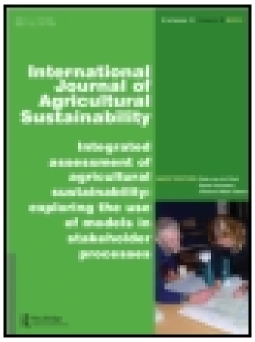

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Examining multi-functionality for crop yield and ecosystem services in five systems of agroecological intensification

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Agroecological intensification (AEI) integrates ecological principles and biodiversity management into farming systems with the aims of increasing farm productivity, reducing dependency on external inputs, and sustaining or enhancing ecosystem services. This review develops an analytic framework to characterize the fulfilment of these objectives by documenting the co-occurrence of positive, neutral, and negative outcomes for crop yield and nine regulating ecosystem services. We provide an illustrative examination of the framework, evaluating evidence for yield and ecosystem service outcomes across five AEI systems: conservation agriculture, holistic grazing management, organic agriculture, precision agriculture, and system of rice intensification (SRI). We reviewed 104 studies containing 245 individual comparisons between AEI and contrasting farming systems. In three of the five AEI systems, conservation agriculture, precision agriculture, and SRI, more than half of reviewed comparisons reported ‘win-win’ outcomes, enhancement of both yield and ecosystem services, or ‘win-neutral’ outcomes relative to contrasting farming systems. The review presents substantial evidence that the five AEI systems can contribute to multi-functional agriculture by increasing ecosystem service provision, or reducing negative externalities associated with agriculture, while maintaining or increasing yields. A framework such as the one presented here can help guide decision-makers considering how best to implement multi-functional agriculture so that both crop yield and ecosystem service delivery can be maintained or increased.

Keywords: conservation agriculture; holistic grazing management; organic; precision agriculture; system of rice intensification

Introduction

There is a growing call to address the challenge of increasing agricultural productivity and sustaining ecosystem services in the context of limited land, water, and other planetary boundaries (Food and Agriculture Organization of the United Nations [FAO], 2011; Foresight, 2011; Rockström et al., 2009). Projections estimate that food demand will double by 2050, which has driven efforts to increase crop production. However, a singular focus on maximizing harvestable goods carries significant costs and risks for broader availability of ecosystem services (Millennium Ecosystem Assessment [MEA], 2005; The Economics of Ecosystems and Biodiversity [TEEB], 2010) and the sustainability of food systems themselves (Garnett et al., 2013). There is substantial

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evidence that agriculture, which relies on continued chemical or synthetic inputs to sustain yield (e.g. large-scale and monoculture cultivation), is often associated with significant degradation of water quality and quantity, increased greenhouse gas emissions, and disruptions of natural pest control, pollination, and nutrient cycling processes (Diaz & Rosenberg, 2008; Klein et al., 2007; Matson, Parton, Power, & Swift, 1997). However, recent analyses suggest that it is both possible and preferable to pursue strategies that reduce trade-offs between food production and ecosystem health, for instance, by incorporating biodiversity within agricultural systems (Baulcombe et al., 2009; Chappell & LaValle, 2011; Clay, 2011; De Schutter, 2011; Perfecto & Vandermeer, 2010).

We investigated the outcomes of agroecological intensification (AEI), reviewing available evidence for both regulating ecosystem services and crop yield (i.e. a provisioning ecosystem service). AEI is a management approach that integrates ecological principles and biodiversity management into farming systems with the aim of increasing farm productivity, reducing dependency on external inputs, and sustaining or enhancing ecosystem services (Wezel, Soboksa, McClelland, Delespesse, & Boissau, 2015). This approach draws on the agroecological principles of sustaining or enhancing soil health, improving recycling of biomass and nutrients, increasing both managed and unmanaged biological diversity and beneficial interactions among species, and optimizing use of water, energy, nutrients, and genetic resources (Altieri, 1999; Francis et al., 2003; Gliessman, Engles, & Krieger, 1998).

In addition to the need to sustain on-farm ecosystem services supporting agricultural production, there is growing awareness of the importance of agricultural lands in delivering key regulating ecosystem services to off-site beneficiaries (MEA, 2005; TEEB, 2010). Major agricultural zones also lie in watersheds critical to urban water supplies, in biodiversity hotspots, and in global centres of crop genetic diversity. Safeguarding these assets will require increased flows of ecosystem services from agricultural landscapes themselves, not just from any non-agricultural land that might be 'spared' through the intensification of existing farming. These considerations underscore the need to manage agricultural lands as multi-functional systems that provide regulating ecosystem services, rather than as ecological sacrifice zones.

AEI practices typically include the diversification of production systems across ecological, spatial, and temporal dimensions (Kremen & Miles, 2012). For example, adding compost or organic matter to soils enhances diversity of the soil microbial and invertebrate communities that facilitate nutrient cycling (Mäder et al., 2002). Intercropping or cover cropping with nitrogen-fixing legumes can reduce or eliminate the need for fertilizers (Drinkwater, Wagoner, & Sarrantonio, 1998). Rotating crops to create spatial or temporal variation can limit pests and pathogens (Crowder, Northfield, Strand, & Snyder, 2010). Diversifying on-farm vegetation by planting insectary strips, field edge plantings and hedgerows, or retaining areas of natural habitat supports or attracts pollinators and natural enemies of pests, which can enhance pest control and pollination services (Kremen et al., 2002; Morandin & Winston, 2005). AEI also encompasses practices that seek to minimize negative externalities of agriculture. These include: using site-specific management zones to meet crop needs, while minimizing excess application of irrigation and nutrients; planting scavenger crops to help capture residual nitrogen to minimize leaching into surface and ground water (Schimmelpfennig & Ebel, 2011); and minimizing soil disturbance through low- or no-till practices to enhance carbon sequestration, nutrient cycling, and support climate regulation (Palm, Blanco-Canqui, DeClerck, Gatere, & Grace, 2014).

AEI has been applied to diverse contexts and farming systems. Aspects of agroecological and conventional intensification can be implemented in concert: agroecological principles can be applied to modify high-input, high-technology systems, while modern mechanization, improved seeds, and fertilizers are incorporated into some agroecological systems. This hybrid or 'consider all options' approach has been endorsed by major global reports (e.g. FAO, 2011; Foresight, 2011;

The Royal Society, 2009), which have advocated the use of ecologically based farming methods without excluding chemical inputs, hybrid seeds, or other management tools.

