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Article

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Policies for ecological intensification of crop production

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30 **Keywords:** agroecology, biodiversity, conventional intensification, crop productivity, ecological
intensification, sustainable agriculture

32

34 Abstract

Ecological intensification aims to increase crop productivity by enhancing biodiversity and
36 associated ecosystem services, while minimizing the use of synthetic inputs and cropland
expansion. Policies to promote ecological intensification have emerged in different countries, but
38 they are still scarce and vary widely across regions. Here we propose ten policy targets that
governments can follow for ecological intensification.

40

42 **The search for a new agricultural paradigm**

43 Globally, an intense search for new agricultural paradigms is on, to correct the failings of current
44 systems. Many, including policymakers, consumers, scientists, and farmers, are calling for a
45 transition from conventional to ecological intensification [1,2]. The aim is to maintain or increase
46 long-term agricultural productivity, while reducing reliance on synthetic inputs and cropland
47 expansion, through effective management of ecosystem services provided by biodiversity [1–3].
48 Resource use efficiency is sought not only by more precise use of synthetic inputs (without
49 necessarily achieving “zero” use of synthetic inputs such as in organic agriculture), but also by
50 working with co-existing biota (e.g., plant microbiome, detritivores, pollinators, natural enemies) to
51 improve plant water and nutrient uptake, stress tolerance, pollination, and defenses against pests and
52 diseases. Such ecological intensification describes a process rather than an endpoint and could be
53 considered a necessary pathway for more comprehensive objectives of agroecology, food security,
54 and sustainable intensification (see [3] for a more detailed definition and history of these terms).
55 Policies to support ecological intensification are being implemented in some countries, but they are
56 usually scarce or inadequate and vary widely across regions. Here we propose ten science-based
57 policy targets that provide a framework for the implementation of ecological intensification (Box 1,
58 Figure 1) and for scientific research aiming to integrate biological and political perspectives (see
59 Table S1 for knowledge gaps). According to the definition adopted here [1–3], targets 1 and 2 are
60 core to ecological intensification, while targets 3–8 are effective ways to achieve targets 1 and 2.
61 Ecological intensification also provides multiple benefits beyond agricultural productivity (target
62 9), but requires participatory action, knowledge and training (target 10). Our list is not exhaustive
63 and, except for targets 9 and 10, we focus on the biophysical aspects of ecological intensification.
64 As we demonstrate below, ecological intensification embraces practices that can be applied by both
65 small- and large-scale farmers [1,4].

