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BIODIVERSITY AND ECOSYSTEM SERVICES OF AGRICULTURAL LANDSCAPES: REVERSING AGRICULTURE'S EXTERNALITIES

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Abstract

Agriculture faces the dual challenge of feeding a 9-12 billion global population by 2050 and reducing its footprint on the environment. While the impact of agriculture on the environment is well recognized, and there are growing calls for efforts to reduce or mitigate this impact, the ecosystem services approach presents an alternative where ecosystems are managed to support and improve agriculture. As the world's single largest terrestrial ecosystem, agro-ecosystems must be managed for the multiple goods and services they provide. A principal question for agroecology is whether the large-scale adoption of ecosystem-based approaches is capable transforming agriculture's environmental externalities from negative to positive, while meeting food production needs. Ecosystem services science plays a significant role in this transformation by focusing attention on how biodiversity in agricultural land-uses and landscapes can be managed for multiple benefits. We provide an example from the Volcanica Central Talamanca Biological Corridor in Costa Rica, where significant research has been undertaken, and is beginning to show where synergistic interactions between conservation, agricultural production and hydropower generation can be managed for multiple benefits. We recognize that significant trade-offs can exist. However, focusing attention on these multiple services, understanding their mechanisms, and quantifying the benefits of the trade-offs between the multiple services of agricultural landscapes provides novel solutions and spaces for managing positive interactions between agriculture and the environment.

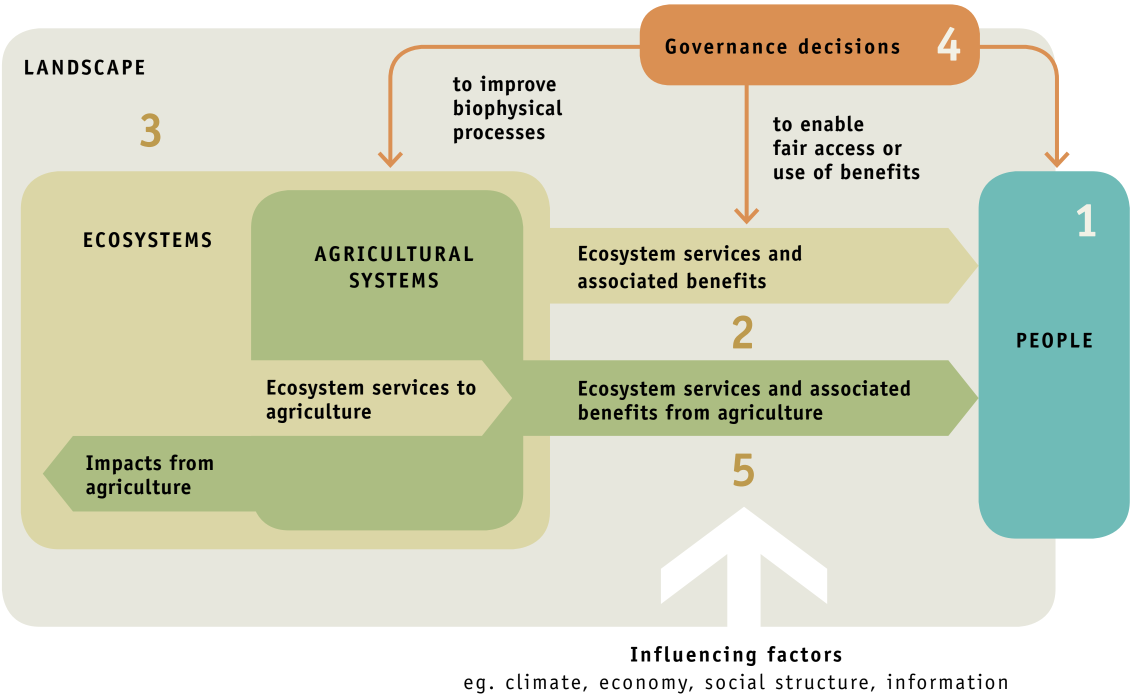
INTRODUCTION

Agriculture is faced with several critical challenges as it enters the twenty-first century. First and foremost agriculture must be managed, or even transformed to ensure that it can provide both the calorific and the nutritional needs of a 2050 population estimated at between 9 and 12 billion. It must achieve this goal without the significant environmental cost of land, water and ecosystem degradation and transformation that have been the signatures of agricultural growth during the second half of the twentieth century – leading to the emergence of the Anthropocene, the proposed name for our current geological era that recognizes the impact of human activities on geological scales (Monastersky, 2015). In reviewing the nine planetary boundaries proposed by Rockström *et al*. (2009) and now Steffen *et al*. (2014), agriculture's footprint is all too visible. This calls for a new vision of agriculture that recognizes the multifunctionality of agricultural systems, and which emphasizes and rewards management options that transform agriculture's externalities from negative to positive.

In their proposed *Solutions for a Cultivated Planet*, Foley *et al.* (2011) identify four key strategies for meeting the dual goals of agricultural production and environmental conservation: (i) stop expanding agriculture; (ii) close yield gaps; (iii) increase agricultural resource efficiency; and (iv) shift diets and reduce waste. While these steps are indeed critical to meeting the dual goals of agriculture, they stop short of proposing how agriculture itself needs to be transformed. As the world's largest and most managed terrestrial ecosystem, covering nearly 40 percent of the global landmass, we believe that agriculture provides the single largest opportunity for ecosystem services-based approaches. Ecosystem services-based approaches to agriculture, which rely on agroecology, are important because they shift our perspective from viewing the environment as a principal victim of agricultural management and expansion, to one where agriculture's dependency on the environment is highlighted, understood and managed.

