Agriculture, Ecosystems and Environment 173 (2013) 20–27

Contents lists available at SciVerse ScienceDirect

Agriculture, Ecosystems and Environment

journal homepage: www.elsevier.com/locate/agee

Review

To close the yield-gap while saving biodiversity will require multiple locally relevant strategies

Saul A. Cunningham[a,*], Simon J. Attwood[b], Kamal S. Bawa[c], Tim G. Benton[d], Linda M. Broadhurst[e], Raphael K. Didham[f,g], Sue McIntyre[a], Ivette Perfecto[h], Michael J. Samways[i], Teja Tscharntke[j], John Vandermeer[h], Marc-André Villard[k], Andrew G. Young[e], David B. Lindenmayer[l]

[a] *CSIRO Ecosystem Sciences, PO Box 1700, Canberra, ACT 2601, Australia*
[b] *Australian Centre for Sustainable Catchments, University of Southern Queensland, Toowoomba, Qld 4350, Australia*
[c] *Department of Biology, University of Massachusetts, Boston, MA 02125, USA*
[d] *Institute of Integrative and Comparative Biology, Faculty of Biological Sciences, University of Leeds, LS2 9JT, United Kingdom*
[e] *CSIRO Plant Industry, PO Box 1600, Canberra, ACT 2601, Australia*
[f] *CSIRO Ecosystem Sciences, Floreat, WA 6014, Australia*
[g] *School of Animal Biology, The University of Western Australia, 35 Stirling Highway, Crawley, WA 6009, Australia*
[h] *School of Natural Resources and Environment, University of Michigan, Ann Arbor, MI 48109, USA*
[i] *Department of Conservation Ecology and Entomology, Stellenbosch University, P/Bag X1, Matieland 7602, South Africa*
[j] *Agroecology, Georg-August University, Grisebachstr. 6, 37077 Göttingen, Germany*
[k] *Département de Biologie, Université de Moncton, Moncton, NB E1A 3E9, Canada*
[l] *Fenner School of Environment and Society, Australian National University, Canberra, ACT 0200, Australia*

ARTICLE INFO

Article history:
Received 14 November 2012
Received in revised form 9 April 2013
Accepted 11 April 2013
Available online 9 May 2013

Keywords:
Conservation
Ecosystem services
Food
Agriculture
Land use
Society

ABSTRACT

Increasing yield has emerged as the most prominent element in strategies to deal with growing global demand for food and fibre. It is usually acknowledged that this needs to be done while minimising harm to the environment, but historically land-use intensification has been a major driver of biodiversity loss. The risk is now great that a singular focus on increasing yields will divert attention from the linked problem of biodiversity decline, and the historical pattern will continue. There *are* options that increase yields while reducing harm to biodiversity, which should be the focus of future strategies. The solutions are not universal, but are locally specific. This is because landscapes vary greatly in inherent biodiversity, the production systems they can support, and the potential for them to be adopted by landholders. While new production techniques might apply at local scale, biodiversity conservation inevitably requires strategies at landscape and larger scales.

Contents

1. Introduction 21
2. Land-use intensification and cross-scale effects 21
3. Why conserve biodiversity in agricultural landscapes? 22
4. Defining better targets 23
5. Different landscapes, different options 23
6. Landscapes of people 24
7. Conclusions 25
Acknowledgements 25
References 25

---

* Corresponding author. Tel.: +61 2 6246 4356.
E-mail address: saul.cunningham@csiro.au (S.A. Cunningham).

0167-8809 © 2013 The Authors. Published by Elsevier B.V. Open access under CC BY license.
http://dx.doi.org/10.1016/j.agee.2013.04.007

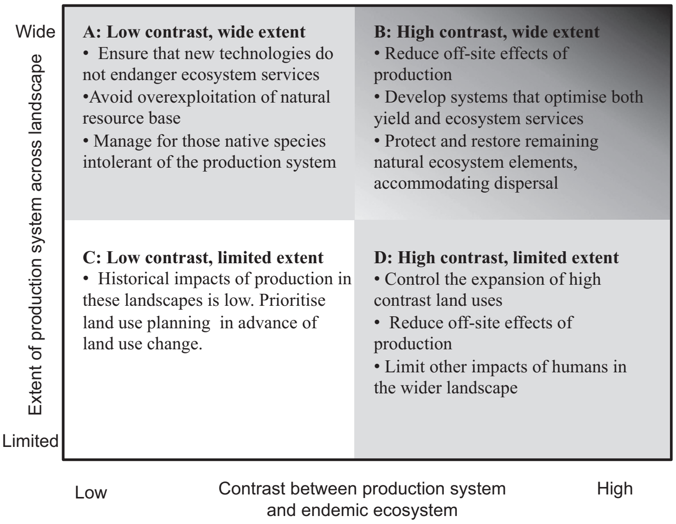
1. Introduction

Feeding the world's growing human population at escalating rates of per capita food consumption is one of the pivotal societal challenges for the coming decades. Doing so in an environmentally sustainable manner while maintaining a global commitment to the conservation of biodiversity will stretch trade-offs between production and conservation to breaking point. Recent global assessments (e.g. Bruinsma, 2009; Foley et al., 2011; Foresight, 2011; Godfray et al., 2010; Herrero et al., 2010) suggest that it will be possible to meet this challenge and limit harm to biodiversity because options exist to intensify food production per unit area, while halting further expansion of the area of land under production. The underlying principle is to close the "yield gap" (Lobell et al., 2009) – the gap between realised and achievable yields across the farms of the world. However, a yield growth prescription does not in itself provide actions for reducing the negative impacts of agricultural intensification on biodiversity. The problem, then, is that while we rally scientific resources to meet the global food and fibre production challenge, we risk falling even further behind on the challenge of reducing the rate of biodiversity loss. In other words, we might close the yield gap, but further widen the sustainability gap (*sensu* Fischer et al., 2007).

It has long been recognised that productive land-use and the practices we adopt to achieve this, are strong drivers of biodiversity loss (e.g. Carson, 1963). But there are concerns that recent rates of biodiversity loss from all causes, not just land-use, are so great (Barnosky et al., 2011) that we might already have exceeded the point where dangerous feedbacks on ecosystem capacity to support biodiversity are expected (Rockström et al., 2009). Moreover, these pressures are intensifying (SCBD, 2010), particularly from the direct and indirect effects of climate change on biodiversity (Bellard et al., 2012). Current rates of biodiversity loss are now considered so severe that the goal must be not just to stabilise them, but to *reduce* them (Butchart et al., 2010).