66

68 **Box 1 to be inserted around here (moved to end for type-setters)**

70

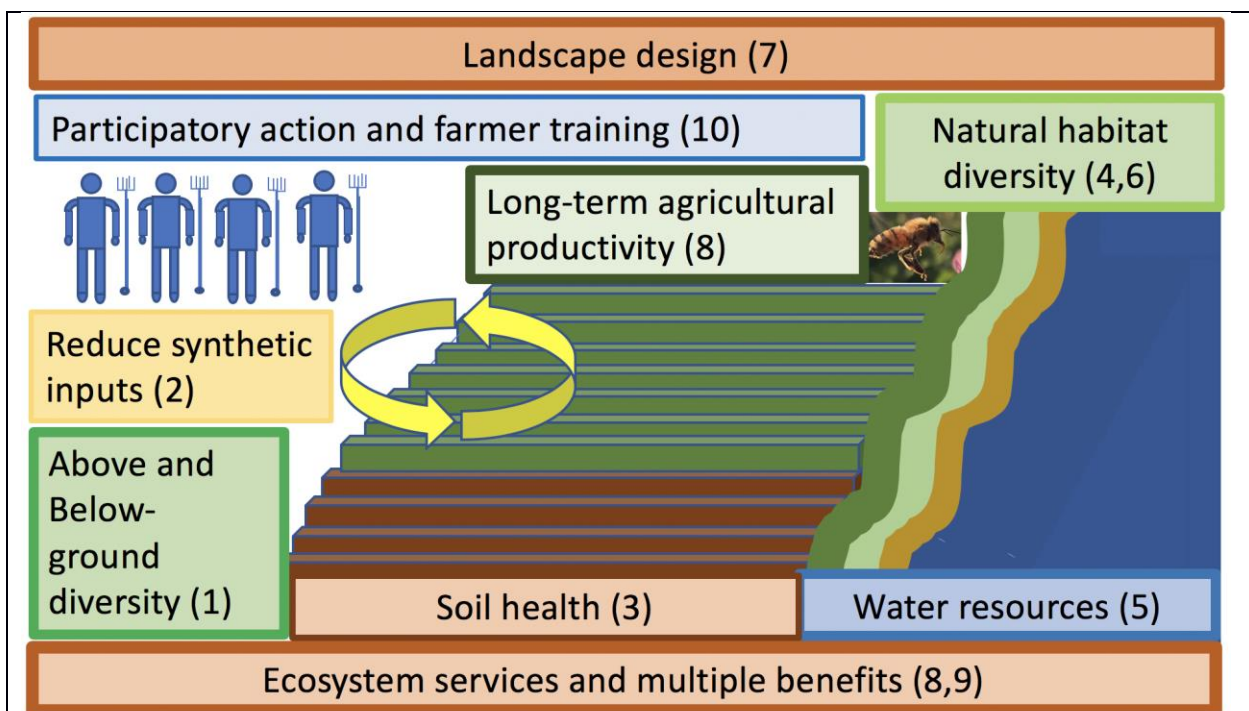


Figure 1. Science-based policy targets for ecological intensification of crop production should consider multiple dimensions. Policies that support one target can often have positive impacts

on other dimensions of the agro-ecological landscape. All targets (see Box 1) are important but, depending on the context, a few should be emphasized.

72

Underpinning ecological intensification

74 Farms with greater below- and above-ground species diversity (**target 1**, Box 1) promote ecosystem
76 services and can increase agricultural productivity [4,5] (detailed references for all targets are
76 provided in Table S1). Indeed, wild and crop plant richness support diverse animal communities,
78 both below- and above-ground [5], as they offer a wider range of feeding resources (Figure S1).
78 Common measures include the establishment of hedgerows, floral or prairie strips, or leaving a
78 proportion of land fallow. Some initiatives such as agri-environment schemes in EU policy, have
80 offered financial incentives for farmers that adopt these measures. In some developing countries
80 where field sizes are small and it is less possible to allocate land to non-crop purposes, farmers have
82 innovated by growing flowering crops that are attractive to beneficial insects in the boundaries of
82 crops that are less attractive [6]. For example, growing nectar-producing plants around rice fields
84 has been shown to enhance predators and parasitoids of rice pests, reduce pest populations, enhance
84 detritivores, reduce insecticide applications by 70%, increase grain yields by 5%, and deliver an
86 economic advantage of 7.5% in Thailand, China and Vietnam [6].

88 Reducing the use of synthetic inputs (**target 2**) such as plastic films, agrochemicals, and
88 non-renewable energy minimizes negative externalities, including greenhouse gases, plastic waste,
88 resistant weeds, biodiversity loss, water and food pollution, and can even increase agricultural
90 productivity and (or) farmers' profit [3,6,7]. Current strategies to reduce the negative impact of
90 agriculture-produced plastic waste, such as the European Strategy for plastics in a Circular
92 Economy, focus on recycling or the development of new bio-based materials (Table S1). All over
92 the world, examples of excessive use of agrochemicals include those (a) in West Africa, where
94 pesticide use levels generate widespread risks to terrestrial and aquatic wildlife [8]; (b) in France,
94 where it was estimated that total pesticide use could be reduced by 42% without any negative
96 effects on both productivity and profitability in 59% of the surveyed farms [9]; and (c) in China,
96 where about 20.9 million small-scale farmers increased average yields (maize, rice, and wheat) by
98 10.8–11.5%, while reducing application of synthetic sources of nitrogen by 15–18%, through an
98 integrated soil-crop system management framework [1]. Common measures to reduce the use of
100 synthetic agrochemicals are to implement precision agriculture, crop rotation, and integrated pest
100 management (Table S1). Multiple policies have supported measures to reduce pesticide use, mostly
102 focusing on direct and lethal toxic effects (e.g. on pollinating bees). For example, recently (May
102 2018), the European Union have agreed to completely ban the use of three neonicotinoid
104 insecticides in outdoor farms. The Government of Vanuatu has built into its National Sustainable
104 Development plan the phasing out of synthetic inputs in its agriculture, while the Danish
106 Government aims to double its organically cultivated area nationally by 2020 (Table S1). Such
106 organic commitments are seen by these Governments as having multiple advantages, including
108 benefits to tourism and fostering greater use of local knowledge on traditional crops and foods (see
108 target 9).

110

Supporting ecological intensification

112 Soil health (**target 3**) is linked with key biological and physical processes (carbon transformations,
112 nutrient cycles, soil structure maintenance, and the regulation of pests and diseases) that support
114 agricultural productivity [10] (Table S1). However, soil organic matter and below-ground
114 biodiversity (both proxies for soil health) are declining in many agricultural systems [5,10,11].
116 Practices such as crop diversification, including legumes into rotations, efficient use of organic
116 fertilizers, and reducing tillage can prevent or reverse such trends [5] (Table S1). In the Indian state
118 of Andhra Pradesh, the Zero Budget Natural Farming initiative (incorporated into government

120 policy at the state level) seeks to help farmers build soil fertility and transition from using chemical
122 to organic inputs. In the USA, California's Healthy Soils Initiative has five main goals to enhance
124 soil health: to protect and restore soil organic matter; to identify sustainable and integrated
financing opportunities; to provide research, education and technical support; to increase
governmental efficiencies on public and private lands; and to promote inter-agency coordination
(Table S1).