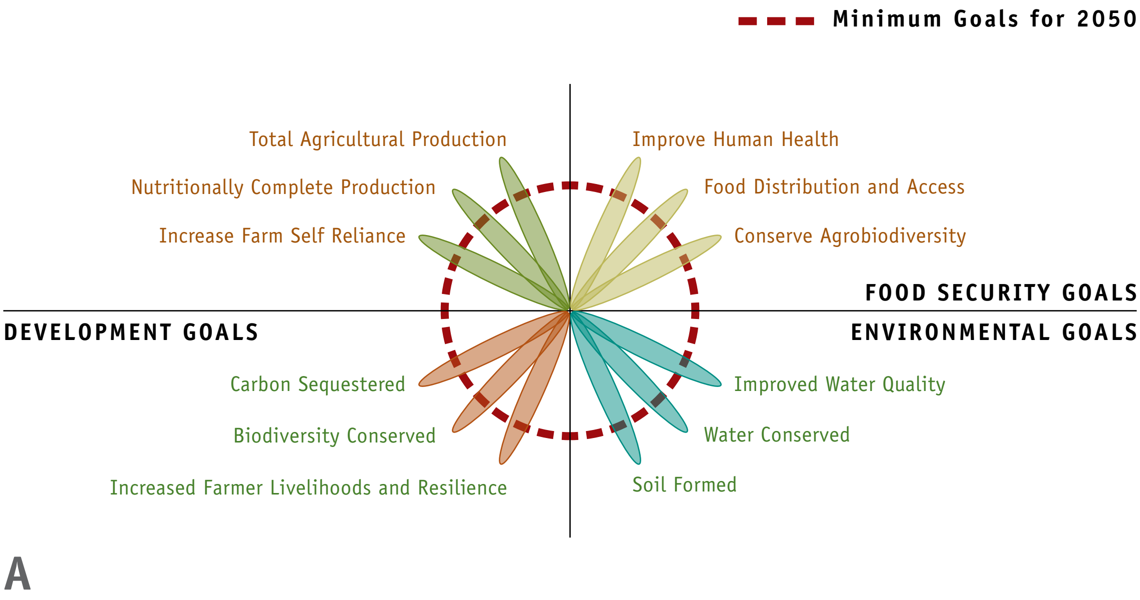
The ecosystem services-based approach to agriculture recognizes the dual role of agriculture (Figure 1). It recognizes that agriculture is fundamentally dependent on ecosystem services as the foundation of agricultural sustainability (e.g. soil nutrients, water for irrigation and growth, pollination services, pest and disease regulation). It also recognizes agriculture's capacity to provide multiple goods and services in addition to its primary crop production function. Agricultural management can be guided to increase the capacity to store carbon, contribute to biodiversity conservation, and improve water quality and soil fertility (Figure 2A). With growing global pressure on food and environmental systems, we must paradoxically expect more from agriculture; focusing on ecosystem services is one approach that contributes to increasing the capacity of agricultural landscapes to provide these multiple functions (Figure 1).

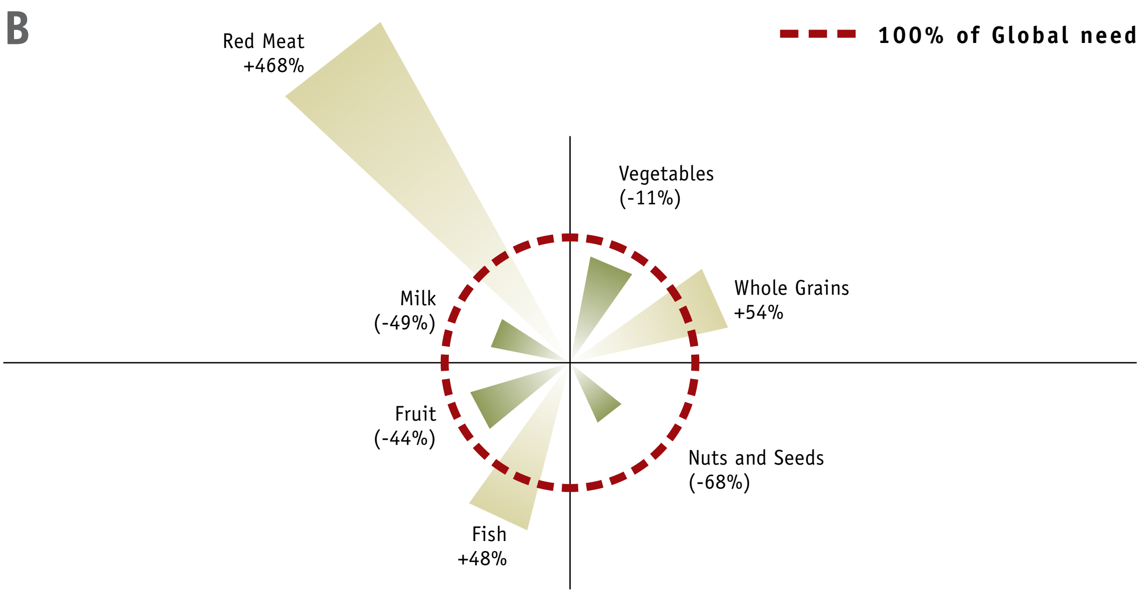
Figure 1. **The CGIAR Water Land and Ecosystems framework for managing ecosystem services and resilience**



The framework highlights the dual role of agriculture as both depending on, and being a provider of, ecosystem services. The framework emphasizes the need to measure the livelihood impacts of ecosystem services-based approaches, and the need for specific institutions capable of managing services and their benefits. The numbers indicate five principles that are critical to managing the ecosystem services of agricultural landscapes: (**1**) meeting the needs of poor people is fundamental; (**2**) people use, modify and care for the environment, which provides material and immaterial benefits to their livelihoods; (**3**) cross-scale and cross-level interactions of ecosystem services in agricultural landscapes can be managed to positively impact development outcomes; (**4**) governance mechanisms are vital tools for achieving equitable access to, and provision of, ecosystem services; (**5**) building resilience is about enhancing the capacity of communities to sustainably develop in an uncertain world.

