Global Assessment of Agricultural System Redesign for Sustainable Intensification

Jules Pretty, School of Biological Sciences, University of Essex, UK
Tim G. Benton, Faculty of Biological Sciences, University of Leeds, UK
Zareen Pervez Bharucha, Global Sustainability Institute, Anglia Ruskin University, UK
Lynn V. Dicks, School of Biological Sciences, University of East Anglia, UK
Cornelia Butler Flora, Kansas State University and Iowa State University, USA
H. Charles J. Godfray, Oxford Martin School, University of Oxford, UK
Dave Goulson, School of Life Sciences, University of Sussex, UK
Sue Hartley, York Environmental Sustainability Institute, University of York, UK
Nic Lampkin, Organic Research Centre, UK
Carol Morris, School of Geography, University of Nottingham, UK
Gary Pierzynski, Department of Agronomy, Kansas State University, USA
P. V. Vara Prasad, Sustainable Intensification Innovation Lab, Kansas State University, USA
John Reganold, Department of Crop and Soil Sciences, Washington State University, USA
Johan Rockström, Stockholm Resilience Centre, Sweden (from Oct 2018: Potsdam Institute for Climate Impact Research, Germany)
Pete Smith, Institute of Biological and Environmental Sciences, University of Aberdeen, UK
Peter Thorne, Sustainable Livestock Systems, International Livestock Research Institute, Ethiopia
Steve Wratten, Bio-Protection Research Centre, Lincoln University, New Zealand

[4250 words and 50 references, word count includes the two tables, but not supplementary information and table; abstract is exactly 150 words]

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)

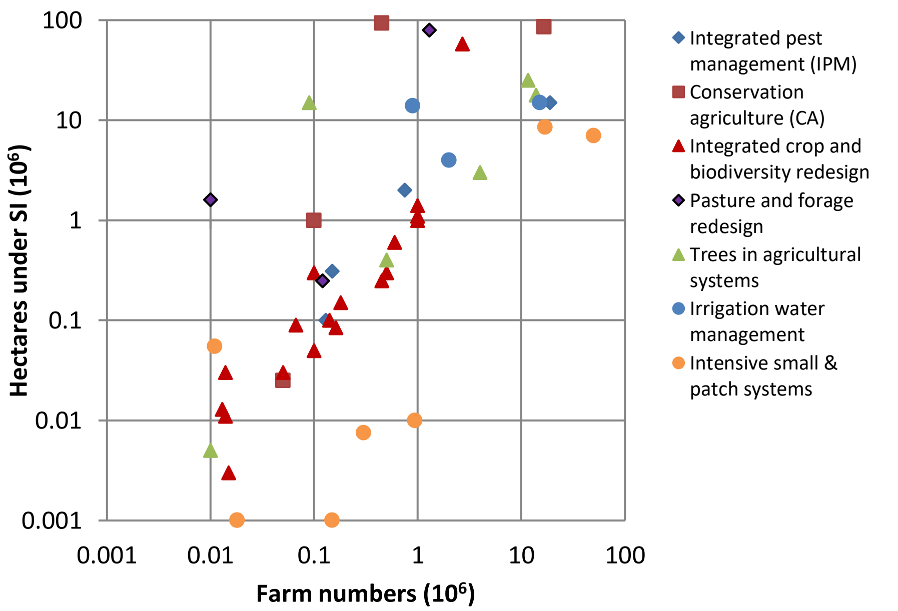
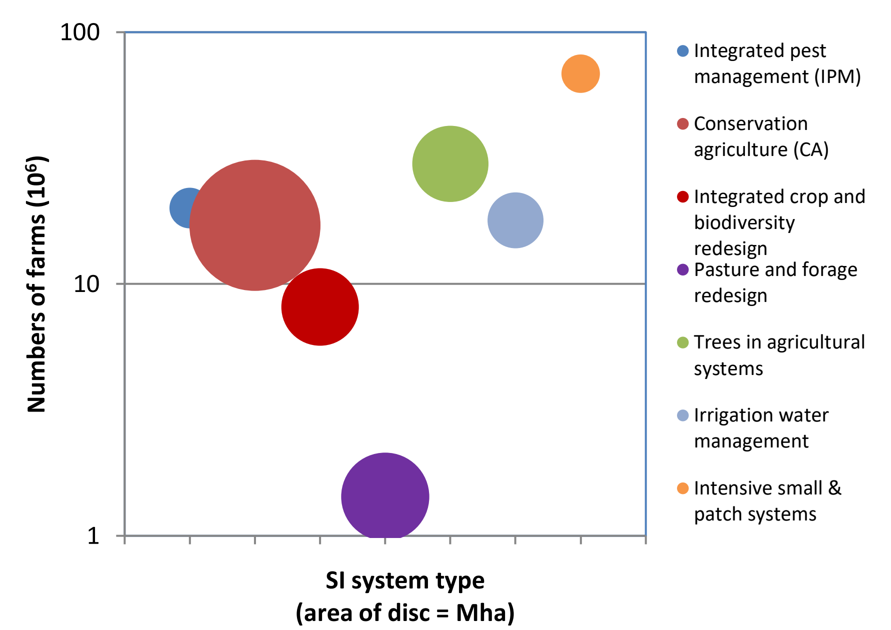


Figure 2: Seven types of sustainable intensification (47 initiatives): disc area (Mha)



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.

Acknowledgements

We are grateful to a number of people for their guidance and updates on numbers of farmers and hectares for some of the illustrative sub-types: Henk van den Berg, Roland Bunch, Kevin Gallagher and Vijay Kumar.

Authors

The author to whom correspondence and requests for materials should be addressed is JP. The design of this study was conducted by JP and ZB; all authors (JP, TB, CBF, LD, CG, DG, SH, NL, CM, GP, VP, JR, JR, PS, PT, SW, ZB) were equally engaged in data gathering, analysis and assessment, and writing of the paper and supplementary file.

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.

