

INVITED VIEWS IN BASIC AND APPLIED ECOLOGY

Designing agricultural landscapes for biodiversity-based ecosystem services

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Abstract

Sustainable and resilient agricultural systems are needed to feed and fuel a growing human population. However, the current model of agricultural intensification which produces high yields has also resulted in a loss of biodiversity, ecological function, and critical ecosystem services in agricultural landscapes. A key consequence of agricultural intensification is landscape simplification, where once heterogeneous landscapes contain increasingly fewer crop and non-crop habitats. Landscape simplification exacerbates biodiversity losses which leads to reductions in ecosystem services on which agriculture depends. In recent decades, considerable research has focused on mitigating these negative impacts, primarily via management of habitats to promote biodiversity and enhance services at the local scale. While it is well known that local and landscape factors interact, modifying overall landscape structure is seldom considered due to logistical constraints. I propose that the loss of ecosystem services due to landscape simplification can only be addressed by a concerted effort to fundamentally redesign agricultural landscapes. Designing agricultural landscapes will require that scientists work with stakeholders to determine the mix of desired ecosystem services, evaluate current landscape structure in light of those goals, and implement targeted modifications to achieve them.

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I evaluate the current status of landscape design, ranging from fundamental ecological principles to resulting guidelines and socioeconomic tools. While research gaps remain, the time is right for ecologists to engage with other disciplines, stakeholders, and policymakers in education and advocacy to foster agricultural landscape design for sustainable and resilient biodiversity services.

Zusammenfassung

Nachhaltige und resiliente Agrarsysteme werden gebraucht, um die wachsende Weltbevölkerung zu ernähren und mit Brennstoffen zu versorgen. Indessen hat das gegenwärtige Modell der landwirtschaftlichen Intensivierung, das hohe Erträge liefert, auch Verluste zur Folge: bei der Biodiversität, bei ökologischen Funktionen und bei wichtigen Ökosystemleistungen in Agrarlandschaften. Eine entscheidende Folge der landwirtschaftlichen Intensivierung ist die Vereinheitlichung der Landschaft, wobei ehemals heterogene Landschaften zunehmend weniger Feldfrucht- und nicht bewirtschaftete Habitate enthalten. Die Vereinheitlichung der Landschaft verschärft die Biodiversitätsverluste, was zur Verminderung der Ökosystemleistungen führt, von denen die Landwirtschaft abhängt. In den letzten Jahrzehnten waren Forschungen in erheblichem Umfang darauf gerichtet, diese negativen Einflüsse abzumildern, vornehmlich durch Management der Habitate, um auf lokaler Ebene die Biodiversität zu fördern und Dienstleistungen zu stärken. Während gut bekannt ist, dass lokale und Landschaftsfaktoren interagieren, wurde wegen logistischer Beschränkungen nur selten eine Veränderung der gesamten Landschaftsstruktur in Erwägung gezogen. Ich schlage vor, dass der durch Vereinheitlichung der Landschaft begründete Verlust von Ökosystemleistungen nur mit einer konzertierten Anstrengung zur grundlegenden Neugestaltung der Agrarlandschaft angegangen werden kann. Die Planung von Agrarlandschaften macht es nötig, dass Wissenschaftler und Interessengruppen zusammenarbeiten, um die Mischung gewünschter Ökosystemleistungen festzulegen, die aktuelle Landschaftsstruktur vor diesem Hintergrund zu analysieren und gezielte Veränderungen vorzunehmen, um diese zu erreichen. Ich untersuche den gegenwärtigen Status der Landschaftsplanung, von fundamentalen ökologischen Prinzipien bis zu Richtlinien und sozio-ökonomischen Instrumenten. Auch wenn Forschungslücken bleiben, ist jetzt der richtige Zeitpunkt für die Ökologen gekommen, die Zusammenarbeit mit anderen Disziplinen, Interessengruppen und Entscheidungsträgern in Erziehungswesen und Meinungsbildung zu suchen, um die Agrarlandschaftsplanung für nachhaltige und belastbare Biodiversitätsleistungen zu stärken.