Despite growing recognition of the potential of AEI to improve farming system performance, there have been few systematic evaluations of AEI systems that consider outcomes for both ecosystem services and yield (but see Kremen & Miles, 2012). Significant debate has focused on whether AEI can deliver enhanced yield relative to non-agroecological practices (e.g. critiques by Cassman, 2007; Giller, Witter, Corbeels, & Tittonell, 2009; McDonald, Hobbs, & Riha, 2006 and support by Altieri, Nicholls, & Funes, 2012; De Schutter, 2011). From an empirical perspective, several recent syntheses focused on yield have found that agroecological approaches can increase crop yield compared to un-intensified or conventional farming systems (Badgley et al., 2007; Pretty, Toulmin, & Williams, 2011; Pretty et al., 2006). But there is also countervailing evidence that points to lower yields, particularly in organic farming systems (Ponisio et al., 2015; de Ponti, Rijk, & van Ittersum, 2012; Seufert, Ramankutty, & Foley, 2012), with varying estimates of production gaps relative to conventional, high-input systems.

Agricultural systems that produce less food than is possible under optimal management for a given combination of crop and environment exhibit a 'yield gap' (Lobell, Cassman, & Field, 2009). A growing body of work emphasizes the importance of evaluating ecosystem service delivery from agricultural systems (Garbach, Milder, Montenegro, Karp, & DeClerck, 2014; Power, 2010; Swinton, Lupi, Robertson, & Landis, 2006; Zhang, Ricketts, Kremen, Carney, & Swinton, 2007) with particular interest in systems, such as AEI, that emphasize multi-functional benefits. However, evaluating the level of ecosystem service delivery that is possible in a given environmental context has proved challenging, as it requires considering multiple dimensions of ecosystem services and positive externalities that AEI seeks to enhance, while considering negative externalities, which AEI seeks to reduce. Conceptually, we may consider agricultural systems that result in lower levels of ecosystem service delivery than is possible for a given combination of environment and agricultural output to exhibit a 'nature gap' relative to specific ecosystem services (e.g. carbon storage, water purification, etc.). This conceptual framing describes a 'nature gap' as *the deficit in the provision of ecosystem services between any given farming system and a system in the same environment and with the same level of agricultural output.* The global imperative of simultaneously increasing food production, ecosystem service delivery, biodiversity conservation, and climate change mitigation (Foley et al., 2011) implies that agriculture will need to be managed to close both yield gaps and nature gaps.

The lack of studies investigating multi-functional outcomes for both yield and ecosystem services has resulted in a critical knowledge and action gap that has hindered implementation of the recommendations emerging from global assessments; it has limited progress towards agroecosystems that sustain multiple ecosystem services.

This paper aims to build knowledge in this area in two ways. First, it develops an analytic framework to characterize the co-occurrence of outcomes for yield and nine regulating ecosystem services. We draw on the Millennium Ecosystem Assessment (2005) and Common International Classification of Ecosystem Services (CICES) for commonly accepted definitions (Haines-Young & Potschin, 2013). Among the nine ecosystem services evaluated in this study, we include four services that primarily benefit on-farm productivity: *pest control* (CICES group: pest and disease control); *pollination* (CICES group: lifecycle maintenance, habitat and gene pool protection; class: pollination and seed dispersal); *soil structure and fertility enhancement* (CICES group: soil formation and composition, e.g. maintenance of bio-geochemical conditions of soils including fertility, nutrient storage, or soil biological, chemical, or physical structure); and *weed control* (CICES group: pest and disease control, e.g. pest control including weedy plants and invasive alien species). We also include five ecosystem services that can accrue to both on-farm and off-farm beneficiaries and thus have the potential to support broader public goods: *biodiversity* *and habitat provision* (biodiversity is foundational to all other services (MEA, 2005) and on-farm agroecological applications often emphasize habitat areas capable of supporting organisms and/or interactions that underpin services (Kremen & Miles, 2012)); *carbon sequestration* that underlies climate regulation (CICES group: atmospheric composition and climate regulation; classes: global climate regulation by reduction of greenhouse gas concentration; micro and regional climate regulation); *erosion control* (CICES group: mass flows; class: mass stabilization and control of erosion rates); *water flow regulation* (CICES group: liquid flows; class: buffering and attenuation of mass flows, hydrological cycle and water flow maintenance); and *water purification* (MEA, 2005, p. 40: ecosystem properties and processes that can help 'filter out and decompose organic wastes introduced into inland waters and coastal and marine ecosystems and can assimilate and detoxify compounds through soil and subsoil processes').

The second aim of this paper is to provide an illustrative examination of the analytic framework by evaluating empirical evidence for yield and ecosystem service outcomes across five AEI systems. These systems, which include conservation agriculture, holistic grazing management, organic agriculture, precision agriculture, and System of Rice Intensification (SRI), were selected because they have been considered as approaches to enhance both food production and ecological benefits of farming systems (Africare, Oxfam-America, & WWF-ICRISAT, 2010; FAO, 2013; TEEB, 2010). Taken together, these systems are representative of a broad spectrum of agroecological approaches. They include a range of practices that are suited to management of large- as well as small-scale agriculture (Table 1); incorporate both traditional knowledge and modern technology; have been the subject of prior research, as well as programme or policy support for agricultural development; and applied to production of major grain and livestock products, thus addressing food security needs.

Although precision agriculture is not commonly associated with agroecology, we included it because it fits the broader conceptualization of AEI as an integrated approach that seeks to boost productivity and efficiency, often limiting externalities, based on nuanced understanding of specific crop requirements and environmental conditions (Francis et al., 2003). Precision agriculture practices include optimal use of inputs as well as their placement in the soil, or application to plants, and consider relationships among inputs and optimal timing. Thus, this system considers approaches to support functional relationships and proper balances among biotic and abiotic factors (Wallace, 1994). Taken together, the practices comprising the precision agriculture approach can have direct and indirect environmental benefits (Wallace, 1994), which can accrue as enhanced ecosystem services or as reduced negative externalities, also called 'dis-services' from agriculture (Zhang et al., 2007).

We reviewed the practices associated with each system, the known extent of the systems' implementation, and availability of data on yield and ecosystem service outcomes relative to contrasting farming systems. The review primarily focuses on practices that can be implemented at the field- to farm-scales (Table 1), thus emphasizing the management scales at which farmers can influence the ecological processes and interactions underpinning ecosystem services. While farmers do not have the power to control the landscape context surrounding their farms, they do implement practices within farm boundaries. Evaluating the interactions between AEI systems, ecosystem services, and landscape context is beyond the scope of this review, although we recognize the importance of landscape complexity and diversity in availability of ecosystem services (e.g. natural habitat beyond the farm edge supports mobile organisms that provide pollination and pest control services).

Methods

For each AEI system, we identified representative scientific literature using Web of Science and Google Scholar search engines by including each system name (conservation agriculture, holistic

Table 1. *Summary of component practices in AEI systems*, based on system descriptions in the reviewed literature.