References

1. FAO. 2017. FAOSTAT Online database. Rome
2. West P C et al. 2014. Leverage points for improving global food security and the environment. *Science* 345 (6194), 325-328
3. Pywell R F et al. 2015. Wildlife friendly farming increases crop yield: evidence for ecological intensification. *Proc Royal Society Lond*. B 282: 20151740
4. Rockström J et al. 2017. Sustainable intensification of agriculture for human prosperity and global sustainability. *Ambio* 46, 4–17
5. Foresight. 2011. *The Future of Global Food and Farming*. London: Government Office for Science London
6. FAO 2016. *Save and Grow: Maize, Rice and Wheat – A Guide to Sustainable Crop Production.* Rome
7. Benton T. 2015. Sustainable intensification. In Pritchard B, Ortiz R and Shekar M (eds). Routledge Handbook of Food and Nutrition Security. Routledge, Abingdon
8. Pretty J. 1997. The sustainable intensification of agriculture. *Natural Resources Forum* 21(4) 247–256
9. Collier W L et al. 1973. Recent changes in rice harvesting methods. Some serious social implications. *Bulletin of Indonesian Economic Studies* 9(2): 36-45
10. Gunton R M et al. 2016. How scalable is sustainable intensification? *Nature Plants* 2: 1-4
11. UN Sustainable Development Platform. 2017. Sustainable Development Goals. http://www.un.org/sustainabledevelopment/sustainable-development-goals/
12. Godfray H C J et al. 2010. Food security: the challenge of feeding 9 billion people. *Science* 327: 812–818
13. Smith P. 2013. Delivering food security without increasing pressure on land. *Global Food Security* 2(1), 18-23
14. Pretty J and Bharucha Z P. 2014. Sustainable intensification in agricultural systems. *Annals of Botany* 205, 1-26.
15. Geertsema W et al. 2016. Actionable knowledge for ecological intensification of agriculture. *Frontiers in Ecology and the Environment*, *14*(4), 209-216

16. Lamb, E G et al. 2017. More than 75 percent decline over 27 years in total flying insect biomass in protected areas. *PLoS ONE* 12 (10). e0185809
17. Buckwell A et al. 2014. *The Sustainable Intensification of European Agriculture.* Brussels: RISE Foundation
18. Francis C A et al. 2012. Farmland conversion to non-agricultural uses in the US and Canada: current impacts and concerns for the future. *Int J Agric Sust* 10(1), 8-24
19. IPCC. 2014. *Fifth Assessment Report (AR5)*. Geneva
20. Pretty J et al. 2006. Resource-conserving agriculture increases yields in developing countries. *Environmental Science and Technology* 40: 1114-19
21. Pretty J et al. 2011. Sustainable intensification in African agriculture. *Internat. J Agric Sustainability* 9(1): 5-24
22. Reganold J P and Wachter J M. 2016. Organic agriculture in the 21st century. *Nature Plants* 2(2): 15221
23. UN. 2017. *World Population Prospects: 2017 Revision*. Department of Economic and Social Affairs, NY
24. Smith M R et al. 2015. Effects of decreases of animal pollinators on human nutrition and global health: a modelling analysis. *Lancet* 386, 1964–1972
25. Hill S. 1985. Redesigning the food system for sustainability. *Alternatives* 12, 32-36
26. Sandhu H et al. 2015. Significance and value of non-traded ecosystem services on farmland. *PeerJ*, 3, p.e762
27. Mulligan K. 2016. *Fertilizer Deep Placement*. Feed the Future, USAID, Washington DC
28. Garbach K et al. 2017. Examining multi-functionality for crop yield and ecosystem services in five systems of agroecological intensification. *Internat J Agric Sust 15*(1), 11-28
29. Lampkin N H et al. 2015. The role of agroecology in sustainable intensification. Report for the Land Use Policy Group. Organic Research Centre, Elm Farm and Game & Wildlife Conservation Trust
30. Gurr G M et al. 2016. Multi-country evidence that crop diversification promotes ecological intensification of agriculture. *Nature Plants 2*(3), 16014
31. Gliessman S R and Rosemeyer M (eds.) 2009. *The Conversion to Sustainable Agriculture: Principles, Processes, and Practices*. CRC Press, Boca Raton
32. Hartley S E et al. 2015. Defending the leaf surface: intra- and inter-specific differences in silicon deposition in grasses in response to damage and silicon supply. *Frontiers in Plant Science* 6: 35
33. Pretty J. 2003. Social capital and the collective management of resources. Science 302: 1912-1915
34. FAO. 2016. *Farmer Field School Guidance Document*. Rome.
35. Pretty J and Bharucha Z P. 2015. Integrated pest management for sustainable intensification of agriculture in Asia and Africa. *Insects* 6, 152-82
36. Goulson D et al. 2015. Bee declines driven by combined stress from parasites, pesticides, and lack of flowers. *Science 347*(6229), p.1255957
37. Lowder S K et al. 2016. The number, size, and distribution of farms, smallholder farms, and family farms worldwide. *World Development* 87, 16-29
38. MacMillan T and Benton T. 2014 Engage farmers in research. *Nature* 509, 25-27
39. Spiegal S et al. 2018. Evaluating strategies for sustainable intensification of US agriculture through the Long-Term Agroecosystem Research network. *Environ. Res. Lett.* 13 (2018) 034031
40. Campbell A et al. 2017. Reflections on four decades of land restoration in Australia. *The Rangeland Journal* doi.org/10.1071/RJ17056
41. Rosset P M et al. 2011. The Campesino-to-Campesino agroecology movement of ANAP in Cuba: social process methodology in the construction of sustainable peasant agriculture and food sovereignty. *The Journal of peasant studies*, *38*(1), 161-191
42. Jatoe J P D et al. 2015. Does sustainable agricultural growth require a system of innovation? Evidence from Ghana and Burkina Faso. *Int J Agric Sust* 13(2): 104-119
43. Malabayabas A J B et al. 2014. Impacts of direct-seeded and early-maturing varieties of rice on mitigating seasonal hunger for farming communities in northwest Bangladesh. *Internat J Agric Sust*, *12*(4), 459-470
44. Zhang W et al. 2016. Closing yield gaps in China by empowering smallholder farmers. *Nature* 537(7622): 671-674
45. Defra. 2018. *A Green Future: Our 25 Year Plan to Improve the Environment*. London
46. Morris C et al. 2017. Sustainable Intensification: the view from the farm. *Aspects of Applied Biology* 136, 19-26
47. Kumar V. T. 2017. Zero-Budget Nature Farming. Department of Agriculture , Government of Andhra Pradesh, Hyderabad
48. Xinhua 2016. CPC and State Council Guide Opinion on Using New Development Concepts to Accelerate Agricultural Modernisation and Realise Moderate Prosperity Society. URL http://news.xinhuanet.com/fortune/2016-01/27/c_1117916568.htm
49. Allen J E et al. 2017. Do Community Supported Agriculture programmes encourage change to food lifestyle behaviours and health outcomes? New evidence from shareholders. *Internat J Agric Sust* 15 (1), 70-82
50. Cui Z L et al. 2018. Pursuing sustainable productivity with millions of smallholder farmers. *Nature* doi:10.1038/nature25785

Global Assessment of Redesigned Sustainable Intensification of Agriculture

Supplementary Information

We developed a typology of seven redesign types according to starting intervention: (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. Summary details of each are presented here with examples of illustrative sub-types. The supplementary table contains details of all 47 initiatives included in the global assessment (Table S1).