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Keywords: Agricultural biodiversity; Ecosystem function; Ecosystem services; Pest suppression; Pollination

Introduction

Agriculture in the 21st century is confronting immense challenges. It is estimated that by 2050, human population of the earth will reach 9.7 billion people (United Nations, Department of Economic and Social Affairs & Population Division, 2015). How and where we produce the food and energy to support this increasing population is a major question given that agriculture is already a dominant land-use globally, with nearly 40% of the ice-free land surface dedicated to farming or grazing (Ramankutty et al., 2008; Foley et al., 2011). Moreover, in many of these areas humans are already appropriating more than 50% of the net primary productivity for their use as food, feed, and fuel (Haberl et al., 2007). While supporting high yields, the intensification of agriculture through monocultures of high-yielding varieties coupled with increased chemical and mechanical inputs, has led to negative environmental impacts on soil, water, air and biodiversity (Matson et al., 1997; Stoate et al., 2001, 2009; Firbank et al., 2008). In short, humans are exploiting the planet's most favorable areas for agriculture and the intensity of current production is pushing the boundaries of sustainability (Steffen et al., 2015), creating uncertainty regarding

how agriculture can sustainably meet future human needs (Robertson, 2015).

Ecologists can play a key role in addressing this question. For example, the growing understanding among basic ecologists of the links between biodiversity and ecosystem function (Loreau et al., 2001), biodiversity and ecosystem services (Duncan et al., 2015), and the resiliency of systems to disturbance (Oliver et al., 2015) can also be applied to the study of agricultural systems (Tscharntke et al., 2005, 2007, 2012a). While the language used by basic and applied ecologists to describe these relationships may differ, there is much to learn from the exchange of concepts across sub-disciplines (Fig. 1). For example, the use of functional trait- versus species-based metrics of biodiversity in basic ecology has prompted similar approaches in agroecosystems, leading to novel findings. Gagic et al. (2015) found that functional traits, including body size and nesting habitat, are better predictors of pest suppression and pollination in agricultural landscapes than species identity. This suggests that trait-based approaches may be critical to inform landscape design, and highlights the unique insights that can be gained from the application of ecological theory to applied questions. In turn, the long-term quest for sustainability in agriculture is increasingly

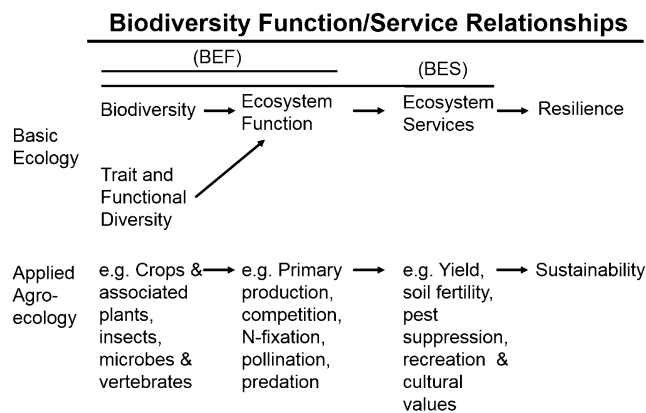


Fig. 1. Biodiversity-ecosystem function (BEF) and biodiversity-ecosystem service (BES) relationships (top), and examples of their application in the agroecological literature (bottom). Note that concepts and relationships map very closely between the subdisciplines but the terminology used to describe them differs. Resilience and sustainability are not interchangeable terms but represent the respective research frontiers.

echoed in basic ecology's exploration of resilience (Oliver et al., 2015).

From both basic and applied perspectives, the outlook for sustainable and resilient agricultural systems is questionable. In many parts of the world, the intensification of agriculture has already resulted in losses of biodiversity which threaten the provision of ecosystems services and the ultimate sustainability of agriculture. Numerous studies suggest that in agricultural landscapes the diversity of plants (Kleijn et al., 2009; José-María et al., 2011), arthropods (Hendrickx et al., 2007), birds (Donald et al., 2001), mammals (Sotherton 1998), or multiple taxa have declined (Firbank et al., 2008; Geiger et al., 2010; Gibbs, Mackey & Currie 2009). Moreover, it is now clear that in addition to species richness, trait and functional diversity is also declining (Flynn et al., 2009; Gagic et al., 2015; Gamez-Virues et al., 2015) and can result in a loss of ecosystem services. For example, there are now clear indications that vital services such as pollination (Kremen et al., 2002; Potts et al., 2010), pest suppression (Bianchi et al., 2006; Gardiner et al., 2009), and groundwater recharge (Wada et al., 2010; Scanlon et al., 2012) have been compromised in highly intensified agricultural landscapes. Part of this effect is the direct impact of intensified within-field practices but equally important is the impact of intensification on agricultural landscape structure itself (Tscharntke et al., 2005).