AEI practices	Conservation agriculture	Holistic grazing management	Organic	Precision agriculture	System of rice intensification
Minimal till and direct seeding	C				
Permanent soil cover	C		S		
Cover crops	S		S	S	
Crop rotations	C		C		
Plant woody perennials	S				
Biological N fixation	S		S		
Planned stocking rates and rotations		C			
Manage pollinators			S		
Integrated pest management			S	S	S
Limited or no use of synthetic chemicals			C		S
Precision input applications				C	
Water harvesting	S				
Laser levelling	S			S	S
Transplant seedlings at a young age					C
Low seedling density and shallow root placement					C
Optimal plant spacing	S			S	C
Intermittent flooding					C
Frequent weeding			S		C
Add compost or organic matter to soils	S		S		C
Completeness of adoption	Med-High	Low-Med	High	Med	Med-High
Consistency of technologies	Med	Low	Med	Low-Med	High
Level of additional practices	Med	Med	Low	Low	Low

Note: From descriptions, we identified *core practices* (C) as those that were mentioned in ≥50% of studies reviewed or are standard parts of published definitions of the AEI system. Other practices mentioned in <50% of studies and applied in addition to the core practices are coded as *sometimes included* (S). *Completeness of adoption* refers to the frequency with which all of the core practices are applied and *consistency of technologies* refers the consistency with which the specific component or management need in the system is addressed with the same type of technology. *Level of additional practices* refers to the frequency with which other practices are combined with core practices.

grazing management, organic agriculture, precision agriculture, and System of Rice Intensification) with all combinations of terms for the focal ecosystem services (biodiversity, pest control, pollination, soil structure and fertility enhancement, weed control, carbon sequestration and climate regulation, erosion control, water flow regulation, and water purification), and crop yield.

To develop the analytic framework, we reviewed papers that described the AEI systems, associated practices, known extent of and outcomes of their implementation, and evaluated availability of studies presenting data on outcomes for yield and ecosystem services relative to contrasting farming systems. The illustrative examination of the framework to evaluate the AEI systems prioritized multi-year studies that included quantitative field data on both yield and ecosystem service outcomes; we then considered shorter term field studies; meta-analyses; quantitative reviews and syntheses. When considering meta-analyses and reviews, we took care that component studies were not also reviewed individually to avoid double counting reported outcomes. We excluded conceptual papers, thought pieces, papers reporting yield alone, and studies that used interviews, self-reporting, or relied exclusively on qualitative methods to estimate changes in ecosystem services.

We coded all studies into an electronic database, using a spreadsheet to organize the comparisons by system and to characterize reported outcomes for yield and the nine ecosystem services. We recorded the published indicators or metrics used for the focal ecosystem services, and whether outcomes were reported as enhanced, similar, or diminished relative to contrasting farming systems. We tallied the outcomes for yield and each service to generate the main figure in the paper; the tally approach is a modified vote-count method appropriate to summarize the proportion of results that report outcomes as enhanced, similar, or diminished relative to contrasting farming systems. Vote-counts are one of three general approaches to meta-analysis, which can also be done through narrative reviews and meta-regression (Stanley, 2001). Vote-counts improve upon narrative literature reviews by including frequency tables that summarize results from the papers reviewed (Prokopy, Floress, Klotthor-Weinkauf, & Baumgart-Getz, 2008). While vote-counts are useful for identifying general trends, they do not aim to calculate effect sizes (e.g. generalized trends in the magnitude of outcomes for yield and ecosystem services). However, this method has been applied to investigate farmers' adoption of conservation agriculture and best management practices (Knowler & Bradshaw, 2007; Prokopy et al., 2008) as well as changes in species interactions with global change (Tylianakis, Didham, Bascompte, & Wardle, 2008). Vote-count methods have been favoured over meta-regression, as they increase transparency as readers are presented with summary information from primary studies. It has been argued that identifying general trends is appropriate and can help avoid a false sense of confidence in trends across a large number of response variables (Ives & Carpenter, 2007). For studies that reported both yield and ecosystem service outcomes, we summarized the proportion of comparisons reporting each combination of positive, neutral, and negative outcomes for yield and ecosystem services: win–win (enhanced yield and ecosystem services); win-neutral (enhanced outcomes in one metric, neutral in the other); and win–lose outcomes (trade-offs of enhanced outcomes in one metric but diminished outcomes in the other). This method allowed us to summarize AEI outcomes relative to contrasting farming systems in the same environmental conditions using the same evaluation metrics for ecosystem services.

The representative literature included 104 studies that met the review criteria, comprising 24 on conservation agriculture, 17 on holistic grazing management, 14 on precision agriculture, 35 on organic farming, and 14 on SRI. Many studies contained more than one comparison of outcomes in AEI systems to those in a contrasting farming system. Contrasting farming systems include conventionally intensified (high external input) agriculture, which was used as a comparison for outcomes most frequently in holistic grazing management, organic agriculture, and precision agriculture studies. Contrasting farming systems also include low-input, un-intensified agriculture, which was used as a comparison for outcomes in most conservation agriculture and SRI studies. When reported, we considered comparisons for each crop and all growing seasons for which both yield and ecosystem outcomes were reported. This approach allowed the vote-count to include variation in outcomes in yield and ecosystem service outcomes by crop over the study period. When annual data were not available, we presented outcomes for the mean yield and mean ecosystem metrics across all years (e.g. means were the only data reported for a multi-year study). Similarly, we recorded outcomes for each ecosystem service reported.

We included all relevant comparisons for a total of 245 comparisons, using this as the primary unit of analysis. Of these, 181 comparisons included data on both yield and ecosystem service outcomes, while 64 included data only on ecosystem services. Some of the comparisons evaluated multiple ecosystem service outcomes (e.g. multiple indicators of availability of focal ecosystem services), resulting in data on a total of 574 reported observations of ecosystem service outcomes associated with the AEI systems.

Results

On the whole, there is considerable evidence that the focal AEI systems can enhance ecosystem services, although this was not universally found to be the case and there was considerable variation in the ecosystem services studied in each system (Table 2). Only a small subset of field studies directly compared AEI with contrasting farming systems at the same location and sampling period and reported outcomes for both yield and ecosystem services at the 95% confidence level. Significant outcomes are noted below in the results and discussion. Based on evidence from the 181 comparisons that included yield data, Figure 1 summarizes the ecosystem services associated with win–win outcomes, those associated with lose–lose outcomes, and trade-offs. Below, we present findings for each AEI system.