The emerging problem we see is that the scale of the global food and fibre production challenge (and the implied risks it brings in terms of social disruption, conflict and famine) is overwhelming environmental concerns. Although the risks to biodiversity arising from the food and fibre challenge are well recognised in the scientific literature (e.g. Godfray et al., 2010; Tilman, 1999) there are few signs that the size and scope of the problem, and the interlinked nature of biodiversity and agriculture, are sufficiently appreciated in broader society. Biodiversity loss continues to be treated as a stand-alone problem, tackled independently from the food and fibre problem. As a consequence, biodiversity conservation risks being relegated to a secondary matter to be considered while solving the primary problem of supplying sufficient food and fibre to the human population. History suggests that as long as we view biodiversity conservation as a secondary consideration it will lose out (Wood, 2000). Prescriptions for better conservation outcomes will suffer from a lack of implementation, especially are if they are perceived as complicated (Hall and Fleishman, 2010) or interfering with other goals.

The first risk of the "closing the yield gap" strategy is that it will fail to prevent further expansion of agriculture. Growth in food production in the past has been strongly correlated with growth in agricultural land area (Pretty, 2008). While opportunities to expand the areal extent of agriculture in some regions are limited because the best land is already developed (Young, 1999), there are other regions where agriculture has expanded dramatically in recent times. Significantly, some of this expansion has occurred in high biodiversity tropical regions, such as for soybean production in South America (Grau et al., 2005) and palm oil in Southeast Asia (Koh and Wilcove, 2007). Moreover, history shows that increasing yield does not by itself prevent expansion of the area under production (Angelsen and Kaimowitz, 2001; Ewers et al., 2009), and is only likely to do so where regulation supports this outcome (Matson and Vitousek, 2006). The second risk of the closing the yield gap strategy, however, is even more difficult to solve. The danger is that the technical solutions to closing the yield gap will increase harm to biodiversity. This problem is typically framed as a trade-off between land-use intensification (LUI) and biodiversity conservation.



A: Low contrast, wide extent
- Ensure that new technologies do not endanger ecosystem services
- Avoid overexploitation of natural resource base
- Manage for those native species intolerant of the production system

B: High contrast, wide extent
- Reduce off-site effects of production
- Develop systems that optimise both yield and ecosystem services
- Protect and restore remaining natural ecosystem elements, accommodating dispersal

C: Low contrast, limited extent
- Historical impacts of production in these landscapes is low. Prioritise land use planning in advance of land use change.

D: High contrast, limited extent
- Control the expansion of high contrast land uses
- Reduce off-site effects of production
- Limit other impacts of humans in the wider landscape

Fig. 1. A global typology of agricultural landscapes, and the top priorities for the management of local biodiversity in a context of increasing demand for agricultural products (dot points). The *y*-axis represents the degree to which the production system extends across the landscape of interest. If production has a relatively low extent then there are many and widespread places in the landscape where endemic biodiversity can persist without coming into conflict with production practice. The *x*-axis represents the degree to which the production system contrasts with the pre-conversion ecosystem in structural traits and disturbance regimes. Thus, a low contrast production system mimics endogenous structural complexity and disturbance regimes. High contrast production systems share little in common with the pre-conversion ecosystem and often involve high levels of inputs and mechanisation. The landscape types are chosen to represent the extremes of the gradients, but in reality intermediates will be common.

Here we aim to provide context for the challenges of achieving biodiversity conservation goals while meeting demand for food and fibre production. We examine the way in which good solutions for both biodiversity and production are shaped by understanding and accommodating differences among landscapes in biodiversity, productive potential, and human populations. To help understand the diversity of landscapes we present a typology that is structured around two axes that are critical to the relationship between production and biodiversity (Fig. 1). The first axis describes the extent to which productive land use occupies the landscape of interest, the second axis describes the degree to which the production system contrasts with the properties of the pre-agricultural ecosystem. The first axis recognises the critical impact of land use conversion, and the second axis reflects that different agricultural systems have different potential to support elements of endemic biodiversity. Replacement of endemic diversity with widespread species is the pattern at the heart of global biodiversity decline. We discuss some archetypal agricultural systems to illustrate landscape diversity and explore these axes. Finally, we consider strategies for attaining better outcomes for biodiversity and production systems that reflect this diversity.

2. Land-use intensification and cross-scale effects

It is widely acknowledged that past LUI has been a primary driver of global biodiversity decline (Foley et al., 2005; Gibson et al.,

Fig. 2. Intensive dairy farming in New Zealand. ©iStockphoto.com/jvdwolf.

2011; Tilman, 1999; Tilman et al., 2002), but there are different views on what precisely constitutes LUI. Some have defined LUI as the degree to which humans appropriate an increasing fraction of potential net primary productivity (Erb et al., 2009; Krebs et al., 1999). This simple concept focuses on production and is neutral on the issue of land area, whereas other definitions emphasise the difference between increasing the land area under agriculture and *intensification* as the means by which gains are made using increased inputs per unit land area (Moller et al., 2008). By contrast, the Food and Agriculture Organisation treats land area as just one of many 'inputs' to the farming enterprise, and defines intensification in terms of the economic efficiency of production output per unit input (FAO, 2004), thereby removing the distinction between area occupied and intensification.

Our interest, however, is not in settling on a definition of LUI, but rather to identify the features of land use change that impact biodiversity. Increased area of land in production is one crucial driver (Fig. 1). However, biodiversity loss does not have to be directly coupled with higher production per area. Rather, it is the specific processes or methods used to produce high yield that can be inimical to biodiversity. For example, simplification of habitats when monocultural production dominates the land area impacts at local and landscape scales (Fig. 1, quadrant B). Pesticides intended to kill unwanted organisms can reduce within-field biodiversity, but also cause larger scale or "spillover" effects. For example, the spillover of agricultural chemicals can dramatically affect neighbouring non-agricultural land or waterways, and non-native species that prosper on production lands can become competitive invaders in adjacent non-agricultural land (Rand et al., 2006). Inefficiencies in the utilisation of inputs can cause excess nutrients to accumulate, causing eutrophication of environments adapted to low nutrient conditions (Kleijn et al., 2009).