Impacts of intensification on landscape structure

Agricultural intensification simplifies landscape structure across multiple spatial scales (Benton et al., 2003). Within fields, agricultural intensification leads to simplified plant

communities as polycultures are abandoned in favor of monocultures, and due to effective weed control. At field boundaries, the diversity of boundary habitat types and their composition become less diverse. As the percentage of crop area within a landscape expands, crop fields are more likely to directly adjoin other crops as opposed to more diverse non-crop habitats. Where non-crop habitats remain, they harbor less biodiversity due to increased fragmentation and isolation, and from off-target pesticide movement which can directly reduce plant and animal diversity (Krupke et al., 2012; Egan et al., 2014; Hallmann et al., 2014). Finally, at the landscape scale the overall mixture of crop and non-crop habitats tends to become more uniform as economic forces drive regional specialization and farm consolidation (MacDonald et al., 2013). Crop diversity declines as farmers focus on the few most economically viable commodity crops. Similarly, non-crop habitat also declines as farmers select for field borders that are easy to maintain.

The process of landscape simplification can be illustrated using an example from southern Michigan, in the midwestern US. In the past century agricultural landscapes in this region commonly included forests, woodlots, fence rows, and windbreaks; as well as pastures, wetlands, and streams that were often bordered by woody vegetation (Fig. 2). As animal agriculture became concentrated in fewer but larger operations (MacDonald et al., 2013), many farms switched to annual crop production (primarily corn, soybean and wheat) allowing the removal of fencerows, and conversion of pastures to cropland. Use of tile drainage allowed small wetlands to be drained and farmed, and the straightening of small streams into drainage ditches required the removal of adjacent woody vegetation. Adoption of larger farm equipment and in some areas, the incorporation of center-pivot irrigation further increased removal of fencerows and smaller woodlots to allow for efficient farming operations. The overall result of this intensification is that formerly heterogeneous landscapes have become greatly simplified with annual crops dominating the landscape and perennial habitats greatly reduced and fragmented.

The impacts of such cropping system and landscape intensification on beneficial insects are now well-known. In a meta-analysis contrasting monocultures to cropping systems with increased plant diversity within fields and adjacent borders, Letourneau et al. (2011) found that natural enemies increased in diverse systems while herbivores and their damage decreased. Similarly, win-win relationships between main crop yield and biological control were found in a meta-analysis of polyculture systems (Iverson et al., 2014). Scaling up, multiple meta-analyses have examined the impact of landscape structure on natural enemy populations, with some also examining pest suppression (Bianchi et al., 2006; Chaplin-Kramer et al., 2011; Shackelford et al., 2013; Veres et al., 2013) and the trends from these analyses are relatively consistent. As landscape complexity increases, typically measured as the amount of non-crop habitat, the abundance and diversity of natural enemies increases. Pest abundance tends



Fig. 2. Typical agricultural landscape in southern Michigan, USA showing, (A) gradient in agricultural landscape complexity. (B) Expanded view of relatively complex landscape with prominent woodlots, fencerows and wooded riparian areas. (C) Expanded view of simplified landscape on higher productivity soils. Note the rounded field corners and centrally located irrigation risers in many fields indicative of center-pivot irrigation. Imagery © 2016 Google.

to decline or remain unchanged, while pest diversity may increase. Overall rates of predation and parasitism generally increase, while pest population growth decreases (Rusch et al., 2016). Overall plant damage may or may not be significantly affected but the trends are towards reduced plant damage.

Pollinators and pollination services are also reduced in intensified agricultural landscapes (Potts et al., 2010; Kennedy et al., 2013). Pollinators rely on natural habitats in agricultural landscapes to provide food and nesting habitat, and the provision of pollination services to crops depends on the scale at which those habitats are available (Benjamin et al., 2014). In a meta-analysis, Shackelford et al. (2013) found that pollinators consistently benefit from natural habitats at both local and landscape levels; however, in many parts of the world agricultural landscapes are losing complexity. For example, in the US, conversion of natural habitats to annual crop land between 2008 and 2013 is estimated to have caused a 23% decline in wild bee abundance, compromising pollination services to 39% of the nation's pollinator-dependent crop area (Koh et al., 2016). However, the addition of native wildflower plantings has the ability to increase wild bee abundance across the variety of agricultural landscapes (Williams et al., 2015) and restoration of diverse floral habitats adjacent to high-value pollinator-dependent crops can increase

pollination and pay for habitat installation in three to four years (Blaauw & Isaacs 2014). Globally, ensuring adequate pollination could increase yields for small farmers by a median of 24%, enhancing small holder livelihoods (Garibaldi et al., 2015).