Conservation agriculture

This AEI system includes three core practices: minimizing soil disturbance, maintaining permanent soil cover, and integrating crop rotations (Table 1). This system has been applied on a wide range of row crops, estimated to cover more than 125 million ha worldwide (FAO, 2013) or about 6% of all land under row crops (Hudson, 2011). In some cases, conservation agriculture includes leguminous trees, which can enhance biological nitrogen fixation and help to maintain vegetative soil cover (Garrity et al., 2010). Comparisons between conservation agriculture and contrasting

Table 2. Summary of ecosystem service outcomes by AEI system.

Ecosystem service	Conservation agriculture			Holistic grazing management			Organic agriculture			Precision agriculture			System of rice intensification		
Ecosystem services primarily benefitting on-farm productivity															
	↑	↔	↓	↑	↔	↓	↑	↔	↓	↑	↔	↓	↑	↔	↓
Pest control	**3**	2	2				3	**7**	0				**8**	0	0
Pollination							**2**	0	0						
Soil structure and fertility enhancement	**13**	7	3	**10**	5	3	**70**	33	10	25	**36**	11	**10**	0	4
Weed control	5	3	**10**				2	**7**	6	**1**	0	0	**7**	0	0
Ecosystem services benefitting off-farm beneficiaries (public goods)															
	↑	↔	↓	↑	↔	↓	↑	↔	↓	↑	↔	↓	↑	↔	↓
Biodiversity & habitat provisioning	**4**	1	0	25	**45**	10	**28**	2	0						
Carbon sequestration	**7**	6	0	2	1	**3**									
Erosion control	**12**	0	0	**8**	6	2	**1**	0	0	**1**	0	0			
Water flow regulation	**19**	6	1	1	**3**	**1**	**5**	1	0	**13**	2	2			
Water purification	**1**	0	0							**2**	1	0	**44**	0	0

Note: Tallies represent observations of indicators of ecosystem service outcomes reported in AEI relative to contrasting farming systems; tallied observations indicate enhanced services (dark grey shading), similar outcomes (light grey shading), or diminished services (no shading). For each AEI system and ecosystem service combination, the outcome with the greatest number of observations is highlighted in boldface ($n = 574$ outcome observations for ecosystem services).

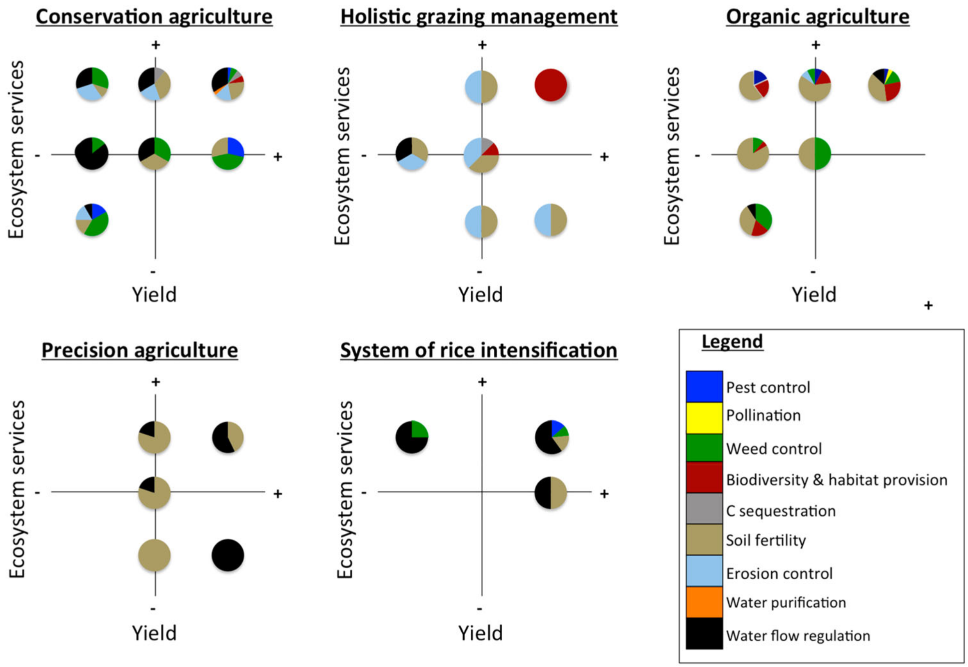

Figure 1. *Synergies and trade-offs between ecosystem services and yield in five AEI systems*. Bubble location indicates a specific combination of outcomes for ecosystem services (*y*-axis: enhanced, upper quadrants; diminished, lower quadrants) and yield (*x*-axis: enhanced, right quadrants; diminished, left quadrants) relative to contrasting farming systems. Bubbles located on the axis indicate no detectable difference from the contrasting farming system. Coloured wedges within each bubble indicate the proportion of the comparisons reporting on each of the nine ecosystem services ($n = 181$ comparisons that included data for both ecosystem services and yield).

farming systems focused primarily on outcomes associated with minimal soil disturbance and mulching treatments versus conventional tillage.

Win–win outcomes for enhanced yield and ecosystem services included significant positive results for water flow regulation, erosion control, and soil structure and fertility enhancement (Figure 1 and Table 2). Field data included significantly enhanced wheat yield paired with erosion control and water flow regulation (Araya et al., 2011). However, synergies may be crop-specific; the same study reported trade-offs of diminished yield for teff crops paired with enhanced erosion control, which may reflect teff's weed sensitivity (Araya et al., 2011). Descriptive data were also presented for enhanced weed control, pest control, carbon sequestration, and habitat to support on-farm biodiversity in systems that reported higher yields than contrasting farming systems.

Lose–lose outcomes included significantly diminished yield and weed control services, measured as greater weed dry matter than comparison systems (Oicha et al., 2010). Other studies described diminished yield in association with greater weed presence (Narain & Kumar, 2005) and reduction of pest control services (Van den Putte, Govers, Diels, Gillijns, & Demuzere, 2010), often through harbouring pests in crop residues.

Neutral outcomes, comprising similar outcomes for yield, paired with similar pest and disease control services relative to contrasting systems were reported for production of canola and peas (Kutcher, Johnston, Bailey, & Malhi, 2011) and wheat (Verhulst et al., 2011a). Comparisons that had win-neutral outcomes, enhanced wheat yield with similar soil structure and fertility and water flow regulation as contrasting farming system were also reported (Verhulst et al., 2011b).