Figure 2. **The multifunctional goals of agricultural systems**





(**A**) While the production role of agriculture is fundamental in meeting the needs of a 2050 population, meeting both global production and conservation goals requires important contributions from agriculture. This requires a shift in thinking from a single function vision of agriculture to a multifunction vision where agricultural systems are expected to contribute to development goals, environmental goals and food security goals.

(**B**) Murray (2014) identifies the components of a low risk diet and compares the demands for these components to their supply from global production systems. This comparison makes the link between food production systems and human health. It also highlights the critical need to diversify production systems to increase the production of seeds, nuts, fruit and vegetables.

This is the fundamental hypothesis posed by the CGIAR research programme on Water Land and Ecosystem's framework for ecosystem services and resilience (WLE, 2014; Figure 1). Notably, it recognizes agricultural ecosystems as ecosystems, or agro-ecosystems, in and of themselves rather than as separate entities (i.e. agricultural systems and ecological systems). While the relationship between natural and agricultural systems is retained, this recognition facilitates the management of agricultural systems and agricultural landscapes for ecosystem services provision, rather than the more traditional notion of focusing on how natural systems embedded or adjacent to agricultural landscapes provide services to agriculture. Second, it highlights the strong link between agricultural systems and human well-being, and the capacity of agro-ecosystem services to contribute to those livelihood outcomes. Because agricultural systems are fully managed (in comparison with protected areas), the scope and opportunity space for managing services though land use and landscape change is much greater than with natural systems that often have specific protections. A further distinction that arises when considering agricultural landscapes is that the conservation focus can become secondary to the livelihood benefits. The growth of research on the ecosystem services of agricultural landscapes, particularly in the developing world, is driving new research aimed at better describing, defining and measuring the specific impacts of ecosystem services provision on human livelihoods and well-being (DeClerck *et al*., 2006; Ingram *et al*., 2012; Wood and DeClerck, 2015). Finally, the framework highlights the need for new or adapted institutions that are capable of fostering the coordination, negotiation and implementation of landscape management for multiple goods and services.

The vision we propose is one of agricultural multifunctionality, where agricultural systems and landscapes are valued and managed for the multiple benefits they provide. The challenges of twenty-first century agriculture necessitate a vision of agriculture that contributes to environmental protection rather than environmental degradation, and of an agriculture that moves beyond the boundaries of its primary function of food or calorie production. For example, can we envisage an agriculture that provides not just calories, but also a nutritionally complete production? In a presentation at the EAT Stockholm Food Forum, Murray (2014) highlighted that the global production system is unable to provide the current population with the ingredients of a low-risk diet; the current global food system under-produces fruit (-44%), milk (-49%), seeds and nuts (-68%), and vegetables (-11%). At the same time Murray estimates that we have a greater proportion of fish (+48%), red meat (+468%), and grains (+54%) being harvested and produced, than is needed in the low-risk diet (Figure 2B).

In addition to shifting agriculture so that it provides nutritionally complete diets, we increasingly expect that agricultural systems will contribute to improving human health, while enabling equitable access to healthy foods (Figure 2A). However, agricultural systems must also contribute to global environmental goals and thus we must push for the management of agriculture so that it contributes to carbon sequestration, biodiversity conservation, soil formation, water quality and conservation, and provides an increase in farmers' livelihoods.

While this vision or challenge for agriculture may seem idealistic, there is evidence that agricultural systems can provide these multiple benefits. In a review by Milder *et al*. (2012), 104 studies were examined, including 574 comparisons between yield and ecosystem services provision in five systems of agroecological intensification: (i) organic agriculture; (ii) System of Rice Intensification; (iii) conservation agriculture; (iv) holistic grazing management; and (v) precision agriculture[1]. While there certainly is evidence of trade-offs between yields and ecosystem services provision, the majority of the cases demonstrated that yields can remain stable and/or increase with simultaneous increases in ecosystem services provision. The System of Rice Intensification (SRI) was particularly effective in this domain. What was difficult to find however, were specific studies that considered the multiple ecosystem services objectives and the yields of production systems simultaneously. These are increasingly needed to understand the conditions and contexts that support agricultural multifunctionality, and to identify the trade-offs that are most often encountered.

REVIEW OF THE EVIDENCE BASE

Whether trying to increase the capacity of agricultural systems to provide nutritionally complete diets, or aiming to increase the capacity of these systems to provide multiple goods and services, biodiversity is fundamental. The combinations of species in space and time determine what services are provided, when, where, and to what degree (Naeem *et al*., 2012). Biodiversity in essence serves as the global operating system. Similarly to the operating systems that run computers, allowing users to complete both simple and complex functions, biodiversity serves the same role for ecosystem services. The abundance, combination and configuration of species in space and time determine which services are provided, where, and to what degree. Failure to recognize this decreases the resilience of the global operating system, and fundamentally impacts its capacity to provide for human well-being. In their revision of Earth's planetary boundaries, Steffen *et al*. (2015) place "biosphere integrity" as one of two core boundaries along with climate change, "each of which has the potential on its own to drive the Earth System into a new state should they be substantially and persistently transgressed." Biodiversity is given special attention for two reasons:

> *"The first captures the role of genetically unique material as the 'information bank' that ultimately determines the potential for life to continue to co-evolve with the abiotic component of the Earth System in the most resilient way possible. Genetic diversity provides the long-term capacity of the biosphere to persist under and adapt to abrupt and gradual abiotic change. The second captures the role of the biosphere in Earth System functioning through the value, range, distribution and relative abundance of the functional traits of the organisms present in an ecosystem or biota."*

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1 Although precision agriculture is not commonly associated with agroecology, we included it because it fits into the broader conceptualization of agroecological intensification as an integrated approach that seeks to boost productivity and efficiency of food systems based on a nuanced understanding of specific crop requirements and environmental conditions (Francis *et al.*, 2003). Including precision agriculture permits explicit consideration of the ways in which technologically intensive practices may contribute to managing agro-ecosystems for multiple ecosystem services.

