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1 **Global Assessment of Agricultural System Redesign for Sustainable**  
2 **Intensification**

3

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22

23 [4250 words and 50 references, word count includes the two tables, but not supplementary  
24 information and table; abstract is exactly 150 words]

25

26 **Abstract**

27

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

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

53

54

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

63

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

74

## 75 **Sustainable Intensification**

76

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

86

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

99

100 SI is a necessary but not sufficient component of transformation in the wider food system. Changes  
101 in consumption behaviours (e.g., in animal products), as well as reductions in food waste, may make  
102 greater contributions to the overall sustainability of food and agriculture systems (7), as well as  
103 helping to address the challenge of over-consumption of calorie-dense food, which has become a  
104 global threat to health. System level changes will be necessary from production to consumption, and  
105 eating better is now a priority for affluent countries. At the farm and landscape level, the need for  
106 effective SI is nonetheless urgent. Pressure continues to grow on existing agricultural lands.

107 Environmental degradation reduces the asset base (4, 16), expansion of urban and road  
108 infrastructure captures agricultural land (in the EU28, agricultural land area fell by 31Mha over 50  
109 years from 1961; in the USA and Canada, 0.5Mha are lost annually (17-18)); and climate change and  
110 associated extreme weather create new stresses, testing the resilience of the global food system  
111 (19).

112

113 Attempts to implement SI can result in beneficial outcomes for both agricultural output and natural  
114 capital (14, 20-21). The largest increases in food productivity have occurred in less developed  
115 countries, mostly starting from a lower output base. In industrialised countries, systems have tended  
116 to see increases in efficiency (lower costs), minimizing harm to ecosystem services, and often some  
117 reductions in crop and livestock yields (22). However, the global challenge is significant: planetary  
118 boundaries are under threat or have been exceeded, world population will continue to grow from  
119 7.6 billion (2018) to 10 billion by 2050 (23), and consumption patterns are converging on those  
120 typical in affluent countries for some sections of populations, yet still leaving some 800 million  
121 people hungry worldwide. One question centres on scale: can agriculture still provide sufficient  
122 nutritious food whilst improving natural capital and not compromising other aspects of well-being;  
123 and can this occur at a scale to benefit millions of lives, reverse biodiversity loss and environmental  
124 contamination, and limit greenhouse gas emissions? A further question centres on how much wider  
125 food system changes towards healthier diets could shape the requirements for agricultural  
126 production to focus on both food and environmental outcomes: healthier diets tend to be higher in  
127 fruit, pulse and nut content, therefore more dependent on pollination services (24). Healthier diets  
128 could also generate enhanced consumer demand for lower pesticide residues.

129

130 As SI is an umbrella term that includes a wide range of different agricultural practices and  
131 technologies, the precise extent of existing SI practice has been largely unknown. We use an

132 analytical framework developed for this global assessment data sets of large-scale changes (by  
133 numbers of farms and hectares) that have been made towards SI in this millennium.

134

135

### 136 **Beyond Improved Efficiency and Substitution to Redesign**

137

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

142

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

156

157 The second stage: *Substitution* focuses on the replacement of technologies and practices. The  
158 development of new crop varieties and livestock breeds deploys substitution to replace less efficient  
159 system components with alternatives, such as plant varieties better at converting nutrients to  
160 biomass, tolerating drought and/or increases in salinity, and with resistance to specific pests and  
161 diseases. Other forms of Substitution include the release of biological control agents to substitute  
162 for inputs); the use of RNA-based gene silencing pesticides; water-based architecture replacing the  
163 use of soil in hydroponics; and in no-tillage systems new forms of direct seeding and weed  
164 management replacing inversion tillage (14).

