infrastructure results in both flows of information and builds trust among individuals and agencies. This should result in the improvement of farmer knowledge and capacity through the use of platforms for cooperation together with digital communication technologies.

The key question thus centres on what could happen next. SI has been shown to increase productivity (4-5), raise system diversity (3), reduce farmer costs (20, 22, 30), reduce negative externalities (12-13, 30), and improve ecosystem services (26, 30). There are thus a range of potential motivations for farmers to adopt SI approaches, and for policy support to be provided by national government, third sector and international organisations. SI requires investments, though, to build natural, social and human capital, so is not costless (6-7). In all 47 initiatives, there are differences in SI adoption by types of farm, farmers, and SI sub-type. All innovations begin on a small scale, yet here expanded to exceed the 10^4 scale for farm numbers and/or hectares. But several hundred more projects remain small in scale or are at early stages of development. In some cases, innovations started with efficiency or substitution interventions, and then spread to redesign (31). In every case, social capital formation leading to knowledge co-creation has been a critical pre-requisite. In every case, too, farmer benefit (e.g. food output, income, health) will have been demonstrated and understood.

In most contexts, though, 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, a process the UK Government has plans to accelerate (45-46), but this seldom guarantees synergistic benefits across whole landscapes. Several countries have offered explicit public policy support to social group formation, such as for Landcare (Australia), watershed management (India), joint forest management (India, Nepal, DR Congo), irrigation user groups (Mexico) and farmer field schools (Indonesia, Burkina Faso). In India's state of Andhra Pradesh, the state government has made explicit its support to zero-budget natural farming (local form of uncertified organic farming), aiming to reach 6 million farmers by 2027 (47); in Bhutan and the Indian states of Kerala and Sikkim, policy commitments have been made to convert all land to organic agriculture; the greening of the Sahel through agroforesty began when national tree ownership regulations were changed to favour local people (12). In China, the 2016 No 1 Central Document emphasises innovation, coordination, greening and sharing as key parts of a new strategy for SI (48). At the same time, consumers are increasingly playing a role in connecting directly with farmers in affluent countries, such as through group purchasing schemes, farmers' markets and certification schemes, which may in turn change consumption choices (49).

With this growing understanding of the positive roles governments can play in structuring incentives and policies, as well as supporting agricultural knowledge economies, we anticipate that SI may be at a tipping point (2, 4). A further small increase in the number of farms successfully operating re-designed agricultural systems could lead rapidly to re-design of agriculture on a global scale. To transform agriculture to provide comprehensive sustainably intensified systems that can deliver adequate, healthy food for all people, will require the integration of different redesign types to create system-wide transitions, and the internalisation of agricultural externalities into prices or through consumer demand. Our hypothesis is that important synergies are occurring, where redesigned systems will deliver more than the sum of the parts, and that when more than one SI sub-type is combined, the likelihood will increase that redesigned systems will be better fitted to local circumstances and thus be more resilient. In the 47 initiatives analysed here, we scored for the number of types used in each initiative (Table 2). Most initiatives are deploying one (25% of farms, 37% of hectares) or two (66% of farms, 52% of hectares) types. The most common paired combinations were integrated crop and biodiversity redesign with either IPM, CA and soil health, agroforestry and irrigation management. The most common deployment of only one sub-type was trees in agricultural systems. This suggests a clear challenge centres on further integration: this might include, for example, combining conservation agriculture for soil health with integrated watershed management, nutrient recycling and integrated pest management.

Table 2. Number of redesign types of SI deployed in each of 47 initiatives, by farm and hectare numbers and proportions

	Number of redesign types deployed				
	1	2	3	4	5-7
Farms (M)	50.7	132.5	16.1	1.0	0.0
Proportion of farms in each redesign type	25.3%	66.1%	8.0%	0.5%	0.0%
Hectares (Mha)	170.2	240.5	32.8	19.5	0.0
Proportion of hectares in each redesign type	36.8%	51.9%	7.1%	4.2%	0.0%

There is much to be done to ensure agricultural and food systems worldwide increase the production of nutritious food whilst ensuring positive impacts on natural and social capital. Some efficiency-based initiatives are reaching large numbers of farmers, such as the 21M reducing fertilizer use in China (50). We conclude that a transition from efficiency through substitution to redesign will be essential, suggesting that the concept and practice of SI of agriculture will be a process of adaptation, driven by a wide range of actors cooperating in new agricultural knowledge economies. This will still need farmers and society to invest in SI, not just for the sake of sustainability, but for livelihoods and profitability. There are risks: technologies could be dis-adopted, advances lost, and competing interests could co-opt and dilute innovations. Positive changes towards consuming healthier food and reductions in food waste may also not occur, putting more pressure on farmers to produce more food at any cost.

We conclude by recommending that three key questions will need addressing for SI to fulfil its potential across agro-ecosystems worldwide:

1. What further evidence is needed to spread SI innovations as options of choice and best practice globally, thus contributing to further progress towards global food security and landscape-wide benefits for natural capital?
2. How can agricultural systems be redesigned to ensure it is more profitable to maintain, rather than erode, natural capital?
3. How can national policy support for the mainstreaming of SI be strengthened and implemented within and across all countries?

A Note on Terminology

There is 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: China has the second largest economy measured by GDP (which does not measure all aspects of economies, environments and societies well), yet might be considered still developing or less-developed. The USA has the largest economy by GDP, yet has nearly 50M hungry people. Here we have simply used *industrialised* and *less-developed*, and acknowledge the shortcomings. We also use the term pesticide to incorporate all synthesised pest, disease, weed and other control compounds.

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Data Statement and Availability

The data that support the findings of this study are available from the corresponding author upon request. The supplemental file contains detail of each of the initiatives (farmers, hectares), and all references to the data are provided in both the paper and supplementary information.

Competing Interests

The authors declare there are no competing interests in this paper, as defined as financial and non-financial interests that could directly undermine, or be perceived to undermine the objectivity, integrity and value of a publication, through a potential influence on the judgements and actions of authors with regard to objective data presentation, analysis and interpretation.

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Figure legends

Figure 1. Farm numbers and hectares under seven types of Sustainable Intensification (47 initiatives)

Figure 2: Seven types of sustainable intensification (47 initiatives): disc area (Mha)