Enhancement of on-site ecosystem services was predominantly related to enhanced soil structure and fertility (Table 2). Indicators included significantly higher soil organic carbon (López, Blanco-Moure, Limón, & Gracia, 2012), and descriptions of enhanced total nitrogen, micronutrients (Garrity et al., 2010), and soil organic matter (SOM). Building organic matter may result from increased biomass production and retention in the system, from minimizing SOM oxidation, and limiting physical disturbance of the soil. With respect to soil structure, no-till practices can result in increased compaction relative to conventional tillage (Narain & Kumar, 2005); however, it is important to consider whether granular structures are retained (or lost) as density may increase as tillage is eliminated without soils becoming compacted (e.g. bulk density exceeding 1.8 is typically classified as compacted). Benefits of pest control were supported with observations of reduced pest presence, damage, and increased presence of beneficial insects (Jaipal, 2005; Kesavan & Malarvannan, 2010).

Increases in ecosystem services that can benefit off-site users included enhanced erosion control, measured as significant reduction in soil loss (Araya et al., 2011). Additional descriptions were presented for reduced soil loss (Giller et al., 2009) and increased aggregate stability (Oicha et al., 2010; Thierfelder & Wall, 2010). Enhanced and neutral outcomes for carbon sequestration were presented in two reviews, reported as CO_2 equivalents (Milder, Garbach, DeClerck, Montenegro, & Driscoll, 2012) and carbon sequestered per surface area (West & Post, 2002). There is qualitative evidence of enhanced biodiversity relative to contrasting systems including increased abundance of soil macroinvertebrates in crop areas (Kesavan & Malarvannan, 2010; Thierfelder & Wall, 2010), which was attributed to reduced soil disturbance. Additional studies describe increased abundance of beneficial birds (Kesavan & Malarvannan, 2010). Enhanced water flow regulation was measured as significantly less runoff in conservation agriculture using permanent beds and contour furrows (Araya et al., 2011; Oicha et al., 2010) and significantly higher water infiltration under direct seeding (Thierfelder & Wall, 2010).

Holistic grazing management

This AEI system emphasizes intensive rotational grazing in which livestock density is increased and animals are moved frequently through different grazing areas (Briske et al., 2008). One variation is holistic resource management (Savory, 1983), described as a whole-farm systems approach that integrates social, ecological, and economic management factors (Malmberg, 2011) (Table 1). Holistic grazing management is estimated to be used on at least 40 million ha worldwide, or 1.25% of the world's 33 million km^2 of managed grazing land (Asner, Elmore, Olander, Martin, & Harris, 2004).

Win–win outcomes in holistic grazing management systems were associated with biodiversity and habitat provision. These included significantly increased cattle production, measured as stocking density (e.g. livestock stocking rate standardized for grazing time, area), associated with greater biomass of riparian vegetation and input of terrestrial invertebrates that were two to three times greater in streams with riparian zones under high-intensity, short-duration rotational grazing compared with those under season-long grazing (Saunders & Fausch, 2007). An AEI grazing approach, which supported greater sheep production, also resulted in greater numbers of soil microbes classified as heterotrophs, nitrifiers, and denitrifiers; functional groups that supported greater soil enzyme activity, which enhanced nitrification and nitrogen cycling relative to less intensive management (Patra et al., 2005). Additional win–win outcomes were described in a review of holistic grazing management in the USA, which reported cases that documented up to a four-fold increase in plant species richness as stocking rates were increased by a factor of two or more (Stinner, Stinner, & Martsolf, 1997). With respect to nutrient retention, rotational grazing reduced phosphorus loads to surface water relative to continuous cattle grazing at similar stocking rates (Haan, Russell, Powers, Kovar, & Benning, 2006). The reviewed studies did not include evidence of lose–lose outcomes of lower provision of ecosystem services paired with reduced livestock production (Figure 1).

Trade-offs were associated with higher animal stocking rates contributing to erosion, regardless of grazing management regimes such as rotational grazing (e.g. moving animals through multiple paddocks) (Briske, Derner, Milchunas, & Tate, 2011). However, Lyons, Weigel, Paine, and Undersander (2000) reported contrasting evidence that intensive rotational grazing was associated with enhanced erosion control, which is expected to help maintain stream habitat by reducing sediment loading to waterways. Nevertheless, intensive rotational grazing did not have a significant effect on trout abundance or index of stream biotic integrity in this system (Lyons et al., 2000).

Enhancement of on-site ecosystem services was predominantly related to enhanced soil structure and fertility (Table 2). In addition to this enhancement under AEI practices, neutral outcomes were reported in studies documenting that soil bulk density (a measure of structure and compaction) was not significantly influenced by changes in grazing management (Abdel-Magid, Schuman, & Hart, 1987; Teague et al., 2011). Neutral-positive outcomes, reporting similar cattle production (measured as stocking rate) under holistic grazing management with rotation through multiple paddocks, paired with SOM and cation exchange capacity that were enhanced under rotational grazing versus continuous grazing (Teague et al., 2011).

This review corroborates other published reports that biodiversity responses to increased grazing intensity are highly taxon-specific for birds, small mammals, and reptiles; positive, negative and neutral outcomes have all been observed (Briske et al., 2011). This suggests that more work is needed to accurately predict potential synergies and trade-offs between biodiversity conservation and livestock production under holistic grazing management. In an earlier review, Briske et al. (2008) report plant production, measured as standing biomass or dry weight biomass in pastures, was lower under rotational grazing (typically associated with AEI) relative to continuous grazing in 87% of reviewed experiments (Briske et al., 2008). With respect to plant diversity, continuous grazing can result in either enhanced or diminished diversity, as plant populations are modified by different pressures in time and space (Briske et al., 2008). Thus, further field investigations are needed to predict how particular sites are expected to respond to changes in grazing management, and which synergies and trade-offs among services are most likely.

Organic agriculture

Organic systems actively manage SOM, plant nutrients, and pests and weeds through practices such as crop rotations with legumes, crop residue management, use of animal manure and green manure, mechanical weeding, application of mined fertilizers, and biological pest control. Organic certification standards prohibit the use of synthetic fertilizers, pesticides, growth regulators, and feed additives. As of 2010, certified organic agriculture was practised on 37 million ha worldwide (Research Institute of Organic Agriculture [FiBL], 2013), or about 1.5% of land under major row crops and tree crops (FAOSTAT, 2013). This estimate, however, does not include farmland that is not involved in certification processes, but is managed without using synthetic inputs.