The case for designing agricultural landscapes

Given the need for productive and sustainable forms of agriculture and the evidence that intensified systems are failing to conserve key functions, future landscapes will likely need to be explicitly designed to support biodiversity and ecosystem services. Current agricultural landscapes have emerged as the result of policy and market forces that drive farmer decisions about what to grow and how to grow it. While individual farms may be highly efficient, the simplified landscapes that emerge are losing functionality. To stem the loss of function will require actions that alter landscape structure at scales larger than individual farms and suggest that mechanisms for planning and coordination will be required. For example, even if many farmers were willing to make individual changes, it is unlikely that the negative aspects of landscape-level intensification can be mitigated by

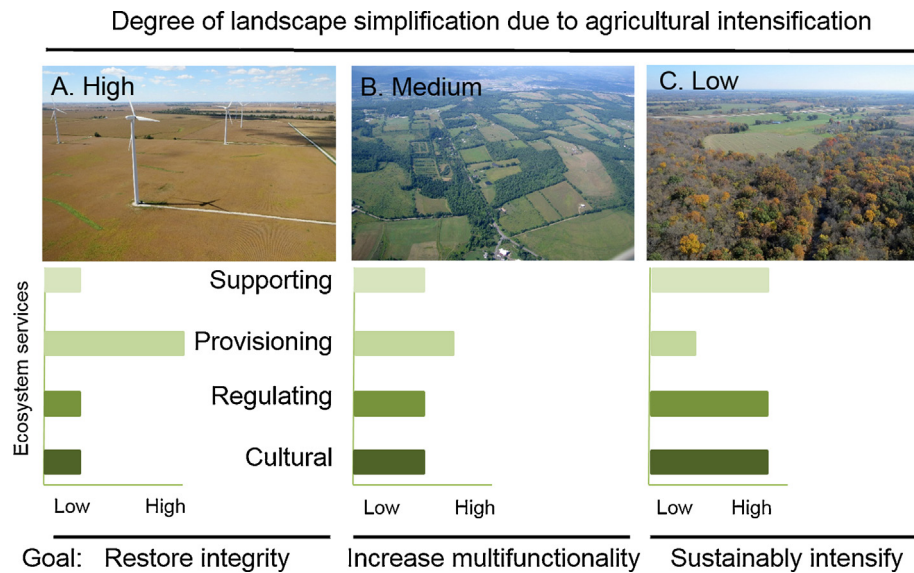


Fig. 3. Relative levels of current ecosystem services provided, and design goals for landscapes across a gradient of agricultural simplification. (A) Highly simplified landscape ranks high in productivity (i.e. provisioning service) but low in supporting, regulation and cultural services as defined in [Millennium Ecosystem Assessment \(2005\)](#). Among the design goals for such landscapes is to restore ecological integrity. (B) Moderately simplified landscapes may be less productive but with good supply of other services. Design goals include increasing their multifunctionality. (C) For landscapes with low levels of simplification, goals may include increasing productivity without undue loss of other services, i.e. sustainably intensified. In all cases, protection or increase of supporting services is needed to maintain the others. Photos A–C © J.S. Aber, kite, glider, and blimp airphotos, respectively.

uncoordinated farmer decisions. In contrast, analyzing particular landscapes and implementing a coordinated landscape design presents the opportunity to alleviate structural deficits in an efficient manner.

Calls for redesign of agricultural systems are not new and have typically been based within the context of particular landscapes in crisis. For example, recognition of severe limitations in water quantity and quality prompted Australian scientists to consider redesign of annual agricultural cropping systems ([Lefroy 2001](#); [Williams & Gascoigne 2003](#)). Similar concerns about the role of extensive monocultures on water quality and biodiversity have motivated calls for action within the US corn belt ([Jackson 2008](#); [Liebman & Schulte 2015](#)), with both academic scientists ([Schulte et al., 2016](#)) and governmental agencies ([Dosskey et al., 2012](#)) responding with potential redesign ideas. In Europe, a recognition of biodiversity losses has resulted in agri-environmental programs to enhance farmland biodiversity. While widely implemented they have met with varying levels of success, in part depending on how biodiversity gains are valued ([Kleijn et al., 2006](#)). These examples suggest that the goals for landscape design are often highly context-specific, and perceptions of success may vary among stakeholders.

