



International Journal of Research in Agronomy

E-ISSN: 2618-0618
P-ISSN: 2618-060X
© Agronomy
NAAS Rating (2026): 5.20
www.agronomyjournals.com
2026; SP-9(5): 524-529
Received: 02-04-2026
Accepted: 05-05-2026

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Ecological intensification of crop production systems, reconciling productivity, biodiversity and resilience in Agroecosystems

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DOI: <https://www.doi.org/10.33545/2618060X.2026.v9.i5Sf.6217>

Abstract

Global crop production faces a persistent tension between raising output on existing land and conserving the biological processes on which long-term productivity depends. Ecological intensification proposes to resolve this tension by deliberately mobilising ecosystem services, natural pest regulation, pollination, nutrient cycling and soil biological function, as productive inputs rather than treating them as externalities of agronomic management. This paper synthesises evidence across entomological, agronomic and landscape ecology literature to evaluate where ecological intensification delivers measurable yield or stability benefits and where the evidence remains equivocal. Particular attention is given to the scale dependence of biological control and pollination outcomes, the frequently weak transfer of plot-level diversification benefits to farm and landscape scales, and the methodological inconsistencies that make cross-study comparison difficult. Trade-offs between diversification practices and short-term yield, labour demand and land-use efficiency are examined critically rather than assumed away. The synthesis argues that ecological intensification is neither a universal substitute for external inputs nor a marginal add-on to conventional intensification, but a context-specific redesign of production systems whose success depends on landscape configuration, farmer knowledge and appropriate institutional support. Gaps in long-term, multi-site experimentation and in standardised metrics for ecosystem service delivery are identified as the principal constraints on translating ecological intensification from a research concept into a widely adopted production strategy.

Keywords: Ecological intensification, biological control, pollination services, agroecosystem diversification, sustainable crop production, landscape ecology

Introduction

Agricultural intensification since the mid twentieth century has relied overwhelmingly on external inputs, synthetic fertiliser, pesticides and mechanisation, to raise per-hectare output (Foley *et al.*, 2011) ^[11]. The productivity gains were substantial, but the accompanying erosion of biodiversity, soil function and water quality has prompted a reassessment of what intensification should mean in practice (Tilman *et al.*, 2011) ^[26]. Ecological intensification, as distinct from conventional and organic intensification, seeks to replace or supplement external inputs with managed ecosystem services derived from biodiversity within and around the production system (Bommarco *et al.*, 2013) ^[14]. The concept sits between two positions that dominate current debate. One holds that closing yield gaps through targeted input use remains the fastest route to food security with the smallest land footprint (Cassman and Grassini, 2020) ^[4]. The other argues that input-intensive systems are approaching biophysical and ecological limits, and that redesigning cropping systems around biological processes is the only durable path to sustained productivity (Tittonell, 2014) ^[27]. Neither position is fully vindicated by the evidence, nor is the disagreement itself informative about where research effort is most needed. Three ecosystem service pathways recur across the ecological intensification literature, biological regulation of insect pests and pathogens, pollination of insect-dependent crops, and biologically mediated nutrient and water cycling (Kremen and Miles, 2012) ^[17]. Each pathway has an entomological or microbial mechanism that operates at a characteristic spatial and temporal scale, and each has generated a distinct body of empirical work with its own

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methodological conventions. Reviews that treat these pathways as interchangeable components of a single "*biodiversity benefits agriculture*" narrative tend to obscure genuine disagreement between researchers over effect size, scale dependence and the conditions under which diversification substitutes for, rather than complements, conventional inputs (Kleijn *et al.*, 2019) ^[14]. This review takes the disagreement as the starting point. Rather than compiling supportive case studies, it asks where the mechanistic evidence for ecological intensification is strong, where it is context-dependent to the point of being unreliable for on-farm decision-making, and where methodological gaps prevent a clear verdict either way.

Biological Regulation of Pests as a Productive Service

The mechanistic case for conservation biological control rests on well-established entomological principles, natural enemies require alternative prey, overwintering refugia and floral resources that monocultures typically fail to provide (Landis *et al.*, 2000) ^[18]. Field margin management, beetle banks and flower strips have each been shown to increase local abundance of parasitoids and predatory arthropods, and several controlled studies report measurable reductions in aphid populations adjacent to such interventions (Tschumi *et al.*, 2016) ^[28]. The difficulty lies not in whether these interventions increase natural enemy numbers, which is reasonably well supported, but in whether that increase translates into economically relevant pest suppression across the whole field rather than a narrow margin effect. Spillover distance from semi-natural habitat into crop interiors is frequently limited to tens of metres, which means that field geometry and habitat placement matter as much as habitat area (Rusch *et al.*, 2016) ^[24].