Unfortunately most Anthropocene indicators show that the state of biodiversity is decreasing, while pressure states continue to mount despite a growing global response to biodiversity loss (Butchart *et al.*, 2010). Steffen *et al.* (2015) similarly highlight that in comparing nine planetary boundaries, the loss of biosphere integrity has passed proposed allowable thresholds which are "beyond the zone of certainly" or high risk. Only the two biogeochemical boundaries of phosphorus and nitrogen cycles share this state and all three of these share important pressures from agriculture. If agriculture is such a significant part of the problem, it can and must be part of the solution. Kolbert (2014) captures the concern well in her book *The Sixth Extinction*: "we are deciding, without quite meaning to, which evolutionary pathways will remain open and which will forever be closed. No other creature has ever managed this, and it will, unfortunately, be our most enduring legacy."

The loss of biodiversity is not only a function of agriculture and its impact on land-use change and invasive species – two major drivers of biodiversity loss – but the feedback effects of this loss on agricultural production functions in a myriad of ways. Measures of agricultural change and biodiversity loss have increasingly been a core tool of ecologists. The research of Daily *et al.* (2001) on countryside biogeography has shown how agriculture drives changes in species composition and richness, as well as the capacity of mosaic landscapes to retain significantly high levels of species richness. A study by Frishkoff *et al.* (2014) took this analysis several steps further. Using avian biodiversity in a Costa Rican landscape, Frishkoff and colleagues demonstrated an important gradient between forests, diversified coffee systems and intensive coffee monocultures in terms of phylogenetic diversity. They conclude that diversified agricultural systems supported 600 million more years of evolutionary history than intensive monocultures but 300 million years fewer than forests. The important message is not only how much evolutionary history we are losing, but also how much we are capable of retaining through agricultural interventions.

Species diversity and evolutionary history are important measures, and relate to the first element of biosphere integrity alluded to by Steffen *et al.* (2015). The second element is more related to functional diversity, and the particular role that species play in the provision of ecosystem functions and services. Several studies show similar trends – shifts from natural to semi-natural and intensive agricultural systems tend to drive changes in both functional composition and richness (Flynn *et al.*, 2009; Laliberte *et al.*, 2010). The implications are that as agriculture intensifies, the functional capacity of organisms to provide services (e.g. to pollinate certain types of flowers or control insect pests) may be eroding faster than the simple loss of species.

Several ecological conditions determine the capacity of biodiversity to provide agroecological services. Understanding these conditions and their interactions are important to the agroecological management of cropping systems. Even for a single ecosystem service, such as pest control, both field- and landscape-scale ecological processes occur simultaneously and interact to keep pest populations from reaching epidemic proportions. Perfecto *et al.* (2004) showed how changes in the canopy structure of a coffee agroforest, from simplified to complex, increased avian functional diversity and subsequently pest removal from test plots. Ricketts (2004), and more recently Karp *et al.* (2013), suggest that proximity to forests is an important driver for bee or bird species spilling over from natural habitats into coffee systems to provide pollination or pest control services, respectively. Steffan-Dewenter (2002) showed the relationship between landscape complexity and pollinator functional diversity in an eloquent study which highlighted how different species respond to landscape complexity at different scales. This study demonstrated the need to maintain landscape heterogeneity from fine to coarse scales in agricultural landscapes, in order to retain the function and resilience of the pollinator community and the services they provide. This highlights the need for agroecological research and practices to foster an increasing ability to manage the interactions between multiple processes in space and time, to provide the multiple functions and services sought from agricultural landscapes.

CASE STUDY: THE VOLCANICA CENTRAL TALAMANCA BIOLOGICAL CORRIDOR

Setting the scene

The Volcanica Central Talamanca Biological Corridor (VCTBC) provides a good case study for demonstrating some of these interactions within and between scales (field, farm and landscape), and highlights three directions in which agroecological research should proceed in order to support the transformation of agriculture's externalities from negative to positive. In this case study, we focus on two specific functions of agricultural landscapes: pest control, and connectivity for wild biodiversity. Other agroecological functions have been studied in this same landscape, notably sediment reduction linking the erosion control needs of hydropower structures with up-stream farm management through a payment for ecosystem services scheme. Sediment control interventions can have important interactions with the pest and connectivity functions (Estrada-Carmona and DeClerck, 2012). The focus in this chapter is on a specific pest, the coffee berry borer, and connectivity for avian biodiversity. We chose this case study for several reasons, but most importantly because it demonstrates a specific example of an ecosystem services-based approach to landscape management, and of the need to consider multiple agroecological functions simultaneously and across scales, even when considering a single ecosystem service.

The case study focuses on three scales. At the coarsest scale, we focus briefly on the Mesoamerican isthmus, followed by more detailed descriptions of the VCTBC, and finally on a single farm at the centre of the corridor and its land uses. These three scales interact; in particular, the actions taken to manage farmscapes at the finest scale can be scaled up and contribute to preserving functions at the largest scale of the Mesoamerican region (DeClerck *et al.*, 2010).