Another kind of off-site effect comes from the environmental costs of producing the inputs that themselves go into the production of food and fibre yields. For example, the manufacture of fertilisers comes at a significant energy cost (West and Marland, 2002), and the production of imported livestock feed requires land and other inputs of its own. Consider the case of the New Zealand dairy industry, which now produces over one-third of global dairy commodities (Baskaran et al., 2009, Fig. 2). Historically, intensification was underpinned by on-farm increases in energy and resource use. Increasingly though, production is now supplemented by feed imports. In the last 30 years, the proportion of farmers using externally grown feed supplements has increased from 20% to 80% (Holmes and Roche, 2007), with a shift in the last decade from feed grown locally to imported feed stocks from overseas. Imports of palm kernel expeller (PKE) from southeast Asia increased from ~1 t to ~1 million t per annum between 1999 and 2009. New Zealand now uses one-quarter to one-half of global PKE production for livestock feed. Imported feed stocks increase New Zealand's agricultural land-base without the need to convert more land to agriculture. Consequently, the apparent ratio of local production to environmental impact (i.e. the sustainability of production) increases favourably, but occurs at the expense of 'exporting' environmental damage because high PKE demand increases the profitability of oil palm plantations, providing further market incentive to convert rainforest to oil palm. This example underlines the point that when considering the drivers and consequences of LUI, it is essential to understand cross-scale dependencies and the coupling of local environmental damage to global market pressures during the life-cycle of the product. Ultimately these cross-scale impacts can be assessed at the global level by assessing sustainability of production in terms of the total flow of energy and materials between humans and their environment (Burger et al., 2012).

But not all technologies for closing the yield gap need to increase pressure on biodiversity. We recognise three different classes of strategy that can lead to better biodiversity outcomes. The first is to better target inputs in space and time so that the agricultural system gets the maximum benefit while reducing spillover and unintended impacts. For example, better application of fertiliser through precision-agriculture (Cassman, 1999) can optimise nutrient uptake by crops and thereby reduce eutrophication of soil and water. Similarly, target-specific pesticides reduce unintended impacts on other animals. The second class of strategies focuses on maximising efficiency benefits by harnessing ecosystem services (Barrios, 2007; Bommarco et al., 2013; Mediene et al., 2011). For example, natural enemies can reduce pest outbreaks (Thompson et al., 2011) and integration of nitrogen-fixing plants in production systems can increase yields (e.g. Akinnifesi et al., 2010). The third class of strategies focuses on spatial planning of land use, recognising that in some landscapes optimising land use decisions at large scales appears likely to lead to real biodiversity gains without compromising landscape wide levels of production (e.g. Polasky et al., 2008; Hodgson et al., 2010; Barraquand and Martinet, 2011).

These strategies give reason for optimism that there are 'win–win' approaches. From the perspective of biodiversity conservation, the critical question is whether we can break the nexus between LUI and biodiversity loss by adopting methods that close the yield gap while simultaneously benefiting biodiversity. The alternative is to continue down the same historical pathway in which pursuing increased yield in the short term comes at a great biodiversity cost, and with negative consequences for yield in the long run.

3. Why conserve biodiversity in agricultural landscapes?

The historical pattern, in which increasing agricultural production has come at a cost of reduced biodiversity, suggests that the desire to protect biodiversity has consistently been outweighed by the desire to produce more food and fibre. Perhaps this is unsurprising given the central role of agricultural productivity in generating wealth and human wellbeing. However, the continuing degradation of biodiversity has exposed two different kinds of risk for future generations. The first is that we lose species (or other elements of biodiversity) that are in fact widely valued by society, not because people do not care, but because the mechanisms to protect biodiversity are ineffective. The second risk focuses on utilitarian values, in that the loss of biodiversity can threaten the provision of ecosystem services to humans (MEA, 2005; Naeem et al., 2009). In this way, biodiversity loss can actually undermine the goal of increased food production, or create other risks to human welfare that exceed any benefits of increased food production (Rands et al., 2010). This is a difficult risk to manage because the negative consequences are often not monitored (Lindenmayer et al., 2012a) and, even if they are, then the link back to fundamental causes is often not made.

Biodiversity is understood to support many ecosystem functions, including many that directly benefit humans (Hooper et al., 2005), so we can make a generic prediction that biodiversity loss is expected to have a real cost to society (Daily, 1997). It is critical that we understand how these feedbacks impinge on food and fibre production in particular. For example, a recent review of four decades of data on 99 crops with varying levels of dependence on pollination, found that crops with greater dependence on this ecosystem service had lower rates of yield growth, and a greater increase in the area planted (Garibaldi et al., 2011). This pattern suggests that yield growth is constrained because the provision of crop pollination as a free ecosystem service is diminishing in the agricultural landscape. Growth in the land area under these crops may help to meet demand, but at the risk of further eroding the ecosystem service. It is critical to establish how general this pattern is for other ecosystem services linked to food and fibre production, and to develop production systems that avoid creating these unwanted trade-offs.

4. Defining better targets

Defining better targets for more environmentally sustainable intensification of production must address the whole food production and distribution system. Although we focus primarily on the production sector, it is also critical to recognise that other efficiencies in the global food system could boost food availability, and some at lower cost to biodiversity than LUI. For example, significant amounts of food are lost in storage or distribution, so that improvements in these areas will in some cases provide benefits that exceed what is possible from closing the yield gap (Cook et al., 2011). In practice, however, we are not choosing between more sustainable LUI *or* better food storage and distribution; both strategies should be adopted.

In the production sector, the yield growth prescription has been motivated primarily by the shortage of productive land, but has also been linked to the goal of reducing the negative environmental impacts of production (e.g. Godfray et al., 2010; Tilman et al., 2002). The driving assumption is that the negative impacts of agriculture are proportional to the area in use. A more detailed assessment of agricultural practices, however, reveals that different forms of agriculture vary greatly in their impact on biodiversity. Some productive land-uses support relatively high biodiversity while others host very low biodiversity, so the relationship between area of productive land use and impact is complex. To accommodate this diversity of systems, we should not assess impact simply by area, but instead favour production practices that support high levels of production with least impact on biodiversity, assessed across the whole extent of the production system (e.g. Hodgson et al., 2010). The science question then becomes one of determining which practices lead to the best outcomes in different landscapes. This question is at the heart of a current debate on different solutions to the production–conservation trade-off, which has been framed around the ideas that there is a spectrum of options which range from integrating conservation and production goals across the whole landscape (land sharing) through to segregating production and conservation goals into different land parcels (land sparing) (e.g. Phalan et al., 2011; Tscharntke et al., 2012). Better biodiversity outcomes will require a more explicit recognition of the particular scales of assessment and the scale on which important processes naturally occur, and clarity in the framework for analysis (Pelosi et al., 2010).