A meta-analysis of landscape complexity effects on pest and natural enemy populations found that complex landscapes generally favour natural enemies but do not consistently reduce pest densities, an asymmetry that undermines any simple assumption that more semi-natural habitat automatically means less crop damage (Chaplin-Kramer *et al.*, 2011) ^[5]. Push-pull systems developed for cereal stem borer management in East Africa offer a contrasting case where diversification at the field scale, intercropping with a repellent legume and a trap grass border, produced consistent reductions in stem borer damage and, in some trial series, comparable suppression of the parasitic weed *Striga* (Khan *et al.*, 2014) ^[13]. The contrast between the equivocal landscape-scale evidence and the more consistent field-scale push-pull results suggests that biological control interventions are most reliable when the mechanism operates at the same spatial scale as the management unit a farmer actually controls. Interventions that depend on landscape-scale habitat configuration are harder to guarantee because an individual farmer rarely controls the surrounding matrix, a constraint that is frequently acknowledged in the discussion sections of landscape ecology papers but rarely addressed in the study design itself.

Pollination Services and the Limits of Field-Scale Management

Insect pollination contributes to yield or quality in a substantial share of global crop species, and wild pollinator communities frequently supplement or outperform managed honeybees for fruit set in several systems (Klein *et al.*, 2007) ^[15]. Garibaldi *et al.* (2014) ^[9] demonstrated across multiple countries that fields visited by a greater diversity of wild pollinators, rather than simply a greater abundance of any single species, achieved more consistent fruit set, an argument for conserving pollinator diversity rather than substituting managed bee density for wild

diversity. Hedgerow and floral strip restoration adjacent to cropland increases wild bee visitation to nearby fields, but the effect attenuates sharply with distance and depends on the surrounding landscape already retaining some semi-natural habitat (Kremen and M'Gonigle, 2015) ^[16]. This dependency on baseline landscape context means that pollinator-focused ecological intensification is unlikely to succeed as a standalone field-level practice in landscapes that have already lost most semi-natural cover, a limitation that is under-emphasised in extension material promoting pollinator strips as a universal solution.

Disagreement in this literature centres less on whether pollinators matter, which is not seriously contested, than on how much yield gain is attributable to managed diversification interventions as opposed to pre-existing landscape structure. Some authors treat pollinator-friendly practices as a scalable input analogous to fertiliser application, while others argue the service is fundamentally landscape-emergent and cannot be reliably purchased at the field level through isolated interventions (Kennedy *et al.*, 2013) ^[12]. The practical implication is that pollination-based ecological intensification requires coordination across multiple farms and land managers, a governance requirement that most current agronomic trials do not test because they are conducted on single experimental fields.

Soil Biological Function and Nutrient Cycling

Below-ground biological processes constitute the least visible but arguably most consistently beneficial pathway in ecological intensification. Legume-cereal rotations exploiting biological nitrogen fixation reduce dependence on synthetic nitrogen and frequently produce a residual yield benefit in the subsequent cereal crop, an effect documented across a wide range of soils and climates (Peoples *et al.*, 2009) ^[20]. Cover cropping increases arbuscular mycorrhizal colonisation and soil microbial biomass in temperate vegetable systems, though the yield response in the same trials was neutral in the short term and only became positive after several years of cumulative soil building (Bowles *et al.*, 2017) ^[2]. This lag between practice adoption and measurable yield benefit is a recurring source of farmer reluctance and is insufficiently addressed in studies that report only single-season outcomes.

Conservation agriculture, combining reduced tillage, permanent soil cover and crop rotation, illustrates how aggregating several ecologically motivated practices under one label can obscure component-level effects. A global meta-analysis found that yield response to conservation agriculture was highly variable and often negative under rainfed conditions unless all three components were implemented simultaneously and residues were retained rather than removed for fodder, a combination rarely achieved in smallholder systems where crop residue has competing uses (Pittelkow *et al.*, 2015) ^[21]. The finding is a useful corrective to advocacy literature that treats conservation agriculture as a single coherent package with predictable benefits; the underlying biological mechanisms, soil carbon accumulation, water infiltration and microbial activity, respond individually and at different rates to each component practice.