Mesoamerican Biological Corridors

The Mesoamerican Biological Corridor (MBC) is an ambitious project launched in the 1990s by conservation organizations, aiming to foster biological connectivity between southern Mexico and northern Colombia. Conceptually, the corridor would allow a jaguar to traverse though the isthmus without leaving forest cover (hence the association of the MBC with *Paseo Pantera*, the panther's trail). The initiative struggled to gain broad support, in part because of the challenge of motivating local populations to alter land-use practices to facilitate jaguar mobility. However the notion of the corridor continues to develop and is particularly strong in Costa Rica where regional corridors receive national recognition. This is the case of the VCTBC located on the country's Caribbean slopes. Unlike the biological corridors that conjure images of linear strips of forest connecting two forest patches, the biological corridor is a 140 000 ha mixed-use matrix comprised of sugar cane, pastures, coffee plantations and forest. The primary livelihood functions of the corridor centre around agricultural production, energy generation through three dams located on the Reventazón River, which bisects the corridor from southwest to northeast, and to a lesser degree on tourism via rafting on the adjacent Pacuare River.

The corridor itself was initiated by the Association of Organic Farmers of Turrialba (APOT), who were concerned about the impact of land-use activities on environmental quality and conservation in the region. The conservation of ecosystem services became one of the ways that APOT was able to galvanize support for the creation, coordination and management of the corridor. Currently, the corridor management committee includes representatives of public and private stakeholders who make use of the landscape. For these stakeholders, biodiversity conservation, hydropower, water quality and agroecological services support their economic and social priorities. Linking increased efficiency of hydropower to soil conservation in erosion-prone regions of the corridor has been an interesting case study in and of itself. For this example, Estrada-Carmona and DeClerck (2012) demonstrate how a specific ecosystem service beneficiary can be linked to an ecosystem service provider, targeting land-use change for service provision.

Connecting conservation and fragmenting agriculture

From an agroecological perspective, through consultation with farmers in the region, pest and disease control was identified as the principal ecosystem service of interest to coffee producers – specifically the control of the coffee berry borer (*Hypothenemus hampei*) – an important agricultural pest of coffee landscapes in Central America. Unlike pollination, which can remain a rather abstract service to some farmers, the control of the coffee berry borer resonates very clearly.

Where coffee is present all year-round, as it is in the VCTBC corridor, the coffee berry borer exceeds eight generations a year. The female coffee berry borer pierces coffee beans laying her eggs in the endosperm. The larvae feed on the endosperm, effectively destroying the bean. The adult female then emerges from the fruit in search of new fruit to colonize. Drilling of a new berry in optimum conditions may take a female up to 8 hours, and this is likely to be one of the stages when the pest is most vulnerable to predation. There are several control mechanisms. One of the most effective (but most labour intensive) is the complete removal of coffee beans (both ripe and unripe, on and off the plant) from the coffee plantation during the harvest. This works to disrupt the reproductive and dispersal cycle. More common is the use of agrochemicals, including the highly toxic pesticide, endosulfan.

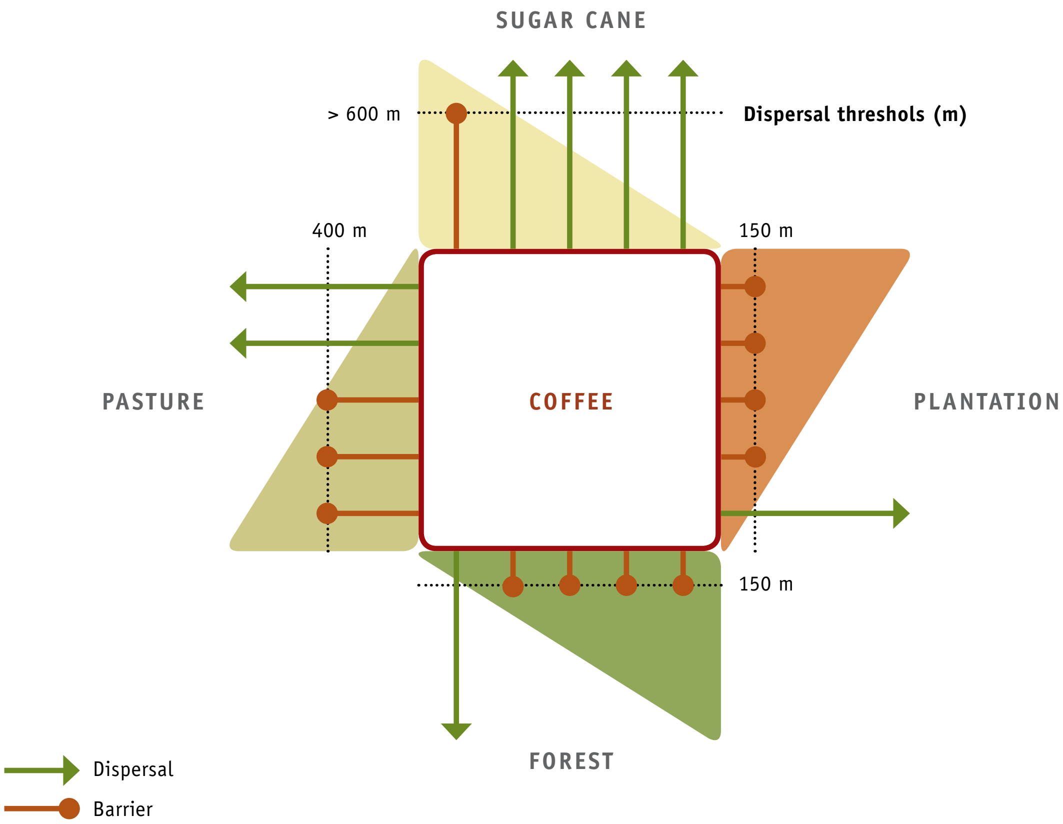
From an agroecological perspective there are four leverage points for the control of the coffee berry borer. As described above, clearing farms during harvest is effective, but labour intensive. A second method is to increase the genetic diversity of the cultivated crop to reduce pest and disease risk, though this is not a common or explicit practice used for coffee. The third method is to alter the agroecological conditions of the plot to make the habitat inhospitable for the coffee berry borer. This can be accomplished by several ecological processes, for example utilizing agroforestry to change the environmental conditions of the plot (i.e. temperature, humidity, exposure, wind velocity). There are some studies in the corridor to this effect, though these are more focused on the management of fungal pathogens with narrower environmental limits. Altering the habitat can also include increasing the predator density. This was demonstrated by Perfecto *et al*. (2004) where increasing the structural complexity of the tree component in coffee agroforests increased the functional diversity of avian insectivores, and increased predation on exposed prey. More recent exclosure studies have demonstrated this effect in coffee agroforests (Karp *et al*., 2013) with prey removal rates of up to 50 percent.

