

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

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27
28 **Abstract**

29
30 The sustainable intensification (SI) of agricultural systems offers synergistic opportunities for the co-
31 production of agricultural and natural capital outcomes. Efficiency and Substitution are steps
32 towards SI, but system Redesign is essential to deliver optimum outcomes as ecological and
33 economic conditions change. We show global progress towards SI by farms and hectares, using
34 seven SI sub-types: integrated pest management, conservation agriculture, integrated crop and
35 biodiversity, pasture and forage, trees, irrigation management, and small/patch systems. From 47 SI
36 initiatives at scale (each >10⁴ farms or hectares), we estimate 163M farms (29% of all worldwide)
37 have crossed a redesign threshold, practising forms of SI on 453Mha of agricultural land (9% of
38 worldwide total). Key challenges include investing to integrate more forms of SI in farming systems,
39 creating agricultural knowledge economies, and establishing policy measures to scale SI further. We
40 conclude that SI may be approaching a tipping point where it could be transformative.

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44 Here we show that the sustainable intensification (SI) of agricultural systems offers synergistic
45 opportunities for the co-production of agricultural and environmental outcomes. Efficiency and
46 Substitution are steps towards SI, but system Redesign is essential to deliver optimum outcomes as
47 ecological and economic conditions change. This global assessment of SI by farms and hectares
48 categorises SI by seven sub-types: integrated pest management, conservation agriculture, integrated
49 crop and biodiversity, pasture and forage, trees, irrigation management, and small and patch
50 systems. From 47 SI initiatives at scale (each >10⁴ farms or hectares), we estimate 163M farms (29%
51 of all worldwide) have crossed a redesign threshold, practising forms of SI on 453 Mha of agricultural
52 cropped and pasture land (9% of worldwide total). The key challenges centre now on creating
53 agricultural knowledge economies and establishing policy measures to scale SI further. We conclude
54 that SI may be at a tipping point where it could be transformative.

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56

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

65

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

76

77 **Sustainable Intensification**

78

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

88

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

101

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

109 Environmental degradation reduces the asset base (4, 16), expansion of urban and road
110 infrastructure captures agricultural land (in the EU28, agricultural land area fell by 31Mha over 50
111 years from 1961; in the USA and Canada, 0.5Mha are lost annually (17-18)); and climate change and
112 associated extreme weather create new stresses, testing the resilience of the global food system
113 (19).

114

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

131

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

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

136

137

138 **Beyond Improved Efficiency and Substitution to Redesign**

139

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

144

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

158

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

167

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

178

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

185

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

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202 **Redesign Typology and Methods**

203

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

210

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

223

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

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

229

230

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

236

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238 Results

239

240 Forty-seven SI initiatives have exceeded the 10^4 scale, of which 17 exceed the 10^5 threshold, and 14
241 the 10^6 scale (Supplementary Table 1; Figures 1 and 2). Many SI initiatives worldwide show promise
242 but remain limited in scale (either demonstrating locally-dependent conditioning, or the lack of
243 attention to scalar mechanisms). We estimate from these projects-initiatives in some 100 countries
244 that 163 million farms have crossed an important substitution-redesign threshold, and are using SI

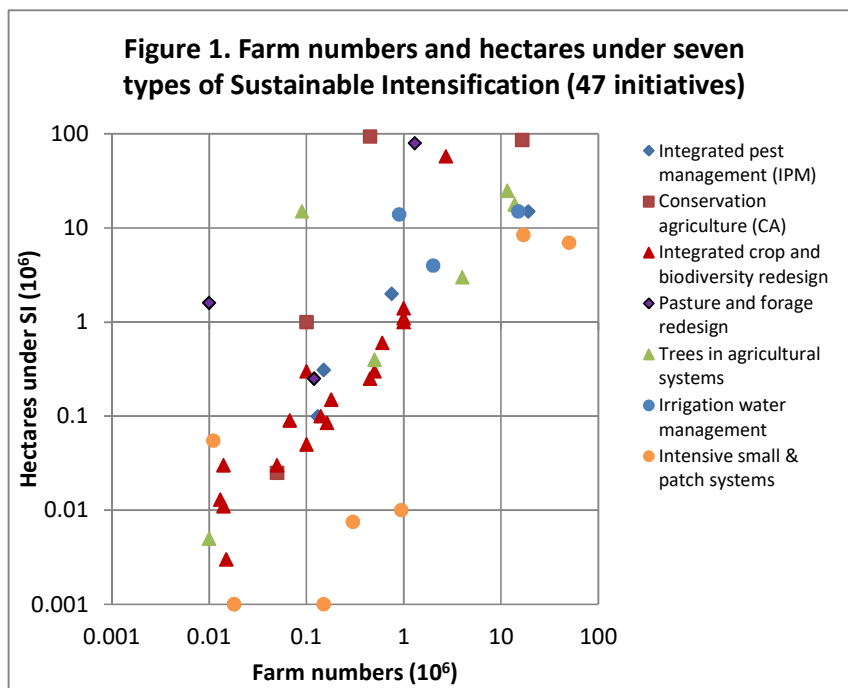
245 methods, in at least one farm enterprise, on an area approaching 453 million ha of agricultural land
 246 (not counting the SI initiatives in home and urban gardens and on field boundaries). This comprises
 247 29% of all farms worldwide; and 9% of agricultural land (total worldwide crop and pasture land is 4.9
 248 $\times 10^9$ hectares).