Comparative Evidence and Points of Disagreement

Cross-system synthesis reveals a broadly positive relationship between plant diversity and productivity, but the strength of that relationship weakens as background management intensity rises, implying that ecological intensification delivers the largest marginal benefit where input use is currently moderate rather

than where it is already very low or very high (Isbell *et al.*, 2017)^[11]. This non-linearity is easily lost in reviews that cite the positive average effect without reporting how it varies with baseline conditions. A synthesis across multiple countries similarly found that crop rotational diversity improved yield stability more consistently than it improved mean yield, a distinction with direct relevance for smallholder risk management that is often collapsed into a single reported effect size in less careful reviews (Gurr *et al.*, 2016)^[10].

Agroforestry systems expose a genuine trade-off rather than a straightforward win. Shade tree diversity in coffee systems improves natural pest regulation and buffers microclimate extremes, but competition for light can depress bean yield under dense shade, and the net economic outcome depends on shade tree species selection and management intensity (Pumarino *et al.*, 2015)^[23]. Authors working from a biodiversity conservation perspective and those working from a smallholder livelihoods perspective have drawn different conclusions from broadly the same dataset, the former emphasising the pest regulation and resilience gains, the latter emphasising the yield penalty under poorly managed shade. Reconciling these positions requires site-specific shade management recommendations rather than a blanket endorsement or rejection of agroforestry intensification, an approach still uncommon in extension guidance.

A further point of disagreement concerns whether ecological intensification should be judged against conventional high-input benchmarks on a per-hectare basis or against a land-sparing versus land-sharing framework that accounts for the total land area needed to meet a given production target. Advocates of targeted input intensification argue that diversified systems with lower per-hectare yield may require more total land to meet demand, offsetting on-farm biodiversity gains with off-farm habitat conversion (Cassman and Grassini, 2020)^[4]. Proponents of ecological intensification counter that yield stability and reduced input dependency have value not captured in a single-season output comparison (Pretty, 2018)^[22]. Both arguments are internally coherent, and the disagreement is ultimately empirical,

resolvable only through longer time horizons and full-system accounting that most existing trials do not attempt.

Current Gaps and Methodological Limitations

Three limitations recur across the literature reviewed here. First, the great majority of ecological intensification trials run for one to three seasons, which is sufficient to detect changes in natural enemy abundance or pollinator visitation but rarely sufficient to detect the slower-accumulating benefits of soil biological restoration or the cumulative yield stability advantage of crop rotation (Kleijn *et al.*, 2019)^[14]. Second, ecosystem service outcomes are measured with inconsistent metrics across studies, some report predator abundance, others report parasitism rate, others report crop damage directly, which makes formal meta-analysis difficult and forces reviewers to compare studies that are conceptually related but not directly commensurable (Duru *et al.*, 2015)^[6]. Third, very few studies test ecological intensification interventions across the full range of farm sizes and tenure arrangements found in smallholder-dominated regions, so recommendations derived largely from research-station or medium to large commercial farm trials in Europe and North America are extrapolated to smallholder systems in South Asia and sub-Saharan Africa with limited direct validation (Garbach *et al.*, 2017)^[8].

A further gap concerns farmer decision-making and adoption. Even where an ecological intensification practice has robust biophysical support, adoption depends on labour availability, land tenure security, access to knowledge and short-term financial risk tolerance, factors that agronomic and entomological studies typically treat as external to the research question rather than as co-determinants of whether a biologically sound practice becomes an agronomically viable one. Coupling biophysical trials with structured adoption studies remains the exception rather than the norm, and this separation between what works ecologically and what is adopted practically is arguably the single largest obstacle to translating ecological intensification research into field-level impact.