Win–win outcomes, with significant differences from contrasting systems, were reported for increased organic cotton yield paired with enhanced soil carbon (Blaise, 2006); greater grain yields paired with enhanced soil nitrogen and total microbial biomass and respiration (Goldstein, Barber, Carpenter-Boggs, Daloren, & Koopmans, 2004); and as enhanced maize and soy yield, supported by greater soil water-holding capacity in organic treatments during years of extreme drought (Lotter, Seidel, & Liebhardt, 2003). Lotter et al. (2003) also noted that organic treatments captured significantly more water during torrential rain events post-drought. Pimentel, Hepperly, Hanson, Douds, and Seidel (2005) reported similar, significant win–win outcomes with higher corn yield in drought years paired with higher soil carbon, nitrogen, and provide qualitative description of greater populations of arbuscular mycorrhizal fungi in plant roots. This 22-year study reported average lower yields in organic fields during the first five years of establishment (Pimentel et al., 2005). Significantly enhanced pollination services, supported by greater wild bee abundance, reduced pollination deficit in organic canola, supporting seed set and therefore greater yield (Morandin & Winston, 2005). Significantly higher apple production (measured as yield/ha; reported in two out of three years) was paired with greater microbial biomass in soil, with no significant difference in pest damage between organic and conventional systems (Swezey et al., 1994); the year for which organic apple yield was significantly lower, also reported significantly higher coddling moth colonization (Swezey et al., 1994), representing a lose–lose outcome (Figure 1).

Other significant lose–lose outcomes, diminished yield paired with diminished services, included increased weed competition (Drinkwater, Janke, & Rossoni-Longnecker, 2000; Entz et al., 2005; Lotter et al., 2003; Teasdale, Mangum, & Coffman, 2007), lower concentrations of available phosphorus in soils (Welsh, Tenuta, Flaten, Thiessen-Martens, & Entz, 2009), and higher levels of phosphorus leaching (Aronsson, Torstensson, & Bergstrom, 2007).

Comparisons between organic farming and contrasting practices were often characterized by significant trade-offs between reduced yield but increased availability of ecosystem services (Figure 1), including lower cereal grain yields but higher biodiversity including plants, birds, invertebrates (Gabriel et al., 2010), greater colonization by arbuscular mycorrhizal fungi (Ryan, Derrick, & Dann, 2004), higher biological control potential (Winqvist et al., 2011), and higher availability of soil macronutrients and enhanced soil microbial activities (Gopinath et al., 2008). Gopinath et al. (2008) emphasize that outcomes were measured during a two-year transition to organic production, which is likely a key consideration in lower yields. Recent review and synthesis work also highlights that the transition period between conventional and organic can be a period of loss to farmers (Reganold & Wachter, 2016). Strawberry crops measured during a three-year study in transition to organic displayed significantly lower fruit yield, despite larger populations of beneficial arthropods; however, price premiums for organic strawberry facilitated better per-acre returns than the conventional comparison (Gliessman et al., 1996). Descriptive data on slightly lower average fruit yield in organic apples (but higher fruit quality ratings) were paired with enhanced soil fertility, reported as higher SOM, calcium, magnesium, and potassium levels (Bertschinger et al., 2004). None of the reviewed comparisons reported trade-offs between reduced ecosystem services and enhanced yield (Figure 1).

Enhanced levels of ecosystem services in organic systems were reported for services benefitting both on- and off-farm beneficiaries (Table 2). On-farm benefits included significantly enhanced soil structure and fertility in diverse crops including organically managed apples (Bertschinger et al., 2004), and grains (Teasdale et al., 2007). Measures of significantly enhanced soil-related services included increased functional diversity of soil microbes (Mäder et al., 2002), increased microbial activity (Appireddy et al., 2008), and enhanced colonization by mycorrhizal fungi (Ryan et al., 2004). Comparisons evaluating biodiversity included the following significant enhancement: increased abundance and richness of birds, predatory insects, and soil organisms (Bengtsson, Ahnstrom, & Weibull, 2005); increased species richness of nematodes, ground beetles (Entz et al., 2005), and pollinators (Morandin & Winston, 2005). In addition to biodiversity and the aforementioned ecosystem services, organic agriculture reduces or eliminates risk of synthetic pesticide pollution of ground and surface waters (Reganold & Wachter, 2016), obviating a negative externality.

Previous work has emphasized the need for landscape-scale perspectives because of the important influence of landscape composition on species pools from which local communities are drawn, which may be more influential than the difference between organic and conventional agriculture (Tscharntke, Klein, Kruess, Steffan-Dewenter, & Thies, 2005). However, there is a dearth of investigations that control for the influence of landscape composition and measure win–win outcomes (or trade-offs) between yield and provision of ecosystem services in organic versus conventional, industrial agriculture (but see Winqvist et al., 2011).

Precision agriculture

This AEI system incorporates technologies such as laser levelling, global positioning systems, and spatially explicit yield monitors to improve input use efficiency and reduce environmental harm associated with fertilizers, pesticides, and above-ground irrigation (Schimmelpfennig & Ebel, 2011). Global extent is unknown, but core precision agriculture practices are applied on 10–40% of US corn, soy, and wheat crops, varying by the specific precision agriculture practice and crop in which it is applied (Schimmelpfennig & Ebel, 2011).

Win–win outcomes focused on enhanced yield together with two enhanced services: water flow regulation and soil structure and fertility enhancement (Figure 1). As this review considers soil structure and fertility enhancement as described by the CICES group 'soil formation and composition', it includes maintenance of bio-geochemical conditions of soils including fertility, nutrient storage, or soil structure, and it considers biological, chemical, physical structure. In precision agriculture, spatially heterogeneous application of irrigation water and fertilizers is based on various monitoring technologies to target application rates to specific crop needs helped to overcome nutrient limitations in corn (Bausch & Diker, 2001) and potato–barley rotations (Khosla, Fleming, Delgado, Shaver, & Westfall, 2002), significantly increasing crop yield while reducing the amount of nitrogen lost to the environment, thus reducing negative externalities associated with this system. Although water savings are not an ecosystem service, it bears mentioning that some ancillary benefits and positive externalities are not fully captured in the ecosystem services framework. For example, precision irrigation resulted in a 15% water savings versus uniform irrigation while eliminating puddle formation and enhancing overall field productivity in pivot-irrigated potato crops (Sadler, Evans, Stone, & Camp, 2005). Only one reviewed study reported that variable rate fertilizer application did not significantly increase yield or enhance nutrient storage relative to uniform application in irrigated corn (Ferguson et al., 2002).

Studies reporting enhanced ecosystem services and similar yield for precision agriculture versus contrasting farming systems also emphasized water flow regulation and soil fertility (Figure 1). Reduced nitrate leaching, a measure of nutrient storage, was described by Bongiovanni and Lowenberg-DeBoer (2004) and attributed to the precise, spatially heterogeneous application of fertilizer and irrigation water. Significantly enhanced water-use efficiency was achieved without diminishing crop yield through precision laser levelling, zero-till (Jat et al., 2009). Neutral outcomes, no significant differences relative to the contrasting farming system, included similar dryland corn yield with little benefit for water flow regulation under precision technology (Allen, 2012), and similar corn yield with no detectable benefit of site-specific fertilizer application on soil structure and fertility (Delgado, Khosla, Bausch, Westfall, & Inman, 2005), and similar irrigated corn yield and soil structure and fertility under variable rate technology (Ferguson et al., 2002). One study reporting enhanced yield and diminished ecosystem services presented models for a profit-maximizing strategy, which would require significantly more irrigation in dry years (Sadler et al., 2005).