Varying goals for different landscapes

The goals and methods for design of particular agricultural landscapes will vary with their degree of intensification and the mix of desired ecosystem services ([Gabriel et al., 2013](#);

[Ekroos et al., 2014](#)). Highly intensified landscapes typically occur where the combination of soil, climatic, and technological resources coexist to support high yields. While such landscapes rank high in provisioning services, they frequently provide only low levels of supporting, regulating and cultural services ([Fig. 3](#)). For example, in parts of the midwestern US crop yields can be exceptionally high but associated rates of soil loss and nutrient export may be unsustainable, pollination and pest suppression reduced, and recreational opportunities limited ([Liebman & Schulte 2015](#)). In such landscapes, a design goal may be to restore their integrity so that production can remain high while mitigating negative impacts. Moderately intensified landscapes may provide a more balanced set of services. While yields are typically more modest, other services such as soil retention, water infiltration and recreational opportunities can be relatively high. The goal for such landscapes may be to increase their overall multifunctionality. Finally, in less intensified landscapes the yields from agriculture may be comparatively low but balanced by increased supporting, regulating and cultural services. The goal for these landscapes may be to increase provisioning services while maintaining current levels of other services; however, some tradeoffs are likely.

Ecological basis for agricultural landscape design

A recent convergence of theoretical and empirical studies are emerging which form the foundation for informed

Table 1. Concepts guiding the design of agricultural landscapes to maintain or enhance biodiversity services and selected references from text.

Concepts	Selected references
Consider landscape impacts on biodiversity	Tscharntke et al. (2012c)
Maintain landscape heterogeneity	(Benton et al., 2003; Chaplin-Kramer et al., 2011; Woltz et al., 2012; Fischer et al., 2013; Fischer et al., 2006; Rusch et al., 2016)
Consider compositional and configurational landscape heterogeneity	(Fahrirg et al., 2011; Perović et al., 2015)
Consider landscape connectivity	(Benton et al., 2003; Fischer et al., 2006)
Manage local habitats to enhance natural enemies and pest suppression	(Landis et al., 2000; Chaplin-Kramer et al., 2011; Jonsson et al., 2015)
Manage local habitats to enhance pollinators and pollination services	(Kennedy et al., 2013; Nicholls & Altieri 2013; Blaauw & Isaacs 2014; Balfour et al., 2015; Garibaldi et al., 2015; Scheper et al., 2015)
Provide early-season resources for natural enemies	(Woltz & Landis, 2013; Raymond et al., 2015)
Maintain resource continuity	Schellhorn et al. (2015)
Importance of native vegetation for biodiversity conservation	(Isaacs et al., 2009; Fischer et al., 2013; Parry et al., 2015)
Reduce field sizes	Fahrirg et al. (2015)
Modify chemical use	(Gibbs et al., 2009; Fischer et al., 2013; Egan et al., 2014)
Manage timing of disturbance events	Fischer et al. (2013)
Increase perennality	(Landis et al., 2000; Isaacs et al., 2009)
Plan for landscape multifunctionality	(Jordan & Warner 2010; Steingrover et al., 2010; Dosskey et al., 2012; Tscharntke et al., 2012c; Shackelford et al., 2013; Westphal et al., 2015)

agricultural landscape design (Table 1). These include basic ecological studies on the relationship of biodiversity to ecosystem services, as well as applied ecological studies examining biodiversity impacts at local to landscape scales. Finally, there is a relatively new axis of research which combines basic and applied ecology with social science to guide implementation of effective habitat and landscape management (Fig. 4).

Tscharntke et al. (2012b) outlined eight major hypotheses on the relationship of biodiversity to landscape structure.

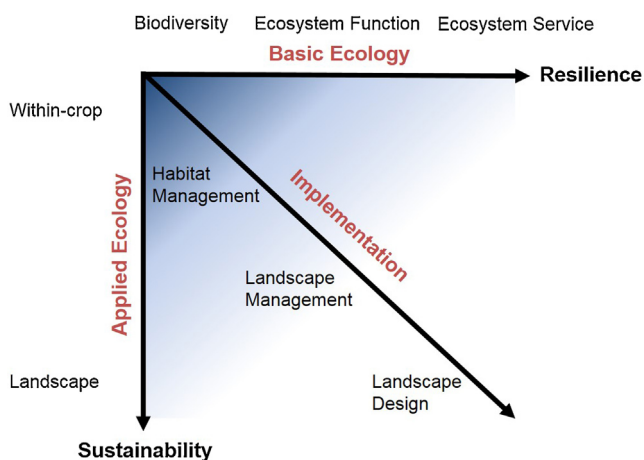


Fig. 4. A framework for integrating basic and applied ecology in the context of agricultural landscape management and design. Concepts in bold represent areas of current study. Arrows represent the main research axes and point towards the research frontiers. Darker shading indicates a greater level of current knowledge.