249

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

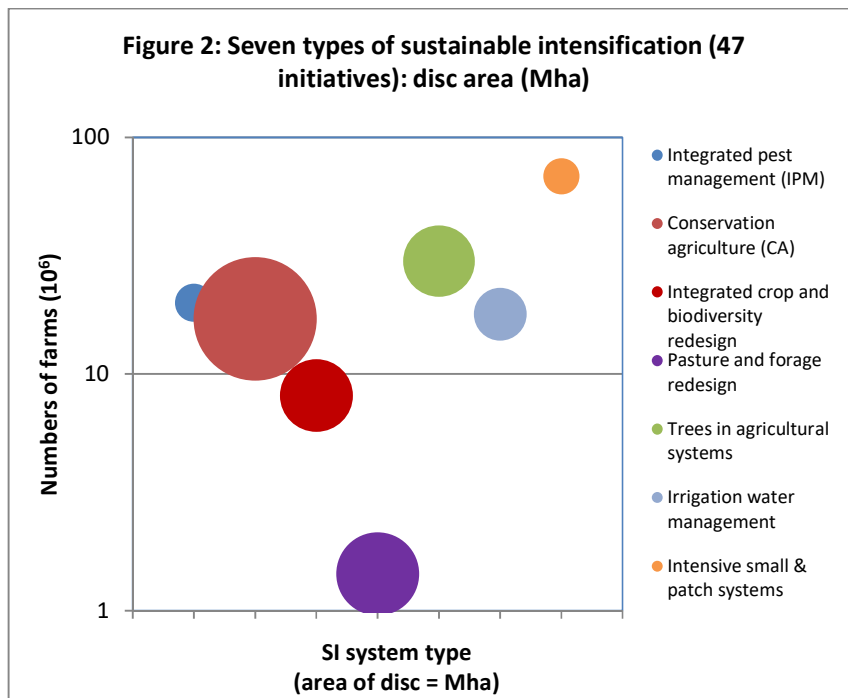
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266 The Co-creation of Agricultural Knowledge Economies

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

282

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

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

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306 **Next Steps: A Tipping Point**

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

315

316 The key question thus centres on what could happen next. SI has been shown to increase
317 productivity (4-5), raise system diversity (3), reduce farmer costs (20, 22, 30), reduce negative
318 externalities (12-13, 30), and improve ecosystem services (26, 30). There are thus a range of
319 potential motivations for farmers to adopt SI approaches, and for policy support to be provided by
320 national government, third sector and international organisations. SI requires investments, though,
321 to build natural, social and human capital, so is not costless (6-7). In all 47 initiatives, there are
322 differences in SI adoption by types of farm, farmers, and SI sub-type. All innovations begin on a small
323 scale, yet here expanded to exceed the 10⁴ scale for farm numbers and/or hectares. But several
324 hundred more projects remain small in scale or are at early stages of development. In some cases,
325 innovations started with efficiency or substitution interventions, and then spread to redesign (31). In
326 every case, social capital formation leading to knowledge co-creation has been a critical pre-
327 requisite. In every case, too, farmer benefit (e.g. food output, income, health) will have been
328 demonstrated and understood.

329

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

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

346

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

365

366

367 **Table 2. Number of redesign types of SI deployed in each of 47 initiatives, by farm and hectare numbers and**
 368 **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%

369

370

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

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

382

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

385

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

393

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397 **A Note on Terminology**

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

407

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412

413 **Authors**

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

418

419 **Data Statement and Availability**

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

423

424 **Competing Interests**

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

429

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515 **Figure legends**

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

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

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