Type 1. Integrated Pest Management

The most significant design innovation for IPM has been the deployment of Farmer Field Schools (FFS) (1). The aims are education, co-learning and experiential learning so that farmers' innovative expertise is improved. FFS are not only an extension method but also increase knowledge of agroecology, problem-solving skills, group building and political strength. FFS have now been used in 90 countries (2-3), with some 19M farmer graduates, 20,000 of whom are running FFS for other farmers as expert trainers. A synthesis of evidence from 92 impact evaluations of FFS related to IPM found a 13% increase in yield and 20% increase in income following engagement with FFS (4). A specific application of agroecological principles for IPM is *push-pull*, which is yielding notable successes from redesign of monocropped maize, millet and sorghum systems (5-6). Interplanting of the legume forage *Desmodium* suppresses *Striga* and repels stem borer adults while attracting natural enemies; planting *Napier* grass as a border crop pulls stem borer moths from the cereal. It is estimated that 132,000 farmers have adopted push-pull in Kenya, Uganda, Tanzania and Ethiopia (5). Positive externalities arise from nitrogen fixation by *Desmodium* and elimination of pesticides, in the provision of high quality fodder, enabling farmers to diversify into dairy and poultry production, in turn increasing the availability of animal manure for crops and soils. One meta-analysis of 85 IPM projects found a mean yield increase across projects and crops of 41%, combined with a decline in pesticide use to 31% compared with the baseline (7); another multi-country study of SI in rice-based systems of China, Thailand and Vietnam found yield increases of 5% with pesticide use reductions of 70% (8).

Type 2. Conservation Agriculture

A central principle of this redesign type is improved soil health. A variety of measures to mitigate soil erosion, improve water-holding capacity and increase soil organic matter are being deployed to improve soil health and boost crop yields. Three key features are reduced soil disturbance through reduced or zero tillage, mulching and green manures, and maintenance of year-round soil cover and crop rotations, seeking to maintain an optimum environment in the root zone in terms of water availability, soil structure and biotic activity (9-11). Optimal CA uses all three features, though many farmers only practice one or two of these. Currently, CA systems are practiced across a range of agro-ecological conditions, soil types and farm sizes. CA practices are spreading by some 6 Mha annually to a total of 180 Mha in 2017. CA covers >50% arable cropland in Australasia and South America, 15% of North America, though adoption has been lower across Europe and Africa.

Type 3. Integrated Crop and Biodiversity Redesign

In both industrialised and developing countries, a growing number of crop systems have been redesigned using agro-ecological principles. A worldwide example of redesign is organic agriculture, now occupying 58 Mha, with yields 5-50% lower than conventional equivalents, though under certain conditions organic yields can match or exceed conventional (12-14). With a wide range of approaches including livestock, pasture, agroforestry and small-scale horticulture, many organic systems have higher biodiversity, landscape diversity and soil carbon, and lower soil erosion and contamination of water systems (15), though some of these benefits come from uncultivated habitats. However, organic systems are generally more profitable, thanks in part to legally-regulated markets, and environmentally friendly, and deliver equally or more nutritious foods that contain fewer pesticide residues. Over the past decade, the number of organic producers has grown by 55% and organic area doubled, and there have been recent calls for a *beyond organic* or *organic 3.0*, focusing on sustainability goals rather than market definitions (12, 16-17). The largest number of organic farmers are in India, Ethiopia, Mexico and Uganda; the largest area in Australia and Argentina, and the largest proportions of country cropland in Austria, Liechtenstein and Samoa (13).

Further redesign and deployment of multiple interventions has seen increased rotational diversity, use of wildflowers for pollinators and other beneficial insects, conservation headlands and trap crops, composted animal manures, and grain legumes (18-20), often with large reductions in input use without yield compromise, such as on 750 farms in France (21). In less-developed countries, fish, crab, turtle and duck have been reintroduced into rice systems, reducing pest and weed incidence, often eliminating the need for pesticides, and thus producing increased system productivity through new animal protein (22). Both the Systems of Rice and Crop Intensification (SRI and SCI) emerged from complete redesign of paddy rice cultivation: reduced planting density, improvement of soil with organic matter, reduced use of water, and very early transplantation of young plants have led to considerable yield increases with reduced requirements for water and other external inputs (23-24). Since inception, SRI principles have been adapted from rice to wheat, sugarcane, tef, finger millet and pulses, all again emphasizing changes in resource use and application combined with crop planting design. The governments of Cambodia, China, India, Indonesia and Vietnam have endorsed SRI/SCI methods in their national food security programmes, with one million Vietnamese rice farmers now using SRI.

Type 4. Pasture Redesign

Pasture redesign has arisen from diversification of cropping, including organic agriculture, the adoption of Management Intensive Rotation Grazing (MIRG), and the deployment of agro-pastoral field schools (25). In Brazil, redesigned *Brachiaria* forages in maize-rice and millet-sorghum systems have through increased net productivity led to large increases in all-year forage, which is used both for livestock and as a green manure (26). MIRGs are an example of widespread pasture redesign, using short-duration grazing episodes on small paddocks or temporarily fenced areas, with longer rest periods that allow grassland plants to regrow before grazing returns (27). These systems replace external inputs including feed with knowledge and high levels of active management to maintain grassland productivity. Well-managed grazing systems have been associated with greater temporal and spatial diversity of plant species, increased carbon sequestration, reduced soil erosion, improved wildlife habitat and decreased input use (28). As many have replaced zero-grazed confined livestock systems, the animals themselves have to be bred for different characteristics: large mouth, shorter legs, stronger feet and hooves, larger rumen. MIRGs were first developed in New Zealand, and are now common in parts of the USA.