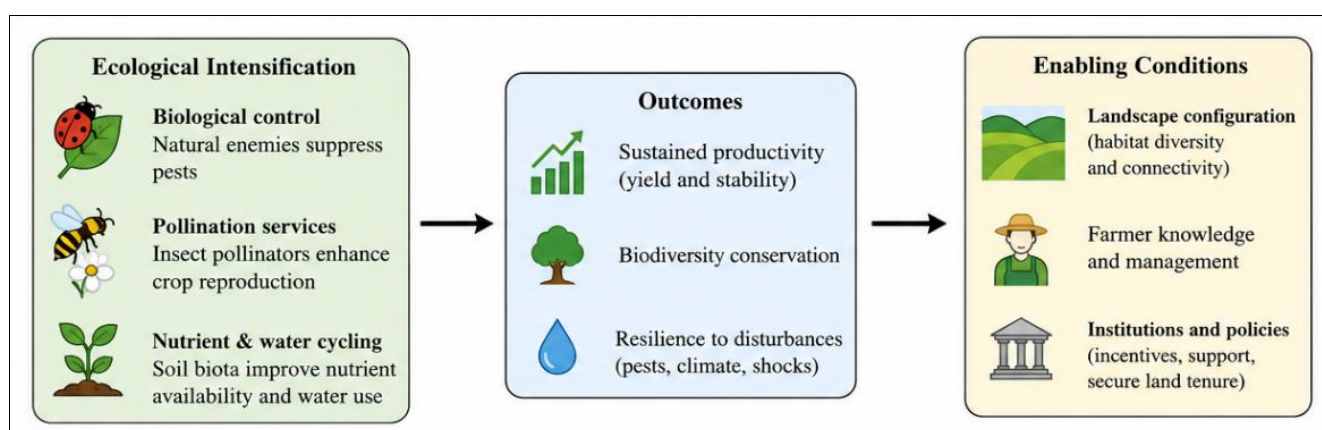


Fig 1: Ecosystem service pathway to outcomes under ecological intensification

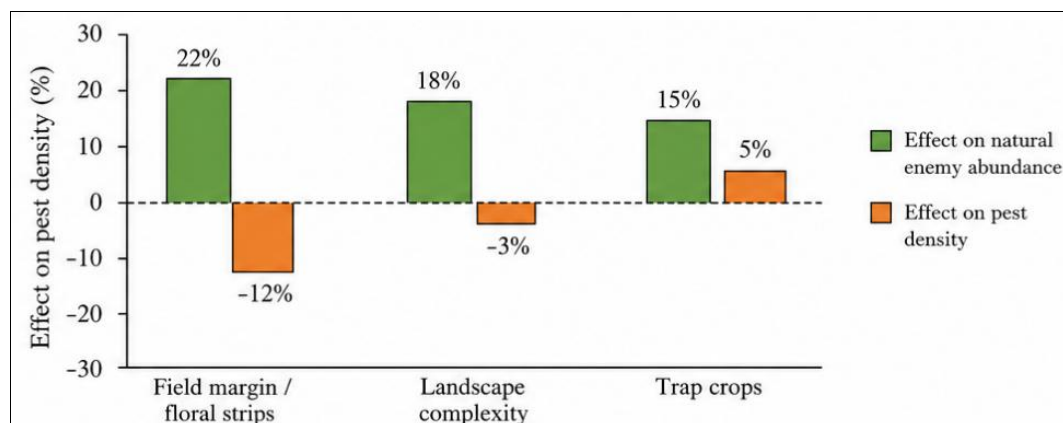


Fig 2: Meta-analytic mean effects of three biodiversity based intervention on natural enemy abundance and pest density

Table 1: Synthesis of ecosystem-service pathways and reported effects of diversification practices across cropping systems