Evaluations of precision agriculture provide substantial evidence for enhancement of two ecosystem services: hydrological flow regulation (Allen, 2012; International Rice Research Institute [IRRI], 2002; Jat et al., 2009; Khakural, Robert, & Koskinen, 1994; Sadler et al., 2005) and soil structure and fertility enhancement, which was chiefly measured as efficiency of nutrient storage (Bausch & Diker, 2001; Bongiovanni & Lowenberg-DeBoer, 2004; Delgado et al., 2005, 2009). Enhanced erosion control was reported in only one comparison (Table 2). An important consideration of interpreting outcomes in this system is that some precision agriculture studies estimate nutrient loads indirectly using simulation models (Bongiovanni & Lowenberg-DeBoer, 2004) such as the Nitrogen Leaching Economic Analysis Package and Environmental Policy Integrated Climate platform. Thus, interpretation of key results, such as reduced nitrogen loads in maintaining water quality, assumes realistic model inputs, calibrations, and capacity to accurately describe system dynamics.

System of rice intensification (SRI)

SRI is an integrated approach to irrigated rice cultivation that includes six main practices: (1) transplanting of seedlings at a young age; (2) low seedling density with shallow root placement; (3) wider plant spacing, in a square grid; (4) intermittent application of water, as opposed to continuous flooding; (5) frequent weeding, preferably with a mechanical weeder; and (6) incorporation of organic matter into the soil, complemented by synthetic fertilizer if needed (Africare, Oxfam-America, & WWF-ICRISAT, 2010). SRI extent has been quantified in 12 countries, totalling 1.5 million ha of land (1% of global land under rice cultivation). This figure is likely an underestimate of global extent, as SRI adoption has been documented in more than 50 countries as of 2013 (SRI-Rice, 2015). As SRI is crop-specific, the reviewed studies focus on rice production.

Significant win–win outcomes were most frequently reported for enhanced rice yield and water flow regulation, often measured as water savings relative to continuous flooding (Adusumilli & Laxmi, 2011; Ceesay, Reid, Fernandes, & Uphoff, 2006; Hameed, Mosa, & Jaber, 2011; Lin, Zhu, Chen, Cheng, & Uphoff, 2009; Lin, Zhu, & Lin, 2011; Thakur, Uphoff, & Antony, 2010; Turmel, 2011; Zhao, Wu, Wu, & Li, 2011; Zhao et al., 2009). Descriptive data from additional studies provided further support for enhancement of this service (Satyanarayana, Thiyagarajan, & Uphoff, 2007; Styger, Aboubacrine, Attaher, & Uphoff, 2011). Significantly enhanced yield was also reported with soil structure and fertility enhancement (Lin et al., 2011; Thakur et al., 2010; Zhao et al., 2009), and supported by descriptive results (Styger et al., 2011). Descriptive win–win outcomes included higher rice yield paired with enhanced weed control (Ceesay et al., 2006; Stoop, Uphoff, & Kassam, 2002) and pest control (Barah, 2009) (Figure 1).

Proponents attribute win–win outcomes to enhanced root growth and rhizosphere activity due to intermittent flooding and the application of organic matter under SRI management (Zhao et al., 2009). Critics note that comparisons may overstate the potential benefits of SRI if they do not compare outcomes from SRI directly with locally relevant best management practices (McDonald et al., 2006). The ancillary benefits reported in SRI systems focused on water savings (Table 2), although empirical reports of this benefit varied widely from 10% to 78% in summary results across nine countries (Kassam, Stoop, & Uphoff, 2011; Satyanarayana et al., 2007).

Win-neutral outcomes comprised enhanced yield paired with two ecosystem services that were similar to comparison systems: soil structure and fertility enhancement and water flow regulation (Figure 1). The reviewed studies did not include evidence of lose–lose outcomes of lower provision of ecosystem services paired with reduced rice yield. Trade-offs comprised diminished yield paired with two enhanced ecosystem services: water flow regulation and weed control

(Figure 1). The variance of yield outcomes under SRI is explained in part by distinct performance of rice varieties. In particular, varieties of rice optimized for chemical-intensive cultivation may underperform in SRI systems because the properties that SRI was developed to exploit are not present in some modern rice varieties (Stoop et al., 2002); heritage or local varieties of rice are expected to have the highest yields.

Discussion

This review found considerable evidence that the five AEI systems can contribute to multi-functional agriculture by increasing ecosystem service provision, or reducing negative externalities associated with agriculture. In SRI and precision agriculture in particular, this was often reported together with increased or similar yield to contrasting farming systems. Enhanced ecosystem services were documented in many cases, ranging from 50% of comparisons in holistic grazing management to 93% for SRI. Win–win outcomes of increased yield and ecosystem services were reported less commonly, with considerable variation across systems: 17% of organic agriculture comparisons were positive on both outcomes versus 87% of comparisons in SRI.

At the outset of the discussion, we note two important considerations in interpreting the results. First, the five AEI systems were applied with differing levels of consistency across the cases reviewed (Table 1). Variations occur when farmers adapt practices to local conditions (soil type, moisture levels, etc.), when some practices are omitted, or when farmers incorporate additional practices beyond the typical suite of practices of a particular AEI system. These variations are inherent in a farming approach that emphasizes context-based decision-making and adaptive management, but can also limit the ability to generalize about AEI practices and outcomes. Second, the systems against which AEI is compared varied considerably, from conventionally intensified agriculture with best management practices to un-intensified (or unsuccessfully managed) farm systems. However, the comparisons held fertilizer, water, and weed control inputs constant except in treatments in which those inputs were directly being evaluated. The choice of comparisons can influence conclusions reached about the yield outcomes of AEI, as epitomized by the divergent conclusions of recent comparisons of organic versus conventional farming (e.g. Badgley et al., 2007; Seufert et al., 2012). However, the issue of different comparison systems is less problematic for the evaluation of ecosystem service outcomes because AEI is hypothesized to improve such outcomes relative to low-input and high-input systems alike. Across these five AEI systems, we found a majority of positive outcomes for two types of ecosystem services relative to contrasting farm systems: erosion control and the water-related services of flow regulation and water quality. However, trends were highly variable for outcomes related to pest control, pollination, and weed control services.