Fig. 3. Temperate eucalypt woodland replaced by grain cropping in Australia. ©CSIRO, photograph by John Coppi.

5. Different landscapes, different options

Different places around the globe vary in their inherent biodiversity value and production potential. They also differ in current composition of native and agricultural elements, which create distinct patterns of landscape heterogeneity (Fahrig et al., 2011). While the normal expectation is that increased production comes at a cost to biodiversity, the functional form of this trade-off relationship will differ from place to place (Perfecto et al., 2005). The history of land-use also determines the potential outcomes in both the production and biodiversity dimensions. Landscapes with a long history of intensive land-use may have relatively little scope for further productivity gains through LUI, and might be among the most difficult landscapes in which to achieve wins for biodiversity conservation. In contrast, newly developed production landscapes begin with the greatest potential for biodiversity conservation (Fig. 1, quadrant C), but if conservation planning fails then the cost might be severe (Gibson et al., 2011). This problem is seen in the oil palm landscapes of tropical Asia, where a productive agricultural system replaces high biodiversity tropical forest (Koh and Wilcove, 2007).

Two examples illustrate our point about the contrasting options available for production and biodiversity in different landscapes of the world. First, cereals are the mainstay of the human diet and global population growth is expected to drive on-going intensification of their production (Cassman, 1999). Production is responsive to world trading markets rather than local needs (Reganold et al., 2011). Cereal production is often associated with the most cleared and homogenised of all the world's landscapes (Matthews, 1983: Fig. 1, quadrant B). Consider the relatively short history of cereal production in Australia, where large areas have been transformed from temperate native woodlands into grain production or grain-and-grazing rotation, with native vegetation sometimes reduced to 10% of the plains landscape (Sivertsen and Metcalfe, 1995; Driscoll, 2005: Fig. 3). As a consequence, woodland species are now overrepresented on Australian threatened and endangered lists. The contrast between the biodiversity on agricultural land versus adjacent native remnant vegetation is stark (McIntyre et al., 2002a), to the extent that there is little compatibility between the agricultural habitat and native biodiversity. Maintaining connectivity for movement of organisms among remnants when there are so few remaining is also difficult. Restoration to achieve better connectivity can be expensive where loss of production land incurs market costs. In short, the history and economics of these highly fragmented landscapes greatly constrains the potential for improved biodiversity outcomes.

Tropical agroforestry systems, on the other hand, offer a stark contrast to the cereal landscapes of warm temperate regions.

Fig. 4. A structurally complex coffee agroforestry farm in Chiapas, Mexico. Photograph by John Vandermeer.

Although many agroforestry commodities like coffee and chocolate are not essential food staples, like basic grains or vegetables, they nevertheless represent an important part of the economies of many poor countries, supporting millions of people throughout the tropics. From an ecological perspective, coffee and cacao are special in that both occur as understory plants and grow well under shade trees, creating an "agroforest" that structurally resembles the forests they replaced (Fig. 4: Fig. 1 quadrants A and C). Coffee and cacao agroecosystems are becoming emblems of managed ecosystems that can be planned to contribute to sustainable agriculture in a variety of contexts. First, as a repository for biodiversity, they sometimes house levels of biodiversity that rival nearby native systems (Perfecto et al., 1996). Second, shaded coffee and cacao systems can contribute a high quality matrix element in landscapes where biodiversity is maintained through dispersal dynamics that promote the persistence in remnant patches (Perfecto and Vandermeer, 2008). Third, because the physical structure of agroforests mimics that of native forests, they are thought to provide a buffer to some of the negative impacts expected under global climate change (Vandermeer et al., 2010). Fourth, the biodiversity harboured within these agroecosystems and the adjacent native habitats contribute to ecosystem services such as pollination and pest control (Vandermeer et al., 2010).

The striking differences between the systems (i.e. cereals in a cleared woodland and coffee in an agroforest), illustrate the point that options for better biodiversity outcomes in agriculture depend on the inherent contrast between the productive land-use options and the pre-agricultural ecosystem (Fig. 1). In regions where trees have made way for annual cropping systems the contrast is so great that there will be few options for significant biodiversity outcomes in the agricultural matrix, because the endemic forest or woodland-dependent biodiversity is not supported by the agricultural habitat. It becomes especially important in these circumstances to ensure that interpatch dispersal can occur, to sustain the remnant populations (Perfecto et al., 2009). In contrast, where complex agroforests replace native forest, it is more likely that agriculture can approximate structurally and spatially complex environments that are productive and support biodiversity (Clough et al., 2011; Perfecto and Vandermeer, 2008). Explicit recognition of the diversity of relationships between production and biodiversity is the first step in balancing trade-offs in different agro-ecological systems. Clearly, not all land-use options or technologies are equivalent in their impact (on production or biodiversity) under different social, economic, biogeographic and ecological contexts (Tscharntke et al., 2011).

Fig. 5. Small scale faming in the Eastern Himalayas. Photograph by Pashupati Chaudhary.

6. Landscapes of people

The examples we have discussed so far treat land-use options as if the only relevant dimensions were productivity and biodiversity. In practice, of course, productive landscapes are also home to people. In spite of the global trend towards urbanisation, it remains the case that many millions of people live in rural landscapes and practice small holder agriculture. Worldwide, there are 500 million small landholders, with the majority (87%) in Asia (World Bank, 2007). Millions of small farms dot these sometimes biodiversity-rich landscapes, and most of the landowners practice subsistence-level farming that is insufficient to meet basic family needs. For example, on the Singalila range on the eastern border between India and Nepal, small farms, less than half a ha in extent, are interspersed within a remnant forest mosaic (Fig. 5: Fig. 1 quadrant A). The landscape, as a part of the Himalayas biodiversity hotspot, has high biodiversity, and is typical of many landscapes in biodiversity hotspots in Asia.

