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).

<u>Type 1. Integrated Pest Management</u>

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).

<u>Type 2. Conservation Agriculture</u>

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).

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) [50-59]	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 [60-65]	Conservation agriculture with zero-tillage	Worldwide: Brazil, Argentina, Kazakhstan, USA, Australia, India		
		Industrialised countries	0.45	94.0
		Developing countries	16.5	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 [66-83]	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	Burkina Faso, Niger, Mali,	0.18	0.15

	integrated plant and pest management with farmer field schools	Senegal		
	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 [84-88]	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 [89-100]	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 [101-104]	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 [105-116]	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.

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