Several of these hypotheses have been tested empirically. In particular, the intermediate landscape-complexity hypothesis, which suggests that manipulation of habitats to enhance beneficial organisms will be most effective within landscapes of moderate complexity, has been supported by pan-European studies on plants, bees, spiders and birds (Concepcion et al., 2012). Jonsson et al. (2015) also found support for the intermediate landscape-complexity hypothesis in their study which examined the utility of floral resources to enhance parasitism of a pest aphid. In contrast, other tests of the hypothesis have found varying effects depending on the identity (Batáry et al., 2011), or mobility of the focal taxa (Dainese et al., 2015), or a lack of interaction between local and landscape factors (Woltz et al., 2012).

Fahrirg et al. (2011) suggested that increasing compositional and configurational heterogeneity of agricultural landscapes may be important components of biodiversity conservation. Testing these ideas, Perović et al. (2015) found that both were involved in shaping communities of grassland butterflies with compositional heterogeneity supporting overall taxonomic diversity, and configurational heterogeneity important in supporting particular vulnerable species. Schellhorn et al. (2015) have proposed that managing for resource continuity at the landscape scale will be important in maintaining ecosystem services, particularly where source habitats for ecosystem service providers may be ephemeral (Vandermeer et al., 2010). Multiple studies have shown that landscapes which support the early arrival of predators is key to the success of aphid control in annual crops (Woltz & Landis 2013; Raymond et al., 2015), and landscapes with higher structural complexity support increased

pest suppression (Gardiner et al., 2009) and reduced insecticide use (Meehan & Gratton 2015; Meehan et al., 2011). Resource continuity and diversity at the landscape scale is also important for pollinators (Garibaldi et al., 2013; Balfour et al., 2015; Scheper et al., 2015) and optimal landscape designs for pollination services have been proposed (Brosi et al., 2008). Overall, a common theme of many of these studies is the need to consider the interaction of local and landscape scales (Concepcion et al., 2012; Gonthier et al., 2014) and the timing of disturbance regimes (Fischer et al., 2013).

While there is considerable variation in the responses of different taxa to changes in landscape structure, the consistent message to emerge from these studies is the vital need to preserve or enhance landscape heterogeneity via management of non-crop habitats (Concepcion et al., 2012; Gonthier et al., 2014; Kennedy et al., 2013; Nicholls & Altieri 2013; Carvell et al., 2015). In particular, perennial habitats including forests, woodlots, hedgerows, and perennial grasslands support high levels of agricultural biodiversity (Landis et al., 2000). Moreover, the role of native vegetation supporting beneficial insects and reducing pests is increasingly apparent (Isaacs et al., 2009; Parry et al., 2015). Estimates suggest that as little as 20% non-crop habitat can preserve effective pest suppression (Tscharntke et al., 2002), while others show that the addition of targeted resource habitats can improve local pest control even in landscapes containing 75% non-crop habitat (Jonsson et al., 2015). While managing for ecosystem services *per se* does not ensure overall biodiversity outcomes (Macfadyen et al., 2012), even relatively simple rules such as preserving or creating smaller-sized fields have been shown to increase diversity of multiple taxa including plants, arthropods, and birds (Fahrig et al., 2015). The successful use of ecological principles to guide landscape design also needs to include the human dimension.

The increasing understanding that successful conservation of biodiversity and ecosystem services is influenced by both the social and physical context adds further dimensions of complexity. For example the primary goal of agricultural biodiversity conservation may vary among stakeholders, with some interested in conserving only species which directly provide services while others may care more about rare species regardless of their role in service provision. Studies in Europe have shown that voluntary agri-environment schemes aimed to support biodiversity-based ecosystem services do not necessarily protect species of conservation concern (Kleijn et al., 2011) but this limitation could be overcome by more explicit spatial allocation of critical habitats (Ekroos et al., 2014). Moreover, conserving the widest range of biodiversity and services is likely to require multi-scale approaches, ranging from within-field to regional levels (Ekroos et al., 2016). A recognition of the mismatches between where service providing organisms are produced, where the benefits occur, and who receives the benefits or bears the cost of their production, has large implications

for public policy and decision-making to enhance ecosystem services (Fisher et al., 2009).