Type 5. Trees in Agricultural Systems

Agroforestry has long been used in traditional agricultural systems, particularly in the tropics (29). Two types of deliberate redesign have been deployed with trees and shrubs: i) their introduction into cropped systems, and ii) new forms of collective management of woodland and forest within agricultural landscapes. Legume tree-based farming systems offer a route to increased availability of nitrogen while avoiding synthetic fertilizers, leading to the use of the term *fertilizer tree* (30). Shrubs (e.g., *Gliricidia, Sesbania*) are introduced into crop rotations, increasing fuelwood production and nitrogen fixation, but still increasing net cereal yield over a five-year rotation. In other systems, perennial trees (e.g., *Faidherbia*) are introduced into dryland and silvo-pastoral systems, with trees leafing when crops are not growing, resulting in re-greening of some 5Mha in Niger, Burkina Faso and Mali, with the outcome of amended local climate, increased wood and tree fodder availability, and better water harvesting (31-32). The success of community-based, joint and participatory forest management has centered on the reversal of past state policy to exclude local people. Local management through new forest institutions, plus devolution of practices, rules and sanctions, have led to the formation of 3000 groups in Mexico, 30,000 in India and Nepal, 1.8M farmers in Vietnam with tree certificates, and 12M forest farmer cooperative users in China (33-34). There is renewed interest in agroforestry in temperate systems, particularly in France and the UK (16).

Type 6. Irrigation Water Management

Without regulation or control, irrigation water tends to be overused by those who have first access, resulting in shortages for tail-enders, conflicts over water allocation, and waterlogging, drainage and salinity problems (34). However where social capital is well-developed, water-user groups with locally developed rules and sanctions are able to make more of existing resources than individuals working alone or in competition (35-36). This increases rice yields, farmer contributions to design and maintenance of systems, changes in the efficiency and equity of water use, decreased breakdown of systems and fewer complaints to government departments. More than 60,000 water-user groups and associations have been established in India, Indonesia, Mexico, Nepal, Pakistan, the Philippines, Sri Lanka, Turkey and Uzbekistan, though many exist only on paper or remain in inefficient centralised control (37-42).

Type 7. Intensive Small and Patch Systems

The intensive use of patches (small areas of land) can be effective, particularly for cultivation of vegetables or rearing fish, poultry or small livestock. These may be located in gardens, at field boundaries, in urban or rural landscapes, and managed individually or collectively. Examples in industrialised countries include allotments, community gardens or farms, vertical and urban farms, and community supported agriculture. In developing countries, patch intensification for aquaculture ponds and tanks has been shown to raise protein production, reduce nitrogen requirements for crops, and positively impact agricultural productivity (43). Raised beds for vegetables in East Africa have been beneficial for large numbers of women, homestead garden production has spread in Bangladesh, and in China full redesign has been exemplified by integrated vegetable and fruit, pig and poultry farms with biogas digesters. Farm plots are very small (0.14 ha), and yet farmers are able to recycle wastes, produce methane for cooking, and reduce burning of wood and crop residues, with implementation on 50 M household plots in China (44-46). An important enabler of small-scale intensification has been provided by access to microcredit. When local groups are trusted to manage financial resources, they are more effective than banks, leading to positive agricultural and community outcomes. All form social groups, all work primarily with women, and all members of groups save money every week in order to create the capital for lending. In Bangladesh, Grameen Bank, Bangladesh Rural Advancement Committee, and Proshika have 1.5M groups with 17M members: many have diversified into social enterprises for rural artisans, providing livestock insemination services, chicken for retail, cold storage for potato farmers, dairy milk processing, services for fish farmers, tree seedlings, iodised salt, seed services, and sericulture (silk production) (47-49).

References for Supplementary Text

1. Kenmore P., Carino F., Perez G. and Dyck V. 1984. Population regulation of the rice brown plant hopper Nilaparvata lugens (Stal) within rice fields in the Philippines. *J. Plant Protect. Trop*. *1*, 19–38
2. Braun A. and Duveskog D. 2009. *The Farmer Field School Approach – History, Global Assessment and Success Stories*. IFAD: Rome
3. FAO 2016. *Farmer Field School Guidance Document*. Rome
4. Waddington, H., Snilstveit, B., Hombrados, J., Vojtkova, M., Phillips, D., Davies, P. et al. 2014. Farmer field schools for improving farming practices and farmer outcomes in low- and middle-income countries: a systematic review. Campbell Syst. Rev. 10, 1–335
5. Khan Z R, Midega C A O, Hooper A and Pickett J A. 2016 Push-Pull: chemical ecology-based integrated pest management technology. *Journal of Chemical Ecology* 42, (7) 689 – 697
6. Dicks, L.V., Wright, H.L., Ashpole, J.E., Hutchison, J., McCormack, C.G., Livoreil, B., Zulka, K.P. and Sutherland, W.J., 2016. What works in conservation? Using expert assessment of summarised evidence to identify practices that enhance natural pest control in agriculture. *Biodiversity and Conservation*, *25*(7), 1383-1399
7. Pretty J and Bharucha Z P. 2015. Integrated pest management for sustainable intensification of agriculture in Asia and Africa. *Insects* 6, 152-82
8. Gurr, G.M., Lu, Z., Zheng, X., Xu, H., Zhu, P., Chen, G., Yao, X., Cheng, J., Zhu, Z., Catindig, J.L. and Villareal, S., 2016. Multi-country evidence that crop diversification promotes ecological intensification of agriculture. *Nature Plants*, *2*(3), p.16014
9. Kassam A., Friedrich T., Shaxson F. and Pretty J.N. 2009. The spread of conservation agriculture: justification, spread and uptake. *Int J Agric Sust* 7(4), 292-320
10. Kassam A, Friedrich T and Derpsch R. 2017. Global spread of Conservation Agriculture: Interim update. 7th World Congress on CA, Rosario, Argentina
11. Ward P S, Bell A R, Droppelmann K and Benton T G. 2018. Early adoption of conservation agriculture practices: Understanding partial compliance in programs with multiple adoption decisions. *Land Use Policy 70*, 27-37
12. Reganold J.P. and Wachter J.M. 2016. Organic agriculture in the 21st century. *Nature Plants* 2(2): 15221
13. FiBL. 2018. *The World of Organic Agriculture 2018*. Research Institute of Organic Agriculture (FiBL), Frick, Switzerland
14. Seufert, V., Ramankutty, N. and Foley, J.A. 2012. Comparing the yields of organic and conventional agriculture. *Nature* 485(7397), p.229
15. Batary P, Baldi A, Kleijn D andTscharntke T. 2011. Landscape-moderated biodiversity effects of agri-environmental management – a metaanalysis. *Proceedings of the Royal Society B* 278**, 1**894–1902
16. Lampkin N.H., Pearce B.D., Leake A.R., Creissen H., Gerrard C.L., Girling R., Lloyd S., Padel S., Smith J., Smith L.G., Vieweger A. and Wolfe M.S. 2015. The role of agroecology in sustainable intensification. Report for the Land Use Policy Group. Organic Research Centre, Elm Farm and Game & Wildlife Conservation Trust
17. Muller, A., Schader, C., El-Hage Scialabba, N., Hecht, J., Isensee, A., Erb, K.H., Smith, P., Klocke, P., Leiber, F., Stolze, M. & Niggli, U. 2017. Can organic agriculture feed the world in 2050: a critical assessment of the challenges and opportunities. *Nature Communication*s 8, 1290. doi: 10.1038/s41467-017-01410-w.
18. MacWilliam S, Wismer M, Kulshreshtha S (2014). Life cycle and economic assessment of Western Canadian pulse systems: The inclusion of pulses in crop rotations. Agricultural Systems 123:43- 53