165

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

176

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

183

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

198

199

## 200 **Redesign Typology and Methods**

201

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

208

209 The seven system types span both industrialised and less-developed countries, and zones from  
210 temperate to tropical. Progress towards SI in developing countries is occurring in the context of the  
211 pressing need to implement sustainable development goals for poverty reduction, improved  
212 livelihoods and better nutrition by building more productive and sustainable systems of smallholder  
213 agriculture. There are some 570 million farms worldwide, 84% of which are landholdings of less than  
214 2 ha (37). These small farms make up 12% of total agricultural area, yet produce 70% of food in  
215 Africa and Asia. Sustainable intensification will have to be effective worldwide, yet will have to reach  
216 larger numbers of farms in less developed countries: 74% of all farms are in Asia (of which 35% are in  
217 China and 24% in India), 9% in Sub-Saharan Africa, 7% in Central Europe and Central Asia, 3% in Latin  
218 America and the Caribbean, and 3% in Middle East and North Africa. Owing to the average size of  
219 the 4% of farms in industrialised countries, the choices made by a single farmer can have landscape-  
220 wide consequences.

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

<b>Redesign type</b>	<b>Illustrative redesign sub-types of intervention</b>
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

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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

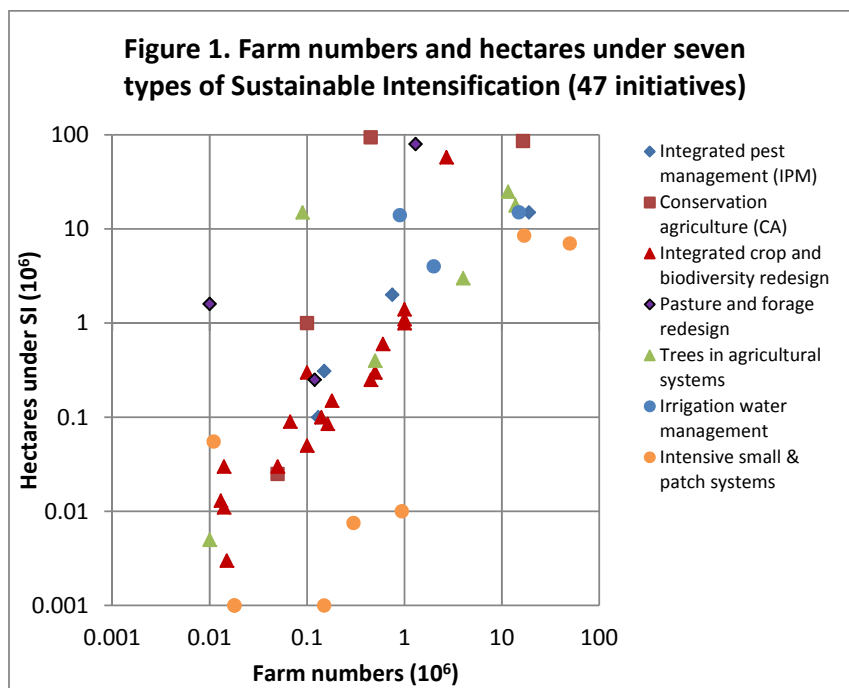
243 methods, in at least one farm enterprise, on an area approaching 453 million ha of agricultural land  
 244 (not counting the SI initiatives in home and urban gardens and on field boundaries). This comprises  
 245 29% of all farms worldwide; and 9% of agricultural land (total worldwide crop and pasture land is 4.9  
 246  $\times 10^9$  hectares).

247

248 We note that this global assessment might imply numbers of farms and hectares are fixed: on the  
 249 ground, there will be a flux in numbers as a result of both adoption and dis-adoption. This may arise  
 250 from farmer choice and agency, but equally from the actions of vested interests, agricultural input  
 251 companies, consolidation of small farms into larger operations, changes in agricultural policy or  
 252 shifts in market demand, and discrepancies between on-paper claims and what farmers have  
 253 implemented. We have also not included apparent adoption in this assessment: for example, EU  
 254 regulations require all farms to use IPM, but this has not yet led to significant uptake of agricultural  
 255 practices that significantly benefit ecosystem services (21).