Engaging with stakeholders

Shifting to ecologically-intensive agriculture models with an emphasis on landscape design to preserve or enhance ecosystem services will require new models of research and extension. In particular, ecologists will need to engage with farmers and other stakeholders to develop context-specific solutions (Geertsema et al., 2016). Fortunately, successful models exist and can be extended to address the needs of varying landscapes (Steingrover et al., 2010; Westphal et al., 2015). Geertsema et al. (2016) examined three case studies where researchers partnered with stakeholders to redesign agricultural systems for increased reliance on ecological processes. They found that in each case, targeted research was necessary to develop the specific knowledge that farmers needed to enact change, which they termed “actionable knowledge.” For example, in Iowa, USA, sub-watershed scale research showing the value of prairie strips in mitigating soil erosion and fertilizer runoff was key to spurring farmer adoption of this practice.

Similar design processes are taking root in other locations as well. For example, in the midwestern US the emergence of cellulosic biomass cropping systems to produce biofuels has created an opportunity to rethink agricultural landscapes. In Minnesota, USA, a team of researchers including experts in agronomic sciences and natural resource conservation are collaborating with geographers, economists, and sociologists to engage with farmers in the process of designing novel agricultural landscapes (Jordan & Warner 2010; Jordan et al., 2013). In one example called collaborative geodesign, scientists use geographic information systems coupled with biogeochemical models and touchscreen technology to allow stakeholders to visualize novel landscapes and the resulting flow of ecosystem services or disservices in real time (Slotterback et al., 2016). By using an iterative process that records the stakeholder decisions and resulting changes to the landscape, researchers can determine how different types of information influence the design process. Coupling this with an understanding and evaluation of the social context allows for more multifunctional solutions to emerge. For example, Stallman and James (2015) found that farmers would be willing to cooperate to control pests but preferred local efforts over county-wide approaches, and were more likely to participate if they were active members of a community organization, among other factors. This suggests that where the most efficient landscape designs require adjacent landowners to coordinative activities, an understanding of social capital and differing motivations is critical. Social scientists are also studying market-based initiatives to achieve coordinated actions even in the absence of direct collaboration (Cooke &