19. Pywell R.F., Heard M.S., Woodcock B.A., Hinsley S., Ridding L., Nowakowski M. and Bullock J.M. (2015) Wildlife friendly farming increases crop yield: evidence for ecological intensification. *Proc Royal Society Lond*. B 282: 20151740
20. Franke, A.C., Van den Brand, G.J., Vanlauwe, B. and Giller, K.E. 2017. Sustainable intensification through rotations with grain legumes in Sub-Saharan Africa: A review. *Agriculture, Ecosystems & Environment*
21. Lechenet M, Dessaint F, Py G, Makowski D and Munier-Jolain N, 2017. Reducing pesticide use while preserving crop productivity and profitability on arable farms. *Nature Plants*, *3*, 17008
22. FAO. 2014. *Aquatic biodiversity in rice-based ecosystems: Studies & reports from Indonesia, LAO PDR and the Philippines.* M. Halwart & D. Bartley (ed). Asia Regional Rice Initiative: Aquaculture and fisheries in rice-based ecosystems. Rome
23. Stoop W, Uphoff N and Kassam A. 2002. A review of agricultural research issues raised by the system of rice intensification (SRI) from Madagascar: opportunities for improving farming systems for resource-poor farmers. *Agric Systems* 71(3), 249-274
24. Adhikari P, Araya H, Aruna G, Balamatti A, Banerjee S, Baskaran P, Barah B C. Behera D, Boruah P, Dhar S, Edwards S, Fulford M, Gujja B, Ibrahim H, Kabir H, Kassam A, Khadka R B, Koma Y S, Natarajan U S, Perez R, Sen D, Sharif A, Singh G, Styger E, Thakur A, Tiwari A, Uphoff N and Verma A. 2018. System of Crop Intensification for more productive, resource-conserving, climate-resilient and sustainable agriculture: Experience with diverse crops in varying agroecologies. *International Journal of Agricultural Sustainability* (in press)
25. FAO. 2013. *Supporting Communities in Building Resilience Through Agropastoral Field Schools*. Rome
26. FAO 2011. *Save and Grow: A Policymaker's Guide to the Sustainable Intensification of Smallholder Crop Production*. Rome
27. NRC 2010. *Towards sustainable agricultural systems in the 21st century*. Committee on Twenty-First Century Systems Agriculture. Washington, DC: National Academies Press
28. Sprague, R., Boyer, S., Stevenson, G.M. and Wratten, S.D., 2016. Assessing pollinators' use of floral resource subsidies in agri-environment schemes: An illustration using Phacelia tanacetifolia and honeybees. *PeerJ*, *4*, p.e2677
29. Lorenz K and Lal R. 2014. Soil organic carbon sequestration in agroforestry systems: a review. *Agronomy for Sustainable Development* 34: 443–454
30. Garrity D.P., Akinnifesi F.K., Ajayi O.C., Weldesemayat S.G., Mowo J.G., Kalinganire A., Larwanou M. and Bayala J. 2010. Evergreen Agriculture: a robust approach to sustainable food security in Africa. *Food Security* 2:197-214
31. Sendzimir J C P, Reij C and Magnuszewski P. 2011. Rebuilding resilience in the Sahel: regreening in the Maradi and Zinder regions of Niger. *Ecology and Society* 16(3): 1
32. Bunch R. 2018 (2012). *Restoring the Soil*. Canadian Foodgrains Bank, Winnipeg, 2nd edition
33. FAO. 2016. *Forty Years of Community-Based Forestry*. Rome: FAO.
34. Liu J and Innes J L. 2015. Participatory forest management in China: key challenges and ways forward. *Int Forestry* Review 17(2) 1-8
35. Molle, F., Foran, T. and Kakonen, M. eds., 2012. Contested waterscapes in the Mekong region: Hydropower, livelihoods and governance. Earthscan
36. Ostrom, E. 1990. Governing the commons: the evolution of institutions for collective action. Cambridge, UK, Cambridge University Press
37. Wang Xihua, Lu Wenxi, Xu Y J, Zhang G, Qu W and Cheng W. 2016. The positive impacts of irrigation schedules on rice yield and water consumption: synergies in Jilin Province, Northeast China. *Int J Agric Sust* 14:1, 1-12
38. Shindo S and Yamamoto K. 2017. Strengthening water users' organization targeting for participatory irrigation management in Egypt. *Paddy and Water Environment 15*(4), 773-785
39. Uysal Ö K and Atış E. 2010. Assessing the performance of participatory irrigation management over time: A case study from Turkey. *Agricultural water management*, *97*(7), 1017-1025
40. Sinha P. 2014. Status of Participatory Irrigation Management (PIM) in India. *National Convention of Presidents of Water Users Associations,* Ministry of Water Resources India NPIM, New Delhi, 7-8 November, 2014
41. Zhou Q, Deng X., Wu F., Li Z. and Song W., 2017. Participatory irrigation management and irrigation water use efficiency in maize production: evidence from Zhangye City, Northwestern China. *Water*, *9*(11), 822
42. Ricks J.I. 2016. Building participatory organizations for common pool resource management: Water user group promotion in Indonesia. *World Development 77*, 34-47
43. Brummett R E and Jamu D M. 2011. From researcher to farmer: partnerships in integrated aquaculture-agriculture systems in Malawi and Cameroon. *Int J Agric Sust* 9(1), 282-289
44. Iannotti L, Cunningham K, Ruel M. 2009. Improving diet quality and micronutrient nutrition: homestead food production in Bangladesh. IFPRI Discussion Paper 00928. Washington, DC: International Food Policy Research Institute
45. Pretty J, Toulmin C, Williams S. 2011. Sustainable intensification in African agriculture. International Journal of Agricultural Sustainability 9(1): 5-24
46. Gu L, Zhang Y-X, Wang J-Z, Chen G and Battye H. 2016. Where is the future of China's biogas? Review, forecast, and policy implications. *Petroleum Science*. 13 (1), 604–624
47. BRAC. 2017. www.brac.net
48. Grameen Bank. 2017. URL www.grameen.com
49. Proshika 2017. URL www.proshika.org