Fourth, landscapes can be managed for the same effects, increasing the mobility and access of predators to the pest populations, and/or the inverse, reducing the mobility of the pest population. Several studies have been conducted on these processes. Avelino *et al*. (2012) working in the VCTBC located 29 coffee plots and characterized the landscape context around these coffee plots in 12 nested circular sectors ranging from 50 to 1 500 m in radius. This permitted classifying the coffee plots as either intact or fragmented at the fine to medium scale, and identifying whether that fragmentation of coffee was surrounded by forest, sugar cane, or pastures. Correlation analysis between the proportions of each land use at scales between 100 and 3 000 m, and coffee pest and disease incidences, then allowed for the assessment of whether fragmenting coffee parcels in the landscapes had an effect on disease incidence. The results from this study showed a significant negative correlation between forest cover and the coffee berry borer, peaking at the 150 m radius, and a significant positive correlation with coffee area, peaking at the same scale (Figure 3). Interestingly, the authors also found a significant negative correlation between the coffee berry borer and pastures, peaking at 400 m.

Olivas (2010) further tested these correlations at finer scales using paired transects of coffee berry borer traps located every 10 m, crossing from 40 m inside coffee plots to 140 m into the adjacent forest, pasture, or sugar cane plots. Checking these traps every two weeks for 120 days during the peak coffee berry borer dispersal period it was found that borer densities were significantly the highest in the coffee plots (95 percent of captures in coffee), with very little evidence of dispersal into adjacent land uses (5 percent of captures). The little dispersal that was observed was found to be highest in the sugar cane (0.035 females day^{-1}), second in pasture (0.023 females day^{-1}), and nearly non-existent in forest (0.005 females day^{-1}). Dispersal was greatest in the first 10 m immediately adjacent to the coffee edge, and dropped off significantly beyond this point, with a much more graduate taper between 20 and 140 m, indicating strong edge effects. These results complement the landscape study of Avelino *et al*. (2012), suggesting that the coffee berry borer does not handle landscape fragmentation well and that there are differentiated dispersal barriers controlled by the characteristics of the adjacent land use. Forests are the greatest barriers to coffee berry borer dispersal, pastures second, and sugar cane is the most porous barrier.

These observations have led us to hypothesize that while forest fragmentation is largely perceived as a negative attribute in conservation, it may very well be a positive attribute

Figure 3. **Graphical representation of the distance weighted dispersal effects of heterogeneous landscapes**



Landscape composition and configuration impact the flow of organisms between adjacent parcels. Work in Costa Rica suggests that forests, pastures and sugar cane can all serve as barriers to the movement of the coffee berry borer, although much greater extents of pasture (400 m) and sugar cane (>600 m) are needed compared with forests (150 m). The results of the borer study and avian research in Costa Rica suggest that matrix landscapes may inherently maintain more services that those dominated by a single land use.

in agricultural landscapes. We propose that there are distance weighted dispersal effects of heterogeneous landscapes (Figure 3). In other words, pests originating from a land use (in this case coffee production), will have a differentiated difficulty/ease of dispersing across a landscape based on the adjacent land uses. In the case of the coffee berry borer, forest land uses serve as an effective barrier at distances of 150 m or more. Pastures can also serve as an effective barrier, but at least 400 m of pasture are required for the barrier effect to be manifested. While such numbers can be determined for specific pest populations and land uses, we can also generalize that landscape homogenization, particularly in tropical environments, facilitates pest infestation and increases the need for pest control interventions. In contrast, the fragmentation of agricultural landscapes by increasing the complexity of land use composition and configuration provides a natural break against pest epidemics. This is in effect what Fahrig *et al.*

(2011; Figure 1) have proposed regarding the impact of land use heterogeneity and biodiversity conservation: increasing the complexity of landscape composition and configuration should increase the biodiversity conservation value of agricultural landscapes, as well as reducing the risk of pest and disease incidence. This hypothesis, which has growing support in both temperate and tropical regions, suggests that land-sharing is an important strategy for addressing the dual goals of agriculture, to enhance food production and reduce its environmental impact.