126 Conservation or restoration of natural or semi-natural areas in agricultural landscapes
(**target 4**) can enhance diversity of beneficial organisms by providing resources that are not
128 available in crop fields, such as nesting sites or food (Table S1). It can be achieved through
incentives such as voluntary agri-environment schemes, or mandatory Ecological Focus Areas in
130 Europe, or the Conservation Reserve Program (CRP), Conservation Stewardship Program (CSP)
and Environmental Quality Incentives Programs (EQIP) in the USA. In Brazil, set asides or "legal
132 reserves" are mandatory. A portion of each farm must focus on the conservation or restoration of
ecological processes and biodiversity, protection of the native fauna and flora, and sustainable use
of natural resources (such as rubber extraction or Brazil nut harvesting in the Amazon forest). The
134 size of the "legal reserves" varies as follows: 80% of the farm when it is in the forest area of the
Legal Amazon biome; 35% of the farm when it is in the Cerrado area of the Legal Amazon biome;
136 and 20% percent of the farm in all the other regions of Brazil.

138 Protecting and efficiently using water resources (**target 5**) can enhance agricultural
productivity and minimizes negative externalities. Common measures include engineering solutions
to prevent droughts or floods, using drought-resistant crops, enhancing soil health (target 3), and
140 protecting natural or semi-natural areas (target 4). Riparian zones are at the intersection of water
resources, biodiversity, and agriculture and their importance has been recognized by the Water
142 Resources Commission of Ghana in developing the Riparian Buffer Zone Policy (although
implementation has been lacking; Table S1). In the main row crop region of the USA, the
144 incorporation of prairie strips directly contributed to improved biodiversity and was able to reduce
total water runoff from catchments by 37%, resulting in retention of 20 times more soil [12]. This
146 practice can be supported, in part, by farmer cost-share under the USDA Conservation Reserve
Program (CRP). In our view, policies which promote the strategic restoration of riparian zones
148 should be able to provide disproportionate environmental benefits (relative to the investment),
especially in the most productive cropping systems.

150 Enhancing habitat diversity (**target 6**) can create agroecosystems that are capable of self-
regulation, including resisting pest and disease infestations. Measures include enhancing the variety
152 of flowering crops, providing different resources that can be exploited across time and space by
beneficial organisms (Table S1). However, agricultural landscapes are increasingly under
154 monocultures, mainly of a few cereal and oil crop species, which compromise habitat diversity [13].
Some countries where monocultures prevail are promoting new initiatives, such as the Strategic
156 Development Plan of the Agricultural Sector (PSDSA) of Benin, to create more heterogeneous
agroecosystems through crop diversification (Table S1). A recent law proposal (December 2017)
158 for *minimum budgets for biodiversity in agricultural landscapes* presented to the Argentinean
Senate, states that at least four different habitats should be established per 200 ha, each covering a
160 minimum of 5 ha with natural areas making up one of the four units.

162 The benefits of ecological intensification are context dependent [14] and creating habitat to
support beneficial organisms must consider the surrounding landscape (**target 7**). For example, the
164 need for species richness to deliver sufficient services increases with spatial scale as the number of
crop types accumulates, as demonstrated for crop pollination [15]. For large-scale farms, there are
166 many examples of extensive networks of flowering strips between production units (Figure 2), with
multiple benefits for both crop pollination and biotic pest regulation [7]. To support healthy
populations that provide ecosystem services to all farms in a region, agricultural policies in the EU
168 promote green infrastructures that facilitate connectivity across crop dominated landscapes (Table
S1). Such strategic, landscape-scale conservation demands coordinated actions that can be beyond

170 the means of individual land managers [16]. Support can be provided for farmers to work together,
172 such as in the Countryside Stewardship facilitation fund in England, which supports coordinated
action by “farm clusters” (Table S1).

174



176 **Figure 2.** Recently planted habitat for natural enemies and pollinators incorporated into a landscape
178 design at a large holding in California’s San Joaquin Valley (USA). This 2.3-mile corridor of
hedgerows and meadow was planted as part of the Xerces Society’s Bee Better Certified™
180 program. Photo: Peter Allbright, Woolf Farming Co.