Supplementary Table S1. Global assessment of sustainable intensification redesign from 47 initiatives at scale

Redesign type	Illustrative sub-types	Country	Farm numbers (million)	Hectares under SI (million)
1. Integrated pest management (IPM) [1-10]	Farmer field schools for integrated pest management	Worldwide, 90 countries in Asia and Africa: especially Indonesia, Philippines, China, Vietnam, Bangladesh, India, Sri Lanka, Nepal, Burkina Faso, Senegal, Kenya	19.0	15.0
	Biological control of pearl millet head miner	Burkina Faso, Niger, Mali, Senegal	0.75	2.0
	Cotton integrated pest management	Egypt	0.15	0.31
	Push-pull IPM	Kenya, Uganda	0.13	0.10
2. Conservation agriculture [11-16]	Conservation agriculture with zero-tillage	Worldwide: Brazil, Argentina, Kazakhstan, USA, Australia, India Industrialised countries Developing countries	 0.45 16.5	 94.0 86.0
	Microbacia groups for watershed management	Brazil, southern: Parana, Santa Catarina	0.10	1.0
	Zai and tassa water harvesting	Burkina Faso, Niger	0.05	0.025
3. Integrated crop and biodiversity redesign [17-34]	Organic agriculture	Worldwide: especially India, Ethiopia, Mexico (for numbers of farmers)	2.70	57.8
	Rice-fish systems	South-East and East Asia	1.0	1.4
	System of Crop and Rice Intensification, multiple crops	Ethiopia, Vietnam, India	3.113	3.013
	Pigeon pea/maize multiple cropping	East and Southern Africa	0.45	0.25
	Crop redesign with integrated plant and pest management with farmer field schools	Burkina Faso, Niger, Mali, Senegal	0.18	0.15
	Landcare	Australia	0.09	0*
	Campesino a Campesino agro-ecological farming	Cuba	0.10	0.05
	Zero-budget natural farming	India: Andhra Pradesh	0.163	0.081
	Farmer agro-ecological wisdom networks	NE Thailand	0.10	0.30
	Science and technology boards	China	0.05	0.03
	Legume-maize intercrops for green manures/cover crops	Honduras, Guatemala, Mexico, Nicaragua	0.067	0.090
	Green manure/cover crop mixed systems	Brazil	0.14	0.10
	All crops with mucuna legumes (for *Imperata* suppression)	Benin	0.014	0.03

		Mokichi Okada natural/nature farming	Japan	0.015	0.003
		Orange-fleshed short-duration sweet potato	Uganda	0.014	0.011
4.	Pasture and forage redesign [35-39]	Management intensive rotational grazing	USA	0.01	1.6
		Brachiaria-grass mixed crop-forage systems	Brazil	1.3	80.0
		Agro-pastoral field schools	Uganda	0.12	0.25
5.	Trees in agricultural systems [40-51]	Agroforestry and soil conservation	Niger, Burkina Faso, Mali	4.0	3.0
		Joint forest management groups and forest protection committees	India, Nepal	11.6	25.0
		Community based forestry	Mexico	0.09	15.0
		Forest farmer cooperatives	China, Vietnam	13.80	17.8
		Agroforestry and multifunctional agriculture	Cameroon	0.010	0.005
		Fertilizer and fodder trees and shrubs	Zambia, Malawi	0.50	0.40
6.	Irrigation water management [52-55]	Water user associations for irrigation management	India	15.0	15.0
		Community irrigation management subaks	Indonesia (Bali)	0.90	14.0
		Water users associations	Mexico	2.0	4.0
7.	Intensive small and patch systems [56-67]	Microcredit group programmes (enablers of small-scale SI): BRAC, Grameen, Proshika	Bangladesh	17.0	8.50
		Intensive vegetable-pig systems with biodigesters	China	50.0	7.0
		Homestead garden production	Bangladesh	0.94	0.01
		Organic small-scale raised beds	Kenya	0.15	0.001
		Allotment gardens	UK	0.30	0.0075
		Community urban gardens	USA and Canada	0.018	0.001
		Group purchasing associations (Community Supported Agriculture, tekei groups, guilds)	USA, France, Japan, Switzerland, Belgium	0.011	0.055
		Integrated aquaculture	Malawi, Cameroon, Ghana	0.018	0.001
Total				**163**	**453**

Note: we do not present data on adoption of GM crops here, as these have mostly resulted in Efficiency/Substitution changes: one crop variety for another, some reductions in insecticide, some increases in herbicide, depending on the traits (Frisvold and Reeves, 2014); a number of GM traits are used in conservation agriculture systems.

*The average farm size in Australia is 3000 hectares, but there is no data on area under SI within Landcare groups and farms.