While the ecological mechanisms are becoming increasingly clear, with both field-scale and landscape-scale mechanisms contributing to pest control, understanding the social variables can be much more difficult. Field-scale interventions are somewhat easier where land tenure rights are clearly defined. Good agroecological evidence on best practices, supported by public or private extension services can support farmer decision-making and implementation of these best practices. However, the discussion on landscape effects highlights that the ecosystem service of pest regulation shares the same attributes of common pool resources (Ostrom, 2009). That is, their benefits are shared by many, but controlled by no single individual. Coordination or communication between farms is needed to secure these services.

In our discussions with farmers of the VCTBC regarding the coffee berry borer, some frustration was evident regarding the pest, including a preoccupation that the individual efforts of farmers were often lost if not replicated on adjacent parcels of land. A certain degree of peer pressure regarding the coffee berry borer could also be recognized – while yield losses to the pest are important, being identified as the source of the pest to neighbouring farms is humiliating. In this way farmers were indirectly familiar with the notion of pest dispersal, and quickly became keen to understand how it might be limited. This highlights a fundamental point in managing ecosystem services; while many services are provided by agricultural landscapes, a subset of these have greater social values, and are capable of motivating behaviour change.

These innovations have been tested on the CATIE farm, a 1 000 ha farm located in the centre of the corridor, which shares many of the same land uses as the larger VCTBC. The relatively large size and composition of the farm mimics the larger VCTBC, including the interactions between multiple individual farms. For the past seven years birds have been mist-netted in the various land uses of the farm in order to understand the conservation value of these land uses (forests, simple/complex coffee agroforests, sugar cane, cacao agroforests and pastures) (Martinez-Salinas and DeClerck, 2010). These data have provided rich insights into how avian biodiversity uses agricultural landscapes, most notably, that while agroforests can play an important role in creating habitat for wild biodiversity, it can also provide important corridors to connect sufficient patches of native habitat. Notably, more than 118 bird species have been detected on the farm. Eighty-five percent of these species include invertebrates as part of their diet and 25 percent are exclusively insectivores.

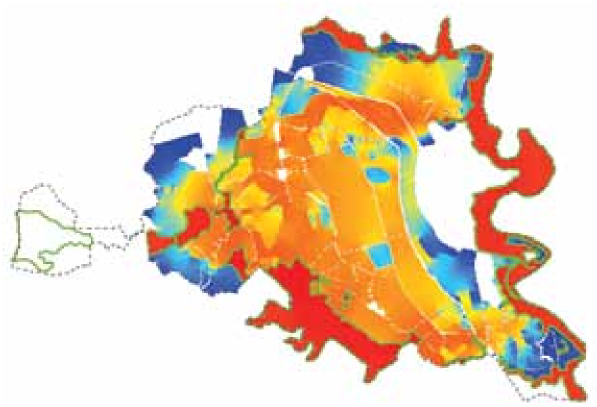
Seeking win-wins and supporting innovation

An opportunity to work on these ideas in practice was provided in collaboration with the CATIE farm manager, Rainforest Alliance, and the United States Fish and Wildlife Service. In an effort to make the CATIE farm one of the first Rainforest Alliance certified farms for livestock production, the planting of live fences was increased around all pastures and their pruning intensity was reduced. The aim is to create a veritable network of paths and corridors by which wild biodiversity can access the protected forest habitats in and around the CATIE farm in the next 5-10 years. While it will take time to produce the evidence that the intervention has the desired impact on avian biodiversity, particularly dispersal measures, computer-based models using the mist-netting data support the notion that the interventions will provide significantly increased connectivity. Figure 4A is a Circuitscape map (McRae *et al.*, 2008) which highlights the connectivity status of the farm for the ochre-bellied flycatcher (*Mionectes oligeaneus*), a forest dependent species commonly found in the Reventazón River riparian forest adjacent to the CATIE Campus, but rare in the agricultural land uses. In the map, forest patches are shown in bright red with a green border. The mixed-use matrix between the patches has been converted to conductance values, borrowing from electrical circuit theory. High conductance (bright red), indicates a high current flow, or in this case, a high probability of movement for the flycatcher. The colour gradation to blue indicates low connectivity. Unfortunately, the map shows a landscape which is fragmented for the flycatcher, with some movement supported along the southern edge of the farm.

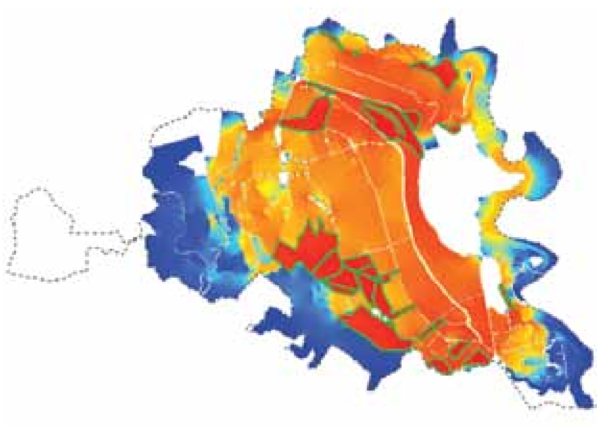
This same modelling exercise was repeated for the coffee berry borer using data from borer trapping experiments in the VCTBC landscapes (Figure 4B). Rather than considering whether the coffee berry borer was capable of moving between forest patches, the coffee patches were identified as the core habitat and the dispersal ability of the pest throughout the farm was assessed. The results are nearly the opposite of those found with the flycatcher exercise, and the farmscape is largely connected for this pest species. The combined results from Avelino *et al*. (2012), Olivas (2010) and this modelling exercise suggest that landscape configuration can be critical for providing ecosystem services, or in the case of the coffee berry borer, ecosystem disservices. Fragmenting coffee landscapes plays the dual role of facilitating spillover effects of functional biodiversity, enhancing the movement of coffee berry borer predators in this case, while simultaneously providing a barrier to the pest's emigration from one coffee parcel to another. We affectionately call this project 'bridges and barriers' for the win-win solution it highlights providing conservation benefits through connectivity, and barriers to pest dispersal.