180

182 Compared with conventional inputs such as pesticide or synthetic fertilizer, ecologically
intensive practices can take time to deliver results, thus requiring their evaluation over the long-
184 term (**target 8**). Habitat interventions such as floral strips for pollinators work by building up
populations over seasons [7]. These can then increase agricultural productivity, returning initial
186 investments in management [17]. Similarly, benefits derived from good soil structure and healthy
below-ground communities accrue slowly (Table S1). The stability and resilience of agricultural
188 productivity derived from greater species richness are only realized over time frames that include
cropping seasons with adverse weather, extreme climatic events, or pest outbreaks (Table S1).
190 Policies that consider these longer time frames include the financial support in the EU for
establishment and maintenance of agro-forestry. Also, the establishment of risk management
192 insurance schemes, parallel to those that exist as part of climate smart agriculture [18], could cover
crop losses in years when the ecological-intensive practice has not delivered as expected. Being
194 aware that solving current agricultural threats requires long-term and sustained actions, the National

196 Landcare Program in Australia was conceived for covering a period of over ten years (2014-2023;
Table S1).

198 **Delivering ecological intensification**

200 Policies for ecological intensification should consider (and balance) multiple costs and benefits, as
well as synergies and trade-offs among benefits (**target 9**) [3]. Examples of benefits beyond crop
202 yield include improved human health from reduced pesticide use, as in many countries foods are
contaminated with pesticide residues (Table S1); increased production of nutritious food in areas
204 with greater agricultural diversity [19]; and conservation of cultural heritages or traditions, such as
the symbolic meaning and use of different species and the diverse landscapes preferred by people in
206 which to live. As people have different preferences, a variety of ecosystem services are necessary to
produce an environment contributing to high value for all. Therefore, policies should account for a
208 plurality of views (legitimacy) and be relevant to the needs (e.g. income or social identity) of the
stakeholders affected (salience). For example, the UK Countryside Stewardship Scheme provides
support for maintaining areas of traditional water meadows and orchards for their cultural and
210 conservation value. These habitats are also important for species which deliver ecosystem services
to agriculture (Table S1). In Bolivia, the Mother Earth Law supports sustainable development,
212 respecting the balance between human life and the natural environment, and prioritizing the rights
and knowledge of the country's majority indigenous population (Table S1).

214 Successful examples of adoption of ecological intensification have commonly involved
farmer training, participatory action research, and building of social capital (**target 10**) (see
216 examples in Table S1 and [20]). Conventional intensification provides a simple package of practices
based on large monocultures and synthetic inputs [3]. Such a model has its roots in the industrial
218 revolution when humans were less than 15% of the current population and environmental
externalities of production systems were not so evident. In contrast, ecological intensification is
220 knowledge-intensive and emerges as an urgent need in a world with more than 7 billion people.
Examples include the Global Farmer Field School Platform, run by the Food and Agricultural
222 Organization of the United Nations, providing support and technical advice to Governments and
national advisory services (Table S1). Effective implementation will also depend on the
224 involvement of large food companies, that could have an enormous influence on farmer practices
through setting environmental targets for the agricultural products they buy. Such environmental-
226 friendly products are being increasingly demanded by consumers all over the world.

228 Overall, given the importance of a wide spectrum of organisms as ecosystem service
providers, policies that target the protection of whole biotic communities in agricultural ecosystems,
rather than just one or a few species are expected to be more efficient in meeting growing demands
230 for produce while maintaining multi-functional agricultural landscapes. Such measures do not
necessarily compete with farmers' profit [9]. They can even be established in areas with lower yield
232 potential but, sometimes, higher conservation value such as river margins or areas with steep slopes.
Indeed, in many cases agricultural productivity and (or) profit increase as a result of enhanced
234 ecosystem services [3,4,17]. In Table S1 we provide 24 examples of our ten policy targets across at
least 14 countries and the European Union (27 Member States). These examples illustrate the
236 diversity of possible implementation routes. The options available to a particular group of
policymakers depend on the political, historic, and environmental context, and also on how the
238 target is interpreted, in terms of its precise objective, scale, and magnitude. Given the variety of
possible implementation routes and outcomes, it is important that policies implemented in support
240 of ecological intensification include clearly stated objectives, with measurable targets, against
which each policy can regularly be evaluated. In our view, the most supportive policies for
242 ecological intensification will consider agriculture as a system that addresses national food security
and provides wellbeing to rural populations, through investment in ecological infrastructure and
244 knowledge management.

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Supplemental Information

256 Supplemental information associated with this article can be found, in the online version, at (...)

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304

Box 1. Science-based policy targets for ecological intensification

- 306 **1.** Enhance below- and above-ground species diversity
- 2.** Reduce synthetic inputs
- 308 **3.** Enhance soil health
- 4.** Maintain or restore natural and semi-natural areas
- 310 **5.** Protect and efficiently use water resources
- 6.** Enhance habitat diversity
- 312 **7.** Integrate practices into a landscape design
- 8.** Evaluate agricultural productivity and ecosystem services over the long-term
- 314 **9.** Consider multiple benefits
- 10.** Facilitate participatory action and farmer training

316