References for Supplementary Table S1

<u>Integrated Pest Management</u>

1. Braun A. and Duveskog D. 2009. *The Farmer Field School Approach – History, Global Assessment and Success Stories*. IFAD: Rome
2. Chhay N, Suon Seng, Toshiharu Tanaka, Akira Yamauchi, Editha C. Cedicol, Kazuhito Kawakita & Sotaro Chiba (2017) Rice productivity improvement in Cambodia through the application of technical recommendation in a farmer field school, International Journal of Agricultural Sustainability, 15:1, 54-69
3. FAO 2016. *Farmer Field School Guidance Document*. FAO: Rome.
4. ICIPE 2013. Stories of our success: positive outcomes from push-pull farming systems. http://www.push-pull.net/farmers_success.pdf
5. Khan Z.R., Midega C., Pittchar J.O., Murage A and Pickett J. 2017. Climate-smart Push-Pull: A conservation agriculture technology for food security and environmental sustainability in Africa. CAB International
6. Khan, Z.R., Midega, C.A.O., Hooper, A.,Pickett, J.A. 2016 Push-Pull: Chemical Ecology-Based Integrated Pest Management Technology. Journal of Chemical Ecology 42, (7) 689 – 697
7. Payne, W., Tapsoba, H., Baoua, I. B., Malick, B. N., N'Diaye, M., Dabire-Binso, C. 2011. On-farm biological control of the pearl millet head miner: realization of 35 years of unsteady progress in Mali, Burkina Faso and Niger. International Journal of Agricultural Sustainability 9(1), 186–193
8. Pretty J and Bharucha Z P. 2015. Integrated pest management for sustainable intensification of agriculture in Asia and Africa. *Insects* 6, 152-82
9. Pretty J, Toulmin C, Williams S. 2011. Sustainable intensification in African agriculture. International Journal of Agricultural Sustainability 9(1): 5-24
10. Yang P.Y., Zhao Z.H. and Shen Z.R. 2014. Experiences with Implementation and Adoption of Integrated Pest Management in China. In Integrated pest management (pp. 307-330). Springer Netherlands

<u>Conservation Agriculture</u>

11. Bunch R. 2018 (2012). *Restoring the Soil*. Canadian Foodgrains Bank, Winnipeg
12. Derpsch R., Friedrich T., Kassam A. and Hongwen L. 2010. Current status and adoption of no-till farming in the world and some of its main benefits. *Int. J. Agric. & Biol Eng* 3(1): 1-25
13. Kassam A, Friedrich T and Derpsch R. 2017. Global spread of Conservation Agriculture: Interim update. 7th World Congress on CA, Rosario, Argentina
14. Kassam A., Friedrich T., Shaxson F. and Pretty J.N. 2009. The spread of conservation agriculture: justification, spread and uptake. *International Journal of Agricultural Sustainability* 7(4): 292-320
15. Li Hongwen, He Jin, Bharucha Z P, Lal R and Pretty J. 2016. Improving China's food and environmental security with conservation agriculture. *International Journal of Agricultural Sustainability* 14, 377-391
16. Sawadogo H. 2011. Rehabilitation of degraded lands by using soil and water conservation techniques in the north western region of Burkina Faso. *International Journal of Agricultural Sustainability* 9(1): 120-128.

<u>Integrated crop and biodiversity redesign</u>

17. Adhikari P, Araya H, Aruna G, Balamatti A, Banerjee S, Baskaran P, Barah B C. Behera D, Boruah P, Dhar S, Edwards S, Fulford M, Gujja B, Ibrahim H, Kabir H, Kassam A, Khadka R B, Koma Y S, Natarajan U S, Perez R, Sen D, Sharif A, Singh G, Styger E, Thakur A, Tiwari A, Uphoff N and Verma A. 2018. System of Crop Intensification for more productive, resource-conserving, climate-resilient and sustainable agriculture: Experience with diverse crops in varying agroecologies. International Journal of Agricultural Sustainability (in press)
18. Bunch R. 2018 (2012). *Restoring the Soil*. Canadian Foodgrains Bank, Winnipeg
19. FAO 2011.*Save and Grow: A Policymaker's Guide to the Sustainable Intensification of Smallholder Crop Production*. Rome: FAO
20. FAO 2016a. *Save and Grow: Maize, Rice and Wheat – A Guide to Sustainable Crop Production,*UN Food and Agriculture Organization, Rome
21. FiBL, 2017. *The World of Organic Agriculture 2017*. Research Institute of Organic Agriculture (FiBL), Frick, Switzerland
22. Holt-Gimenez E and Altieri M A. 2013. Agroecology, food sovereignty, and the new green revolution. Agroecology and Sustainable Food Systems 37: 90–102
23. Kumar V. T. 2017. Zero-Budget Nature Farming. Department of Agriculture , Government of Andhra Pradesh, Hyderabad
24. Mwanga R O M and Ssemakula G. 2011.Orange-fleshed sweet potatoes for food, health and wealth In Uganda. International Journal of Agricultural Sustainability 9(1), 42–49
25. Pretty J, Toulmin C, Williams S. 2011. Sustainable intensification in African agriculture. International Journal of Agricultural Sustainability 9(1): 5-24
26. Pretty J.N. and Bharucha Z P. 2014. Sustainable intensification in agricultural systems. *Annals of Botany* 205, 1-26.
27. Reganold J.P. and Wachter J.M. 2016. Organic agriculture in the 21st century. *Nature Plants* 2(2): 15221

28. Rosset P.M. and Martínez-Torres M.E. 2012. Rural Social Movements and Agroecology: Context, Theory, and Process. *Ecology and Society* 17(3): 17.
29. Rosset, P.M., Machín Sosa, B., Roque Jaime, A.M. and Ávila Lozano, D.R., 2011. The Campesino-to-Campesino agroecology movement of ANAP in Cuba: social process methodology in the construction of sustainable peasant agriculture and food sovereignty. The Journal of peasant studies, 38(1), pp.161-191
30. Rosset, P.M., Machín Sosa, B., Roque Jaime, A.M. and Ávila Lozano, D.R., 2011. The Campesino-to-Campesino agroecology movement of ANAP in Cuba: social process methodology in the construction of sustainable peasant agriculture and food sovereignty. *The Journal of peasant studies*, *38*(1), pp.161-191
31. Settle W and Hama Garba M., 2011. The FAO integrated production and pest management programme in the Senegal and Niger river basins of francophone West Africa. International Journal of Agricultural Sustainability 9(1), 171–185
32. SRI-Rice (2014). The System of Crop Intensification: Agroecological Innovations for Improving Agricultural Production, Food Security, and Resilience to Climate Change. SRI International Network and Resources Center (SRI-Rice), Cornell University, Ithaca, New York, and the Technical Centre for Agricultural and Rural Cooperation (CTA), Wageningen, Netherlands
33. Xu, Hui-lian. 2006. *Nature Farming*. Research Signpost 37/661, Trivandrum, Kerala
34. Zhang W., Cao G., Li X., Zhang H., Wang C., Liu Q., Chen X., Cui Z., Shen J., Jiang R. and Mi G. 2016. Closing yield gaps in China by empowering smallholder farmers. *Nature* 537(7622): 671-674