Conventional LUI is neither desirable nor feasible in this context because inputs are too expensive for landholders. Moreover, such inputs could endanger surrounding biodiversity, and have already done so in many places. Setting aside land for conservation without drastically altering the socio-ecological system is seldom possible. In fact, in many areas of the Himalayas and other regions, the establishment of protected areas with centralised management has created social, economic and political problems. A viable option to enhance rural incomes and conserve biodiversity is for the farmer to sustainably generate a diversified portfolio of goods and services from their lands and local ecosystems (Bawa et al., 2012). Exploitation of resources from the non-farmed part of the landscape is an opportunity, but one that must be managed to avoid unsustainable harvesting (Kangalawe and Noe, 2012).

In a landscape of small-holder subsistence farmers a decline in productivity could have immediate and dire impacts on human welfare. At the same time, if most production is consumed locally rather than traded, the role of policy or market mechanisms to shape land-use choices is limited unless those policies are directed at local institutions. Likewise, if LUI diminishes ecosystem services and resilience, poorer agriculturalists are likely to be more affected by this loss (MEA, 2005).

Even beyond the smallholder landscape, food production is intimately linked to culture (Boogaard et al., 2008). Many food production systems have cultural values that make them important regardless of whether or not they offer the most efficient production option in terms of nutrition. These values create another constraint to the rapid transformation of agriculture towards high efficiency options, and offer another important set of values that need to be accommodated in land-use planning for biodiversity conservation.

7. Conclusions

Considering the complex choices in different landscapes and different social and economic circumstances, it might be tempting to think that conservation in production landscapes is too hard, and that one is more likely to achieve good biodiversity outcomes in other arenas. This strategy cannot succeed, however, because land-use for food and fibre now occupies more than 50% of the earth's ice-free terrestrial surface (Ellis et al., 2010). At landscape scale the potential to maintain biodiversity is greatest when productive land use is limited in extent, or when production systems mimic features of the pre-conversion ecosystem. As pressure grows to increase production we need methods that do not further increase the extent of land under production, or that diminish the contrast between the production system and the native ecosystem, or hybrids of these elements. We are always constrained by the present day starting point for a future trajectory of change, and by the social context of land use and production. By appreciating these dimensions we can better identify realistic strategies matched to the potential of each landscape.

Biodiversity conservation requires that we manage for movement of organisms or their propagules, recognizing that dispersal might be achieved by allowing permeability of the matrix (especially in low contrast landscapes) or by facilitating connection through the non-production patches (especially in high contrast landscapes: Lindenmayer and Franklin, 2002; Perfecto et al., 2009). The science challenge is to understand how this can be achieved in a production context (Fahrig et al., 2011). In heavily cleared cereals landscapes (Fig. 3), biodiversity outcomes rely on the protection and restoration of the relatively small amount of remnant vegetation in the landscape. Small landscape features, such as scattered trees can have a disproportionate benefit to biodiversity (Gibbons and Boak, 2002), with little cost in agricultural area. As long as spillover effects are managed, and some inter-patch dispersal is possible, increasing yield from the farmed land need not increase pressure on biodiversity. In less heavily cleared woodland areas there is potential to manage a mosaic that includes a matrix of woodland remnants with intensive grazing, lower impact grazing of native vegetation, and areas of annual crops, creating a landscape that supports woodland biodiversity and sustainable productive agriculture (McIntyre et al., 2002b, Fig. 1 quadrant D). By contrast, the coffee or cacao agroforestry system (Fig. 4) can provide spatially continuous biodiverse communities. Increasing yields from these systems is not a requirement for food security reasons, because the crops are not essential to human diet. Rather, the benefits come from supporting local livelihoods and in a landscape of relatively high biodiversity. In the Indian smallholder landscape (Fig. 5) production is important to local food security and the existing landscape supports significant biodiversity. Techniques for improved yield are only appropriate if they can be implemented in the smallholder context, and avoid homogenisation of the diverse landscape. Opportunities for improved human welfare come from diversification of goods and services that smallholders can sell. Of course, there are many other example landscapes, and not all of them will offer true win–win opportunities, but we argue that in each case it is likely that there are opportunities for production and biodiversity outcomes that are better than business as usual. Increased production will be achievable in some contexts, and in others it will be incompatible with good outcomes biodiversity and for local people.

There are many reasons for optimism that good regional solutions are possible, but they risk being overlooked if the solution to the food and fibre production challenge is oversimplified to a single goal, i.e. to increase yields. Maximising global human welfare should be the underlying driver, with all its attendant complexity. Forms of land-use intensification that ultimately undermine biodiversity and the ecosystem services that support agriculture will not, in the long run, meet that goal. As with any *real* global challenge, there cannot be a single recipe to solving the problem (Lindenmayer et al., 2012b). The solutions must be tailored to different landscapes, with different potential for productive land-use, different inherent capacity for biodiversity, and different human populations. Outcomes need to be assessed at the scale that really encompasses most of the costs and benefits: goods are routinely transported long distances, but biodiversity and its benefits are localised. Therefore while regionally relevant solutions are required, impacts must be understood at larger and more inclusive scales so that improved production and biodiversity outcomes in one landscape do not come at the cost of worse outcomes in another.

Acknowledgements

This work was supported by funding from CSIRO's Sustainable Agriculture Flagship. We dedicate this paper to the late Navjot Sodhi, who worked to improve conservation outcomes in Southeast Asia and globally.

References

Akinnifesi, F.K., Ajayi, O.C., Sileshi, G., Chirwa, P.W., Chianu, J., 2010. Fertiliser trees for sustainable food security in the maize-based production systems of East and Southern Africa. A review. Agron. Sustain. Dev. 30, 615–629.

Angelsen, A., Kaimowitz, D., 2001. Agricultural Technologies and Tropical Deforestation. CABI Publishing, Wallingford.

Barnosky, A.D., Matzke, N., Tomiya, S., Wogan, G.O.U., Swartz, B., Quental, T.B., Marshall, C., McGuire, J.L., Lindsey, E.L., Maguire, K.C., Merse, y.B., Ferrer, E.A., 2011. Has the Earth's sixth mass extinction already arrived? Nature 471, 51–57.

Barraquand, F., Martinet, V., 2011. Biological conservation in dynamic agricultural landscapes: effectiveness of public policies and trade-offs with agricultural production. Ecol. Econ. 70, 910–920.

Barrios, E., 2007. Soil biota, ecosystem services and land productivity. Ecol. Econ. 64, 269–285.

Baskaran, R., Cullen, R., Colombo, S., 2009. Estimating values of environmental impacts of dairy farming in New Zealand. N. Z. J. Agric. Res. 52, 377–389.