256

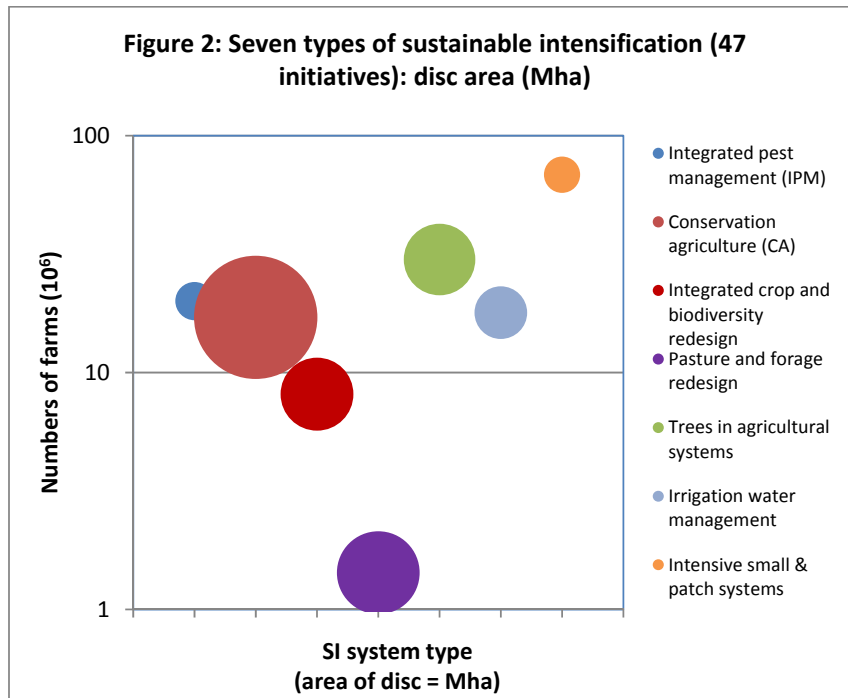
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#### 264 **The Co-creation of Agricultural Knowledge Economies**

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

280

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

288 6000 groups, farmer-led watershed councils and the long-term agroecosystem research network in  
289 the USA, the French network of agroecology farms, and the 49 Farmer Cluster Initiatives in the UK  
290 (39-40). These have created platforms for creation of practices to address locally specific problems  
291 of erosion, nutrient loss, pathogen escape and waterlogging. In Cuba, the *Campesino-a-Campesino*  
292 movement integrates agroecology into redesign, with knowledge and technologies spread through  
293 exchange and cooperatives: productivity of 100,000 farmers increased by 150% over ten years, and  
294 pesticide use fell to 15% of former levels (41). In West Africa, innovation platforms have increased  
295 yield in maize and cassava systems (42), and in Bangladesh have resulted in the development and  
296 spread of direct seeded and early-maturing rice (43). In China, Science and Technology Backyard  
297 (STB) platforms operate in 21 provinces covering many crops: wheat, maize, rice, soybean, potato,  
298 mango and lychee (44). STB platforms bring agricultural scientists to live in villages, and use field  
299 demonstrations and farm schools to engage farmers in developing innovations: reasons for success  
300 centre on in-person communication, socio-cultural bonding, and the trust developed among farmer  
301 groups of 30-40 individuals.

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#### 304 **Next Steps: A Tipping Point**

305

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

313

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

327

328 In most contexts, though, state policies for SI remain poorly developed or counter-productive. In the  
329 EU, farm subsidies have increasingly been shifting towards targeted environmental outcomes rather  
330 than payments for production, a process the UK Government has plans to accelerate (45-46), but  
331 this seldom guarantees synergistic benefits across whole landscapes. Several countries have offered  
332 explicit public policy support to social group formation, such as for Landcare (Australia), watershed

333 management (India), joint forest management (India, Nepal, DR Congo), irrigation user groups  
 334 (Mexico) and farmer field schools (Indonesia, Burkina Faso). In India’s state of Andhra Pradesh, the  
 335 state government has made explicit its support to zero-budget natural farming (local form of  
 336 uncertified organic farming), aiming to reach 6 million farmers by 2027 (47); in Bhutan and the  
 337 Indian states of Kerala and Sikkim, policy commitments have been made to convert all land to  
 338 organic agriculture; the greening of the Sahel through agroforestry began when national tree  
 339 ownership regulations were changed to favour local people (12). In China, the 2016 No 1 Central  
 340 Document emphasises innovation, coordination, greening and sharing as key parts of a new strategy  
 341 for SI (48). At the same time, consumers are increasingly playing a role in connecting directly with  
 342 farmers in affluent countries, such as through group purchasing schemes, farmers’ markets and  
 343 certification schemes, which may in turn change consumption choices (49).