Pasture and forage redesign

35. CIAT. 2016.Livestock, climate change and Brachiaria. Eco-Efficient Agriculture for the Poor. CIAT Brief 12. www.ciat.cgiar.org
36. FAO 2011.*Save and Grow: A Policymaker's Guide to the Sustainable Intensification of Smallholder Crop Production*. Rome: FAO
37. FAO. 2013. *Supporting Communities in Building Resilience Through Agropastoral Field Schools*. Rome
38. NRC 2010. Towards sustainable agricultural systems in the 21st century. Committee on Twenty-First Century Systems Agriculture. Washington, DC: National Academies Press Ostrom, E. 1990. Governing the commons: the evolution of institutions for collective action. Cambridge, UK, Cambridge University Press
39. Pretty J.N. 2014. *The Edge of Extinction*. Ithaca and London: Cornell University Press

Trees in agricultural systems

40. Ajayi O C, Place F, Akinnifesi F K and Sileshi G W. 2011. Fertilizer tree systems in Southern Africa (Malawi, Tanzania, Mozambique, Zambia and Zimbabwe). *International Journal of Agricultural Sustainability* 9(1), 129–136
41. Asaah, E. K., Tchoundjeu, Z., Leakey, R. R. B., Takousting, B., Njong, J., Edang, I., 2011, 'Trees, agroforestry and multifunctional agriculture in Cameroon', International Journal of Agricultural Sustainability 9(1), 110–119
42. Blomley, T. 2013. Lessons learned from community forestry in Africa and their relevance for REDD+. Washington, DC, Forest Carbon, Markets and Communities Program
43. Bunch R. 2018 (2012). *Restoring the Soil*. Canadian Foodgrains Bank, Winnipeg
44. FAO. 2016c. *Forty Years of Community-Based Forestry*. Rome: FAO.
45. Garrity D.P., Akinnifesi F.K., Ajayi O.C., Weldesemayat S.G., Mowo J.G., Kalinganire A., Larwanou M. and Bayala J. 2010. Evergreen Agriculture: a robust approach to sustainable food security in Africa. Food Security 2:197-214
46. Liu, J. and Innes, J.L. 2015. Participatory forest management in China: key challenges and ways forward. International Forestry Review, 17(2): 1-8.
47. Liu, J. and Innes, J.L. 2015. Participatory forest management in China: key challenges and ways forward. International Forestry Review, 17(2): 1-8.
48. Ministry of Forest and Soil Conservation, Nepal (MFSC). 2013. Persistence and change: review of 30 years of community forestry in Nepal. Kathmandu
49. Reij C.P. and Smaling E.M.A. 2008. Analyzing successes in agriculture and land management in Sub-Saharan Africa: Is macro-level gloom obscuring positive micro-level change? *Land Use Policy* 25: 410–420
50. Sendzimir J.C.P., Reij C. and Magnuszewski P. 2011. Rebuilding resilience in the Sahel: regreening in the Maradi and Zinder regions of Niger. Ecology and Society 16(3): 1
51. Wahl C T and Bland W L. 2013. Faidherbia albida on the Tonga Plateau of southern Zambia: an agroecological analysis, International Journal of Agricultural Sustainability 11 (4) 382-392

Irrigation water management

52. Shindo, S. and Yamamoto, K., 2017. Strengthening Water Users' Organization targeting for Participatory Irrigation Management in Egypt. *Paddy and Water Environment*, *15*(4), 773-785
53. Sinha P. 2014. Status of Participatory Irrigation Management (PIM) in India. *National Convention of Presidents of Water Users Associations,* Ministry of Water Resources India NPIM, New Delhi, 7-8 November, 2014
54. Uysal Ö K and Atış E. 2010. Assessing the performance of participatory irrigation management over time: A case study from Turkey. *Agricultural water management*, *97*(7), 1017-1025
55. Yekti, M.I., Schultz, B., Norken, I.N., Gany, A.H.A. and Hayde, L., 2017. Learning from Experiences of Ancient Subak Schemes for Participatory Irrigation System Management in Bali. *Irrigation and Drainage*, *66*(4), pp.567-576.

Intensive small scale systems

56. AMAP (Associations pour le maintien d'une agriculture paysanne) 2017. www.reseau-amap.og
57. American Community Gardening Association 2014. https://communitygarden.org/resources/faq/
58. American Community Gardening Association. 2014. https://communitygarden.org/resources/faq/
59. BRAC. 2017. www.brac.net
60. Brummett R E and Jamu D M. 2011. From researcher to farmer: partnerships in integrated aquaculture-agriculture systems in Malawi, Ghana and Cameroon. International Journal of Agricultural Sustainability 9(1), 282–289
61. Grameen Bank. 2017. URL www.grameen.com
62. Gu L, Zhang Y-X, Wang J-Z, Chen G and Battye H. 2016. Where is the future of China's biogas? Review, forecast, and policy implications. Petroleum Science. 13 (1), 604–624
63. Iannotti L, Cunningham K, Ruel M. 2009. Improving diet quality and micronutrient nutrition: homestead food production in Bangladesh. IFPRI Discussion Paper 00928. Washington, DC: International Food Policy Research Institute.
64. National Allotment Society 2014. Brief history of allotments. http://www.nsalg.org.uk/allotment-info/brief-history-of-allotments/
65. Pretty J and Bharucha Z P. 2015. Integrated pest management for sustainable intensification of agriculture in Asia and Africa. *Insects* 6, 152-82
66. Proshika 2017. URL www.proshika.org
67. USDA 2016. Farmers' Market Promotion Program. 2016 Report. Connecting Rural & Urban Communities. URL: https://www.ams.usda.gov/reports/farmers-market-promotion-program-2016-report