Bawa, K.S., Rai, S., Kamal, S., Chaudhary, P., 2012. Land use intensification, small landholders, and biodiversity conservation: perspectives from the eastern Himalayas. In: Lindenmayer, D.B., Cunningham, S.A., Young, A.G. (Eds.), Land Use Intensification: Effects on Agriculture, Biodiversity and Ecological Processes. CSIRO Publishing, Collingwood, pp. 65–72.

Bellard, C., Bertelsmeier, C., Leadley, P., Thuiller, W., Courchamp, F., 2012. Impacts of climate change on the future of biodiversity. Ecol. Lett. 15, 365–377.

Bommarco, R., Kleijn, D., Potts, S.G., 2013. Ecological intensification: harnessing ecosystem services for food security. Trends Ecol. Evol. 28, 230–238.

Boogaard, B.K., Oosting, S.J., Bock, B.B., 2008. Defining sustainability as a socio-cultural concept: citizen panels visiting dairy farms in the Netherlands. Livestock Sci. 117, 24–33.

Bruinsma, J., 2009. The Resource Outlook to 2050: by How Much Do Land, Water and Crop Yields Need to Increase by 2050? Food and Agriculture Organization of the United Nations, Rome, Italy.

Burger, J.R., Allen, C.D., Brown, J.H., Burnside, W.R., Davidson, A.D., Fristoe, T.S., Hamilton, M.J., Mercado-Silva, N., Nekola, J.C., Okie, J.G., Zuo, W., 2012. The macroecology of sustainability. PLoS Biol. 10 (6), e1001345.

Butchart, S.H.M., Walpole, M., Collen, B., van Strien, A., Scharlemann, J.P.W., Almond, R.E.A., Baillie, J.E.M., Bomhard, B., Brown, C., Bruno, J., Carpenter, K.E., Carr, G.M., Chanson, J., Chenery, A.M., Csirke, J., Davidson, N.C., Dentener, F., Foster, M., Galli, A., Galloway, J.N., Genovesi, P., Gregory, R.D., Hockings, M., Kapos, V., Lamarque, J.F., Leverington, F., Loh, J., McGeoch, M.A., McRae, L., Minasyan, A., Morcillo, M.H., Oldfield, T.E.E., Pauly, D., Quader, S., Revenga, C., Sauer, J.R., Skolnik, B., Spear, D., Stanwell-Smith, D., Stuart, S.N., Symes, A., Tierney, M., Tyrrell, T.D., Vie, J.C., Watson, R., 2010. Global biodiversity: indicators of recent declines. Science 328, 1164–1168.

Carson, R., 1963. Silent Spring. Hamish Hamilton, London.

Cassman, K.G., 1999. Ecological intensification of cereal production systems: yield potential, soil quality, and precision agriculture. Proc. Natl. Acad. Sci. U.S.A. 86, 5952–5959.

Clough, Y., Barkmann, J., Juhrbandt, J., Kessler, M., Wanger, T.C., Anshary, A., Buchori, D., Cicuzza, D., Darras, K., Dwi, D.P., Erasmi, S., Pitopang, R., Schmidt, C., Schulze, C.H., Seidel, D., Steffan-Dewenter, I., Stenchly, K., Vidal, S., Weist, M., Wielgoss, A.C., Tscharntke, T., 2011. Combining high biodiversity with high yields in tropical agroforests. Proc. Natl. Acad. Sci. U.S.A. 108, 8311–8316.

Cook, D.C., Fraser, R.W., Paini, D.R., Warden, A.C., Lonsdale, W.M., De Barro, P.J., 2011. Biosecurity and yield improvement technologies are strategic complements in the fight against food insecurity. PLoS ONE 6 (10), e26084.

Daily, G.C., 1997. Natures Services: Societal Dependence on Natural Ecosystems. Island Press, Washington, DC.

Driscoll, D.A., 2005. Is the matrix a sea? Habitat specificity in a naturally fragmented landscape. Ecol. Entomol. 30, 8–16.

Ellis, E.C., Goldewijk, K.K., Siebert, S., Lightman, D., Ramankutty, N., 2010. Anthropogenic transformation of the biomes, 1700 to 2000. Global Ecol. Biogeogr. 19, 589–606.

Erb, K., Krausmann, F., Gaube, V., Gingrich, S., Bondeau, A., Fischer-Kowalski, M., Haberl, H., 2009. Analyzing the global human appropriation of net primary production – processes, trajectories, implications. An introduction. Ecol. Econ. 69, 250–259.

Ewers, R.M., Scharlemann, J.P.W., Balmford, A., Green, R.E., 2009. Do increases in agricultural yield spare land for nature? Global Change Biol. 15, 1716–1726.

Fahrig, L., Baudry, J., Brotons, L., Burel, F.G., Crist, T.O., Fuller, R.J., Sirami, C., Siriwardena, G.M., Martin, J.-L., 2011. Functional landscape heterogeneity and animal biodiversity in agricultural landscapes. Ecol. Lett. 14, 101–112.

FAO (Food and Agriculture Organization), 2004. The Ethics of Sustainable Agricultural Intensification. FAO Ethics Series, vol. 3. Food and Agriculture Organization of the United Nations, Rome, Italy.

Fischer, J., Manning, A.D., Steffen, W., Rose, D.B., Daniell, K., Felton, A., Garnett, S., Gilna, B., Heinsohn, R., Lindenmayer, D.B., MacDonald, B., Mills, F., Newell, B., Reid, J., Robin, L., Sherren, K., Wade, A., 2007. Mind the sustainability gap. Trends Ecol. Evol. 22, 621–624.

Foley, J.A., DeFries, R., Asner, G.P., Barford, C., Bonan, G., Carpenter, S.R., Chapin, F.S., Coe, M.T., Daily, G.C., Gibbs, H.K., Helkowski, J.H., Holloway, T., Howard, E.A., Kucharik, C.J., Monfreda, C., Patz, J.A., Prentice, I.C., Ramankutty, N., Snyder, P.K., 2005. Global consequences of land use. Science 309, 570–574.