Ecosystem-service pathway	Field/landscape practice	Reported effect	References
Natural pest regulation	Flower strips adjacent to cereal fields	Higher parasitism of aphids, variable spillover distance	Tschumi <i>et al.</i> (2016) ^[28]
Natural pest regulation	Landscape complexity (semi-natural habitat cover)	Positive but context-dependent effect on natural enemy abundance	Chaplin-Kramer <i>et al.</i> (2011) ^[5] ; Rusch <i>et al.</i> (2016) ^[24]
Natural pest regulation	Habitat management / beetle banks	Enhanced overwintering of generalist predators	Landis <i>et al.</i> (2000) ^[18]
Natural pest regulation	Crop diversification (intercropping, push-pull)	Reduced stem borer damage in maize systems	Khan <i>et al.</i> (2014) ^[13]
Pollination	Wild pollinator conservation strips	Yield gains in pollinator-dependent crops	Garibaldi <i>et al.</i> (2014) ^[9] ; Klein <i>et al.</i> (2007) ^[15]
Pollination	Hedgerow restoration	Increased wild bee visitation rate to adjacent fields	Kremen and M'Gonigle (2015) ^[16]
Soil biological function	Reduced tillage with residue retention	Improved soil organic carbon and microbial biomass	Palm <i>et al.</i> (2014) ^[19]
Soil biological function	Legume-cereal rotation	Enhanced biological nitrogen fixation, reduced synthetic N need	Peoples <i>et al.</i> (2009) ^[20]
Soil biological function	Cover cropping	Greater arbuscular mycorrhizal colonisation	Bowles <i>et al.</i> (2017) ^[2]
Landscape-level diversification	Crop rotational diversity across regions	Yield stability gains independent of external inputs	Gurr <i>et al.</i> (2016) ^[10]
Landscape-level diversification	Agroforestry integration	Improved microclimate buffering and pest suppression	Pumarino <i>et al.</i> (2015) ^[23]
Water and nutrient cycling	Conservation agriculture (no-till, cover, rotation)	Mixed yield response, context and rainfall dependent	Pittelkow <i>et al.</i> (2015) ^[21]
Biodiversity-yield relationship	Multi-site synthesis across cropping systems	Positive diversity-productivity relationship, weaker under intensive management	Isbell <i>et al.</i> (2017) ^[11]

Table 2: Diversification metrics, yield outcomes and ecosystem services measured across representative study systems

Study system	Diversification metric	Yield outcome	Ecosystem service measured	Sources
Rice-based systems, South and Southeast Asia	Varietal and habitat diversity	Neutral to positive	Natural enemy abundance, pest suppression	Settle <i>et al.</i> (1996) ^[25]
Cereal systems, Europe	Field margin flower strips	Neutral at field scale, positive at margin	Parasitism rate, aphid control	Tschumi <i>et al.</i> (2016) ^[28]
Maize systems, East Africa	Push-pull intercropping	Positive	Stem borer and Striga suppression	Khan <i>et al.</i> (2014) ^[13]
Coffee agroforestry, Central America	Shade tree diversity	Trade-off with light-dependent yield	Pest regulation, pollination	Pumarino <i>et al.</i> (2015) ^[23]
Global cropland synthesis	Species richness across trial sites	Positive, attenuated under high-input management	Aggregate productivity	Isbell <i>et al.</i> (2017) ^[11]
Oilseed rape, Europe	Landscape-scale semi-natural habitat	Indirect, mediated through pollination	Pollinator visitation, seed set	Garibaldi <i>et al.</i> (2014) ^[9]
Wheat systems, temperate zones	Rotational diversity (3+ crops)	Positive yield stability over time	Soil nitrogen supply, disease break	Bowles <i>et al.</i> (2020) ^[3]
Vegetable systems, California	Cover crop and reduced tillage	Neutral short-term, positive long-term soil function	Microbial biomass, mycorrhizal colonisation	Bowles <i>et al.</i> (2017) ^[2]
Multiple biomes, meta-analysis	Conservation agriculture components	Highly variable, rainfall dependent	Water infiltration, soil carbon	Pittelkow <i>et al.</i> (2015) ^[21]
Legume-cereal systems, sub-Saharan Africa	Rotation with grain legumes	Positive residual yield effect	Biological nitrogen fixation	Peoples <i>et al.</i> (2009) ^[20]

Conclusion

Ecological intensification is best understood not as a single technology but as a design principle whose payoff depends on

matching a specific biological mechanism to the spatial scale at which a farmer or a landscape actually operates. The evidence for field-scale interventions such as push-pull cropping and

legume rotation is comparatively strong and consistent. The evidence for landscape-scale interventions such as habitat restoration for pollinators and natural enemies is real but conditional on surrounding land-use context that individual farmers rarely control. Soil biological benefits are the most durable but the slowest to appear, which creates a mismatch between the time horizon of most research trials and the time horizon farmers need to justify a change in practice. Progress in this field will depend less on generating further isolated case studies demonstrating that biodiversity can benefit agriculture, a point already well established, and more on longer-duration, multi-scale trials that report standardised ecosystem service metrics alongside yield, and on research designs that treat farmer adoption constraints as part of the scientific question rather than an afterthought. Framed this way, ecological intensification becomes a testable, context-specific redesign strategy rather than a general claim, and its future contribution to global food production will be judged by how well research closes the gap between demonstrated biological mechanism and reliable on-farm outcome.

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