In sum, there is substantial evidence that AEI can deliver greater multi-functional benefits relative to comparison farming systems; however, there is very limited evidence that AEI comprehensively offers multi-functional benefits for the full range of ecosystem services of interest to both on-farm and off-farm beneficiaries. For the most part, such broad multi-functionality has simply not been well studied: in most reviewed studies, only one ecosystem service was evaluated, with some field studies evaluating up to three ecosystem services. Additionally, even to the extent that the results revealed win–win outcomes, these results do not necessarily substantiate a core hypothesis of AEI: that management-induced increases in on-farm ecosystem services will automatically lead to increased productivity.

We posit several reasons why this review did not identify clearer or more consistent relationships between yield and ecosystem services. First, many of the available studies examining both yield and ecosystem services focused on services that accrue primarily to off-site beneficiaries (e.g. carbon sequestration, habitat provision to support mobile organisms, and water quality and flow regulation) and therefore would not necessarily be expected to support increased yields at the farm scale. Second, most studies were conducted over a short time scale (i.e. one to three years), during which long-term productivity benefits associated with practices that conserve resources or build effective ecological communities (and, conversely, yield penalties associated with poor management of natural assets) might not manifest. Third, the empirical literature of AEI may under-represent the suite of mechanistic relationships mediating key ecosystem services: for instance, none of the reviewed AEI systems specifically aims to increase pollinator or pest predator densities, by including core practices such as habitat conservation or restoration along field margins. While these practices may be voluntarily applied on some farms, several main considerations may make it difficult to detect a clear signal in outcomes associated with such specific practices in the context of overall AEI systems. These considerations are sparse data coverage, the influence of other management practices, and distinct landscape contexts across studies. Finally, additional research is needed to disaggregate AEI outcomes by biophysical factors such as soil type, rainfall regime, or crop, all of which may significantly affect the potential for synergies between yield and ecosystem services associated with AEI practices.

Notwithstanding these limitations, the frequency of win–win or win-neutral outcomes for AEI suggests that mosaics of farms managed under AEI may, in aggregate, increase multi-functionality of agricultural systems. Evidence of improved multi-functional performance from AEI included examples from both small-scale and large-scale agriculture, suggesting that AEI can deliver benefits for yield and ecosystem services in a range of settings. AEI merits further consideration for application in both large-scale, input-intensive farming systems and the smallholder farms that have been considered more frequently in development contexts.

Knowledge gaps

This review revealed three main knowledge gaps related to AEI and its outcomes. First, the literature on each AEI system tends to focus on a subset of ecosystem services, typically those that are expected to be most influenced by the core practices in that system (Table 1). While this pattern reflects the logic underlying research design, it means that there are very few studies that examine multi-functionality of AEI systems in a comprehensive way. As a result, there is little evidence on whether suites of desirable ecosystem services, benefitting both on-site farmers and off-site beneficiaries, respond in a similar direction under shifts to AEI management.

A related knowledge gap is the relative paucity of studies examining quantitative measures of yield and ecosystem services in the same system. While we identified 181 comparisons providing data on both yield and ecosystem services, these comparisons were spread across five AEI systems and nine ecosystem services. This study did not aim to estimate effect sizes for individual AEI systems or ecosystem services under AEI management. Rather, our aim was to investigate the extent to which AEI systems report positive, win–win outcomes or trade-offs between yield and ecosystem service outcomes, and describe the general availability of indicators of ecosystem services benefitting both on- and off-site beneficiaries. Clearly, more work is needed to evaluate ecosystem services in greater depth within individual AEI systems. In-depth investigation of each system would generate the volume of data points needed for detailed statistical analysis and calculation of effect sizes. In contrast, yield outcomes alone have been much better studied for many AEI systems; for example, three recent reviews of organic agriculture have each included approximately 300 comparisons of yield outcomes in that single system (e.g. Ponisio et al., 2015; de Ponti et al., 2012; Seufert et al., 2012).

A third knowledge gap is a lack of data from long-term studies. The period of time required for impacts of AEI to be detectable has not been well documented. However, a review of conservation agriculture suggests that this system's benefits may not manifest for up to 10 years (Giller et al., 2009). Conversely, some farming practices are productive in the short term but may be harmful in the long term (e.g. chemical fertilizers that increase nitrogen availability to crops but enable the progressive depletion of SOM). In both instances, biological factors (e.g. weed dynamics, pest dynamics, and soil fertility) and social factors (e.g. labour limitations) can contribute to temporally heterogeneous AEI outcomes for both yield and ecosystem services. In bridging this knowledge gap, long-term studies may also clarify whether a critical establishment period exists, and, if so, what type of support (e.g. technical assistance, access to inputs or capital, or specialty market pricing) is needed to support adoption and maintenance of AEI practices.

The influence of AEI management on outcomes for ecosystem services that accrue off farm also merits additional attention, and a fundamental change in how we view agricultural landscapes. Understanding how agricultural systems provide off-farm services requires landscape-scale analytical approaches, and combining field observations with ecological modelling. It also requires institutional recognition of the role that farmers and agricultural land managers play in providing critical ecosystem services that benefit users well beyond farm boundaries. For example, the increased public pressure to reduce the environmental damage of agriculture may help foster policy support for certification systems, payments for ecosystem services, or government incentives for agricultural management that increases delivery of ecosystem services.

Linking AEI to global efforts

AEI management is estimated to cover at least 200 million hectares worldwide, or roughly 6% of land under annual and perennial crops and 1.25% of land under managed pasture. These are likely underestimates, as they omit several important AEI systems (e.g. agroforestry and mixed intensive crop-livestock systems) and fail to account for a great deal of land managed under traditional or indigenous resource-conserving practices, uncertified organic farming, and other practices that are not easy to systematically document. Given the substantial scale of AEI management and its potential to enhance the multi-functionality of agriculture, it is clear that AEI merits further consideration regarding contributions to meaningfully addressing growing needs for food production and ecosystem services. To date, however, discourse about the relative merits of AEI and conventional, high-input intensification of agricultural have tended to be polarized and ideologically driven, framed in 'either-or' terms, and rarely informed by balanced and holistic comparisons of different production system alternatives. The concept of nature gaps may help bridge this divide, and it corresponds to an emerging framework put forth within The Economics of Ecosystems and Biodiversity (TEEB) for Agriculture and Food (2010) for understanding and accounting for the true costs of agriculture. In initiatives such as TEEB, it is equally important to document the positive externalities of sustainable agricultural systems (i.e. provision of ecosystem services) as it is to document the negative externalities. Reviews such as this emphasize the importance of evaluating different farming approaches through a lens of broad multi-functionality. Doing so is essential to support evidence-based decision-making about the future of food, agriculture, and land use.

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