Foley, J.A., Ramankutty, N., Brauman, K.A., Cassidy, E.S., Gerber, J.S., Johnston, M., Mueller, N.D., O'Connell, C., Ray, D.K., West, P.C., Balzer, C., Bennett, E.M., Carpenter, S.R., Hill, J., Monfreda, C., Polasky, S., Rockström, J., Sheehan, J., Siebert, S., Tilman, D., Zaks, D.P.M., 2011. Solutions for a cultivated planet. Nature 478, 337–342.

Foresight, 2011. The Future of Food and Farming: Challenges and Choices for Global Sustainability. The Government Office for Science, London.

Garibaldi, L.A., Aizen, M.A., Klein, A.M., Cunningham, S.A., Harder, L.D., 2011. Global growth and stability of agricultural yield decrease with pollinator dependence. Proc. Natl. Acad. Sci. U.S.A. 108, 5909–5914.

Gibbons, P., Boak, M., 2002. The value of paddock trees for regional conservation in an agricultural landscape. Ecol. Manag. Restor. 3, 205–210.

Gibson, L., Lee, T.M., Koh, L.P., Brook, B.W., Gardner, T.A., Barlow, J., Peres, C.A., Bradshaw, C.J.A., Laurance, W.F., Lovejoy, T.E., Sodhi, N.S., 2011. Primary forests are irreplaceable for sustaining tropical biodiversity. Nature 478, 378–381.

Godfray, H.C.J., Beddington, J.R., Crute, I.R., Haddad, L., Lawrence, D., Muir, J.F., Pretty, J., Robinson, S., Thomas, S.M., Toulmin, C., 2010. Food security: the challenge of feeding 9 billion people. Science 327, 812–818.

Grau, H.R., Aide, T.M., Gasparri, N.I., 2005. Globalization and soybean expansion into semiarid ecosystems of Argentina. Ambio 34, 265–266.

Hall, J.A., Fleishman, E., 2010. Demonstration as a means to translate conservation science into practice. Conserv. Biol. 24, 120–127.

Herrero, M., Thornton, P.K., Notenbaert, A.M., Wood, S., Msangi, S., Freeman, H.A., Bossio, D., Dixon, J., Peters, M., van de Steeg, J., Lynam, J., Parthasarathy Rao, P., Macmillan, S., Gerard, B., McDermott, J., Seré, C., Rosegrant, M., 2010. Smart investments in sustainable food production: revisiting mixed crop-livestock systems. Science 327, 822–825.

Hodgson, J.A., Kunin, W.E., Thomas, C.D., Benton, T.G., Gabriel, D., 2010. Comparing organic farming and land sparing: optimizing yield and butterfly populations at a landscape scale. Ecol. Lett. 13, 1358–1367.

Holmes, C.W., Roche, J.R., 2007. Pastures and supplements in dairy production systems. In: Rattray, P.V., Brooks, I.M., Nicol, A.M. (Eds.), Pasture and Supplements for Grazing Animals, vol. 14. NZ Society of Animal Production, Hamilton, NZ, pp. 221–224.

Hooper, D.U., Chapin, F.S., Ewel, J.J., Hector, A., Inchausti, P., Lavorel, S., Lawton, J.H., Lodge, D.M., Loreau, M., Naeem, S., Schmid, B., Setala, H., Symstad, A.J., Vandermeer, J., Wardle, D.A., 2005. Effects of biodiversity on ecosystem functioning: a consensus of current knowledge. Ecol. Monogr. 75, 3–35.

Kangalawe, R.Y.M., Noe, C., 2012. Biodiversity conservation and poverty alleviation in Namtumbo District, Tanzania. Agric. Ecoyst. Environ. 162, 90–100.

Kleijn, D., Kohler, F., Baldi, A., Batary, P., Concepcion, E.D., Clough, Y., Diaz, M., Gabriel, D., Holzschuh, A., Knop, E., Kovacs, A., Marshall, E.J.P., Tscharntke, T., Verhulst, J., 2009. On the relationship between farmland biodiversity and land-use intensity in Europe. Proc. R. Soc. B 276, 903–909.

Koh, L.P., Wilcove, D.S., 2007. Cashing in palm oil for conservation. Nature 448, 993–994.

Krebs, J.R., Wilson, J.D., Bradbury, R.B., Siriwardena, G.M., 1999. The second silent spring? Nature 400, 611–612.

Lindenmayer, D.B., Cunningham, S.A., Young, A.G. (Eds.), 2012b. Land Use Intensification: Effects on Agriculture, Biodiversity and Ecological Processes. CSIRO Publishing, Collingwood.

Lindenmayer, D.B., Franklin, J.K., 2002. Conserving Forest Biodiversity: A Comprehensive Multiscaled Approach. Island Press, Washington, DC.

Lindenmayer, D.B., Gibbons, P., Bourke, M., Burgman, M., Dickman, C.R., Ferrier, S., Fitzsimons, J., Freudenberger, D., Garnett, S.T., Groves, C., Hobbs, R.J., Kingsford, R.T., Krebs, C., Legge, S., Lowe, A.J., McLean, R., Montambault, J., Possingham, H., Radford, J., Robinson, D., Smallbone, L., Thomas, D., Varcoe, T., Vardon, M., Wardle, G., Woinarski, J., Zerger, A., 2012a. Improving biodiversity monitoring. Austral. Ecol. 37, 285–294.

Lobell, D.B., Cassman, K.G., Field, C.B., 2009. Crop yield gaps: their importance, magnitudes, and causes. Annu. Rev. Environ. Resour. 334, 1–26.

Matson, P.A., Vitousek, P.M., 2006. Agricultural intensification: will land spared from farming be land spared for nature? Conserv. Biol. 20, 709–710.

Matthews, E., 1983. Global vegetation and land use: new high-resolution data bases for climate studies. J. Clim. Appl. Meteorol. 22, 474–487.

McIntyre, S., Heard, K.M., Martin, T.G., 2002a. How grassland plants are distributed over five human-created habitats typical of eucalypt woodlands in a variegated landscape. Pac. Conserv. Biol. 7, 274–285.

McIntyre, S., McIvor, J.G., Heard, K.M. (Eds.), 2002b. Managing and Conserving Grassy Woodlands. CSIRO Publishing, Collingwood.

MEA (Millennium Ecosystem Assessment), 2005. Ecosystems and Human Well-being: Synthesis. Island Press, Washington, DC.

Mediene, S., Valantin-Morison, M., Sarthou, J.P., de Tourdonnet, S., Gosme, M., Bertrand, M., Roger-Estrade, J., Aubertot, J.N., Rusch, A., Motisi, N., Pelosi, C., Dore, T., 2011. Agroecosystem management and biotic interactions: a review. Agron. Sust. Dev. 31, 491–514.