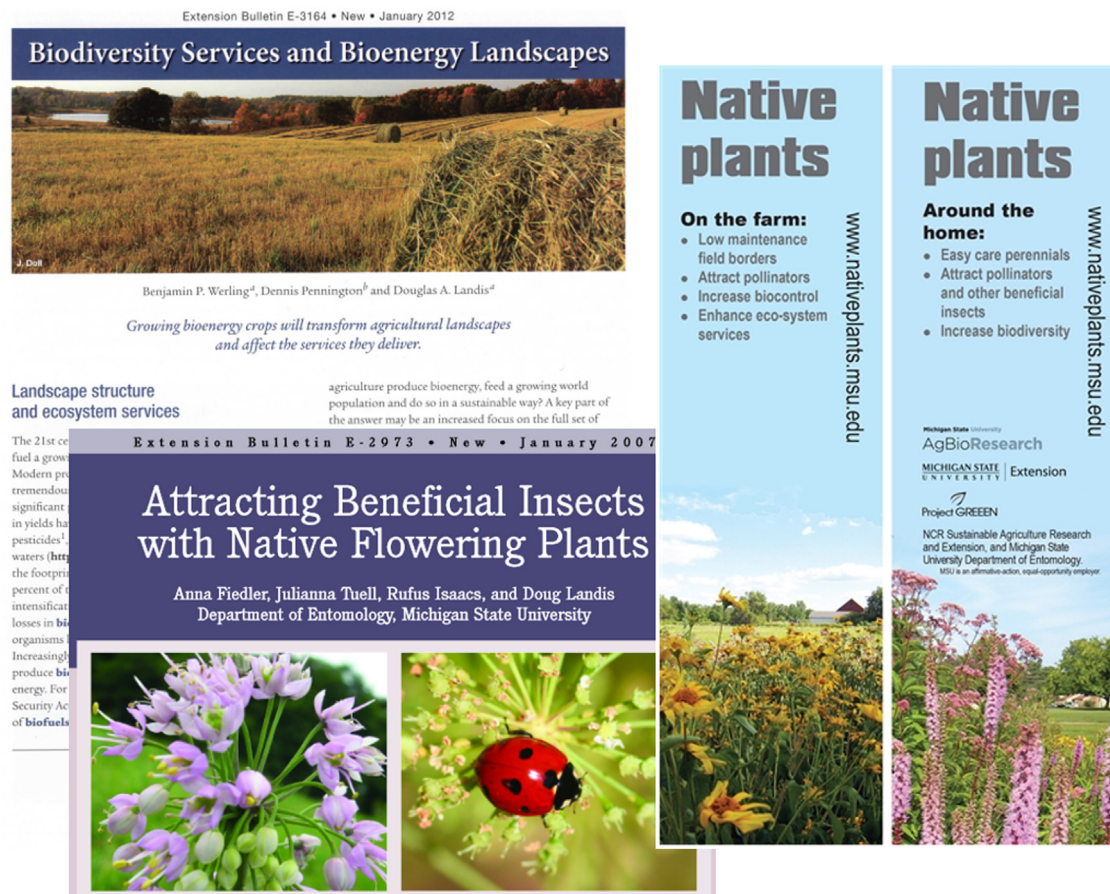


Fig. 5. Examples of outreach publications translating fundamental research into stakeholder accessible formats. Upper right shows the front and back of a bookmark used as an inexpensive handout to direct viewers to additional information on web-based portals. Publications available from MSU Extension Bookstore at www.shop.msu.edu.

Moon 2015) and examining the policy implications (Prager 2015).

Can design enhance agricultural sustainability and resilience?

At the frontier of our current knowledge is the question of whether agricultural landscapes designed for biodiversity-based ecosystem services will prove to be more sustainable and resilient than our current systems, particularly in light of a changing climate. While guidelines for the design of resilient working landscapes have been proposed (Fischer et al., 2006), we still lack many of the tools to assess ecological resilience (Spears et al., 2015). In particular, the assessment of sustainability and resilience in agricultural systems will require long time frames (Knapp et al., 2012; Hamilton et al., 2015). New experimental paradigms such as those used to assess resilience in natural systems show promise (Carpenter et al., 2011), as well as emerging theoretical (Allen et al., 2014) and policy frameworks (Slight et al., 2016). However, there is also a critical need to actually test design concepts at large spatial and temporal scales (Pace et al., 2015).

Conclusions

Multiple studies from around the world clearly show that agricultural intensification leads to landscape simplification and loss of biodiversity. In turn, biodiversity losses lead to losses of ecosystem function, compromise the delivery of ecosystem services, and likely reduce the resilience of these systems to disturbance. Given the importance of agriculture for human well-being, it is critical that ecologists continue to study these relationships. For example, a majority of the studies elucidating the relationship of biodiversity to ecosystem function and ecosystem service have come from Europe, North America, and Australia. Similar studies need to be extended to all agricultural regions of the globe (Mailafiya 2015). Research to develop tools for early warning of impending tipping points in agricultural landscapes is also critically needed; in particular, in those places where landscape heterogeneity has not been lost. We also need to refine our understanding of what elements of design will yield the greatest impact on sustainability in particular landscapes so that clear recommendations can emerge. However, research alone is unlikely to promote needed changes at the landscape scale, and ecologists also need to engage in education

and advocacy to promote effective landscape design and implementation.

Ecologists can play a key role in engaging scientists and other critical stakeholders in landscape design. Landscape ecologists have led the way in articulating how their science can move from descriptions and hypotheses of how landscapes function, to application of that knowledge in landscape design for desired outcomes (Nassauer & Opdam 2008; Opdam et al., 2013). However, we also need to move beyond calls to the scientific community, to dialogue with farmers and other land managers, agricultural educators, and resource management agencies about the advantages and drawbacks of landscape design. Regularly translating our research findings into formats that are accessible to these audiences can facilitate discussions of the need for both local and landscape management (Fig. 5). Finally, we need to work with policy makers and funding agencies to develop programs that support long-term and landscape-scale research into agricultural landscape design.

Redesigning agricultural landscapes for biodiversity services is not a trivial undertaking, nor is it an impossible one. The pressing need to feed and fuel an expanding human population in a time of accelerating global change should motivate ecologists to continue to articulate the potential of landscape design. Indeed, the explosion of relevant research across biological and social sciences – more than half of the publications cited here have been published in the last 4 years – suggest that the scientific community is heeding the call. While we still have much to learn, the ability to design agricultural landscapes for sustainable and resilient biodiversity services appears to be within our grasp.

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