The data do not suggest that agroecological methods are capable of eliminating the coffee berry borer entirely. What they do show, however, is the need to manage multiple ecological functions simultaneously to increase the efficiency of practices (i.e. genetic diversity, making habitat inhospitable/hospitable to the pest/predator, increasing/decreasing mobility of predator/pest populations). These functions must be further complemented by supporting management practices, such as cleaning. As this case illustrates, whether the ecosystem provides services or disservices is a function of management decisions regarding land use composition and configuration. Agroecology is at a critical point in its evolution to foster a focus on the ecosystem services provided by agro-ecosystems and improving their management in order to change agricultural externalities from negative to positive.

Figure 4. **Connectivity modelling of the 1 000 ha CATIE farm in Costa Rica for two species: the forest dependent ochre-bellied flycatcher *(Mionectes oligeaneus)* and the agricultural pest, the coffee berry borer *(Hypothenemus hampei)***



Ochre-bellied Flycatcher (*Mionectes oligeaneus*)



Coffee berry borer (*Hypothenemus hampei*)

The primary habitat of each species is indicated by the red patches encircled by green (forests for the flycatcher and coffee parcels for the beetle). The matrix between the habitat patches is modelled for connectivity, with bright red indicating high degrees of connectivity, and dark blue indicating low connectivity.

CONCLUSIONS

The VCTBC case study provides an example of researchers, farmers and other landscape stakeholders attempting to understand how to manage a shared landscape for its multiple ecosystem benefits and services. The past ten years of engaging in this process has taught us the importance of matching ecological and governance scales in securing the provisioning of ecosystem services (Fremier *et al.*, 2013). Our initial assessment of the land uses and priorities in the corridor identified several stakeholder priorities which are also shared by many other landscapes in Latin America (Estrada-Carmona *et al.*, 2014). What stands out as significant is the desire of communities to have options and institutions for managing common pool resources – such as biodiversity and the services that it provides.

Specifically in the VCTBC, sediment reduction was identified as a priority for increasing the efficiency of hydropower, managing biological connectivity was a priority to support the function of the corridor, and farming communities expressed an interest in pest regulation. For each of these services, several ecological processes can be identified, the provider of the service can be identified using targeting mapping tools, and the beneficiary is also readily identifiable. These are the necessary prerequisites for ecosystem services management. The absence of any of these three elements puts ecosystem services management at risk. The identification of ecological mechanisms is crucial for assuring that the process by which services function can be understood and that management options are grounded in a recognized evidence base. The identification of a specific service provider and beneficiary (individuals, groups of individuals, or public entities) then determines the appropriate intervention options and management scales. These can range from individual farms or farming families serving as both the ecosystem services provider and beneficiary in the case of farm-scale agroecological services; to farming communities in the case of adjacency-based functions such as pollination and pest control; to larger landscape-scale functions as in the case of sediment reduction for increasing the efficiency of hydropower generation in the corridor, or for managing biological connectivity.

We highlight three additional considerations which we consider to be fundamental in ecosystem services management. First, if ecosystem services-based approaches are to become viable options for managing agroecological landscapes, we must become better equipped to understand and manage the multiple processes that interact to provide a single function. In the case of pest and disease control, this includes managing genetic diversity for resilience, and habitat suitability/unsuitability for predator/pest populations, respectively. Similarly, understanding functional diversity and its connectivity is important to manage immigration and emigration rates of predator and pest communities, as well as possible predator spillover effects and distances. The combination and interaction between these multiple processes contributes to pest control functions, yet these are rarely studied simultaneously. Rather, most studies consider a single ecological process in isolation to measure its effect.

The second point is similar to the first. Scale plays a critical role in ecosystem services management from fields to landscapes. The agroecological processes mentioned above operate at different scales. Therefore, understanding these scales provides an insight into which management functions are available, and more importantly, which types of institutions are needed to secure the service – agricultural extension for field-based services, farmer cooperatives for farm-scale functions, and eventually payments for ecosystem services for landscape-scale functions.

The third point refers to the need to better recognize the value of biodiversity for the services it provides in agricultural landscapes. In some cases this can be through economic valuation. For example, Ricketts (2004) estimated that the pollination services provided by forests adjacent to two larger farms in Costa Rica provide US\$60 ha^{-1} year^{-1} in pollination services. Similarly, Karp *et al*. (2013) estimated that pest control services provided by forests adjacent to coffee plantations are worth US\$75-310 ha^{-1} year^{-1}. These values are already higher than payments from the national Costa Rican payments for ecosystem services scheme that are in the order of US\$80 ha^{-1} year^{-1}. Valuation does not necessarily imply monetization; it can also be social, or individual. However, it must be high enough to influence decision-making including changes in land use composition and configuration.

To conclude, the rather singular focus on production functions in agriculture, while understandable and a principal priority for agricultural landscapes, has been achieved at an all too high environmental cost. Although it may seem that our world is becoming more digital, with the expectation that technological fixes will resolve the majority of our problems, the reality is that we inhabit a biological planet where critical life-support systems are provided by biological interactions. We urgently need novel technologies that support biological, or agroecological functions, rather than supplant them. Similarly, institutions and incentive mechanisms that recognize the efforts of farmers and farming communities in providing multiple ecosystem functions are needed to support the transition to make positive agricultural externalities the norm, rather than the exception. Agroecology is no panacea, but the central role that agriculture plays in environmental and human health places it squarely in the centre of renewed global efforts to meet sustainable development goals.

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