Moller, H., MacLeod, C.J., Haggerty, J., Rosin, C., Blackwell, G., Perley, C., Meadows, S., Weller, F., Gradwol, M., 2008. Intensification of New Zealand agriculture: implications for biodiversity. N. Z. J. Agric. Res. 51, 253–263.

Naeem, S., Bunker, D.E., Hector, A., Loreau, M., Perrings, C. (Eds.), 2009. Biodiversity, Ecosystem Functioning, and Human Wellbeing. Oxford University Press, New York.

Pelosi, C., Goulard, M., Balent, G., 2010. The spatial scale mismatch between ecological processes and agricultural management: do difficulties come from underlying theoretical frameworks? Agric. Ecosyst. Environ. 139, 455–462.

Perfecto, I., Rice, R.A., Greenberg, R., VanderVoort, M.E., 1996. Shade coffee: a disappearing refuge for biodiversity. Bioscience 46, 598–608.

Perfecto, I., Vandermeer, J., 2008. Biodiversity conservation in tropical agroecosystems: a new conservation paradigm. Ann. N. Y. Acad. Sci. 1134, 173–200.

Perfecto, I., Vandermeer, J., Mas, A., Pinto, L.S., 2005. Biodiversity, yield, and shade coffee certification. Ecol. Econ. 54, 435–446.

Perfecto, I., Vandermeer, J., Wright, A., 2009. Nature's Matrix: Linking Agriculture, Conservation and Food Sovereignty. Earthscan, London.

Phalan, B., Onial, M., Balmford, A., Green, R.E., 2011. Reconciling food production and biodiversity conservation: land sharing and land sparing compared. Science 333, 1289–1291.

Polasky, S., Nelson, E., Camm, J., Csuti, B., Fackler, P., Lonsdorf, E., Montgomery, C., White, D., Arthur, J., Garber-Yonts, B., Haight, R., Kagan, J., Starfield, A., Tobalske, C., 2008. Where to put things? Spatial land management to sustain biodiversity and economic returns. Biol. Conserv. 141, 1505–1524.

Pretty, J., 2008. Agricultural sustainability: concepts, principles and evidence. Philos. Trans. R. Soc. B 363, 447–465.

Rand, T.A., Tylianakis, J.M., Tscharntke, T., 2006. Spillover edge effects: the dispersal of agriculturally subsidized insect natural enemies into adjacent natural habitats. Ecol. Lett. 9, 603–614.

Rands, M.R.W., Adams, W.M., Bennun, L., Butchart, S.H.M., Clements, A., Coomes, D., Entwistle, A., Hodge, I., Kapos, V., Scharlemann, J.P.W., Sutherland, W.J., Vira, B., 2010. Biodiversity conservation: challenges beyond 2010. Science 329, 1298–1303.

Reganold, J.P., Jackson-Smith, D., Batie, S.S., Harwood, R.R., Kornegay, J.L., Bucks, D., Flora, C.B., Hanson, J.C., Jury, W.A., Meyer, D., Schumacher Jr., A., Sehmsdorf, H., Shennan, C., Thrupp, L.A., Willis, P., 2011. Transforming U.S. agriculture. Science 332, 670–671.

Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin, F.S., Lambin, E.F., Lenton, T.M., Scheffer, M., Folke, C., Schellnhuber, H.J., Nykvist, B., de Wit, C.A., Hughes, T., van der Leeuw, S., Rodhe, H., Sörlin, S., Snyder, P.K., Costanza, R., Svedin, U., Falkenmark, M., Karlberg, L., Corell, R.W., Fabry, V.J., Hansen, J., Walker, B., Liverman, D., Richardson, K., Crutzen, P., Foley, J.A., 2009. A safe operating space for humanity. Nature 461, 472–475.

Secretariat of the Convention on Biological Diversity (SCBD), 2010. Global Biodiversity Outlook 3. SCBD, Montréal.

Sivertsen, D., Metcalfe, L., 1995. Natural vegetation of the southern wheat belt. Cunninghamia 4, 103–128.

Thompson, I.D., Okabe, K., Tylianakis, J.M., Kumar, P., Brockerhoff, E.G., Schellhorn, N.A., Parrotta, J.A., Nasi, R., 2011. Forest biodiversity and the delivery of ecosystem goods and services: translating science into policy. Bioscience 61, 972–981.

Tilman, D., 1999. Global environmental impacts of agricultural expansion: the need for sustainable and efficient practices. Proc. Natl. Acad. Sci. U.S.A. 96, 5995–6000.

Tilman, D., Cassman, K.G., Matson, P.A., Naylor, R., Polasky, S., 2002. Agricultural sustainability and intensive production practices. Nature 418, 671–677.

Tscharntke, T., Clough, Y., Bhagwat, S.A., Buchori, D., Faust, H., Hertel, D., Holscher, D., Juhrbandt, J., Kessler, M., Perfecto, I., Scherber, C., Schroth, G., Veldkamp, E., Wanger, T.C., 2011. Multifunctional shade-tree management in tropical agroforestry – a review. J. Appl. Ecol. 48, 619–629.

Tscharntke, T., Clough, Y., Wanger, T.C., Jackson, L., Motzke, I., Perfecto, I., Vandermeer, J., Whitbread, A., 2012. Global food security, biodiversity conservation and the future of agricultural intensification. Biol. Conserv. 151, 53–59.

Vandermeer, J., Perfecto, I., Philpott, S., 2010. Ecological complexity and pest control in organic coffee production: uncovering an autonomous ecosystem service. Bioscience 60, 527–537.

West, T.O., Marland, G., 2002. A synthesis of carbon sequestration, carbon emissions, and net carbon flux in agriculture: comparing tillage practices in the United States. Agric. Ecosyst. Environ. 91, 1–3.

Wood, A., 2000. An emerging consensus on biodiversity loss. In: Wood, A., Stedman-Edwards, P., Mang, J. (Eds.), The Root Causes of Biodiversity Loss. Earthscan, London, pp. 1–10.

World Bank, 2007. World Development Report 2008: Agriculture for Development. World Bank, Washington.

Young, A., 1999. Is there really spare land? A critique of estimates of available cultivable land in developing countries. Environ. Dev. Sustain. 1, 3–18.