344  
 345 With this growing understanding of the positive roles governments can play in structuring incentives  
 346 and policies, as well as supporting agricultural knowledge economies, we anticipate that SI may be at  
 347 a tipping point (2, 4). A further small increase in the number of farms successfully operating re-  
 348 designed agricultural systems could lead rapidly to re-design of agriculture on a global scale. To  
 349 transform agriculture to provide comprehensive sustainably intensified systems that can deliver  
 350 adequate, healthy food for all people, will require the integration of different redesign types to  
 351 create system-wide transitions, and the internalisation of agricultural externalities into prices or  
 352 through consumer demand. Our hypothesis is that important synergies are occurring, where  
 353 redesigned systems will deliver more than the sum of the parts, and that when more than one SI  
 354 sub-type is combined, the likelihood will increase that redesigned systems will be better fitted to  
 355 local circumstances and thus be more resilient. In the 47 initiatives analysed here, we scored for the  
 356 number of types used in each initiative (Table 2). Most initiatives are deploying one (25% of farms,  
 357 37% of hectares) or two (66% of farms, 52% of hectares) types. The most common paired  
 358 combinations were integrated crop and biodiversity redesign with either IPM, CA and soil health,  
 359 agroforestry and irrigation management. The most common deployment of only one sub-type was  
 360 trees in agricultural systems. This suggests a clear challenge centres on further integration: this  
 361 might include, for example, combining conservation agriculture for soil health with integrated  
 362 watershed management, nutrient recycling and integrated pest management.

363  
 364

365 **Table 2. Number of redesign types of SI deployed in each of 47 initiatives, by farm and hectare numbers and**  
 366 **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%

367  
 368

369 There is much to be done to ensure agricultural and food systems worldwide increase the  
 370 production of nutritious food whilst ensuring positive impacts on natural and social capital. Some

371 efficiency-based initiatives are reaching large numbers of farmers, such as the 21M reducing  
372 fertilizer use in China (50). We conclude that a transition from efficiency through substitution to  
373 redesign will be essential, suggesting that the concept and practice of SI of agriculture will be a  
374 process of adaptation, driven by a wide range of actors cooperating in new agricultural knowledge  
375 economies. This will still need farmers and society to invest in SI, not just for the sake of  
376 sustainability, but for livelihoods and profitability. There are risks: technologies could be dis-  
377 adopted, advances lost, and competing interests could co-opt and dilute innovations. Positive  
378 changes towards consuming healthier food and reductions in food waste may also not occur, putting  
379 more pressure on farmers to produce more food at any cost.

380

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

383

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

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395 **A Note on Terminology**

396 There is no single accepted terminology for grouping of types of countries. Terms relate to past  
397 stages of development (developed, developing, less developed), state of economy or wealth  
398 (industrialised, affluent), geographic location (global south or north), or membership (OECD, non-  
399 OECD). None are perfect: China has the second largest economy measured by GDP (which does not  
400 measure all aspects of economies, environments and societies well), yet might be considered still  
401 developing or less-developed. The USA has the largest economy by GDP, yet has nearly 50M hungry  
402 people. Here we have simply used *industrialised* and *less-developed*, and acknowledge the  
403 shortcomings. We also use the term pesticide to incorporate all synthesised pest, disease, weed and  
404 other control compounds.

405

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410

411 **Authors**

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

416

417 **Data Statement and Availability**

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

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507 **Figure legends**

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

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

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

