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REVIEW

Towards environmentally sustainable agriculture in Brazil: challenges and opportunities for applied ecological research

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Summary

1. Brazil is one of the world's major producers of food and biofuels. Agricultural expansion has driven rapid economic development but has also had major impacts on biodiversity and the conservation of ecosystem services in the country.

2. Here, we analyse recent advances in applied ecological research on the consequences of agricultural expansion for biodiversity in Brazil, identify knowledge gaps, and discuss how ecological science can help guide the development of more sustainable agricultural systems.

3. The majority of native vegetation in Brazilian biomes is found within private lands, emphasizing the importance of recent reforms to the Brazilian Forest Act legislation. Using the example of the Forest Act, we critically assess the extent to which ecological research has provided guidance for policy decisions to date. We identify important knowledge gaps regarding the ecological impacts of agricultural expansion in Brazil and the general disconnection between ecological science and environmental policy processes.

4. *Synthesis and applications*. Increased efforts are needed from both researchers and policy makers to engage from the earliest stage possible in the identification, assessment and communication of environmental issues and possible management solutions. Narrowing the gap between research and policy is essential if the academic community is to capitalize effectively on recent governmental investments in research and provide the necessary evidence basis for reconciling agricultural production and environmental conservation in Brazil.

Key-words: Brazilian Forest Act, environmental policy, science-policy gap, tropical biodiversity

Introduction

Brazil exemplifies the global tension between biodiversity conservation and economic growth. It is both a mega-diverse country holding *c.* 1·8 million species (Lewinsohn & Prado 2005), and one of the world's leading agricultural producers (FAO 2012), playing an increasingly important role in the global challenge to supply a growing and more affluent human population (Foley *et al.* 2011).

The 'miraculous' expansion of Brazilian agriculture (The Economist 2010) has been at the centre of Brazil's recent economic growth, corresponding to 28% of the nation's total exports (FAO 2012). However, there are rising concerns about the threats that these changes represent to Brazil's globally sig-

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nificant biological wealth, including widespread deforestation and clearance of native vegetation (e.g. Sano *et al.* 2010), and rapid increases in the use of fertilizers, pesticides and other agricultural chemical supplies (Martinelli *et al.* 2010; Schiesari & Grillitsch 2011).

The urgent need to reconcile the goals of agricultural production and environmental conservation has attracted increased attention in recent years, offering new opportunities for the development of more sustainable approaches to agriculture – an area where Brazil has the potential to play a world-leading role (Martinelli *et al.* 2010). Here, we present a brief overview of the main consequences of agricultural expansion for biodiversity, assess known impacts and highlight important remaining knowledge gaps. We then use a benchmark example of the science-policy interface – the ongoing revision of the Brazilian legislation for the protection of natural vegetation in private landholdings (Brazilian Forest Act) – to explore in more detail the extent to which ecological research has thus far been applied to help guide policy and land-management decisions. We finish by reflecting on the future prospects for applied ecology in Brazil and make recommendations to help Brazilian science capitalize on recent increases in research funding.

Environmental consequences of agricultural expansion in Brazil: key findings and knowledge gaps

HABITAT CONVERSION AND LAND-USE CHANGE

About one-third of Brazilian territory has already been converted for agricultural production (Fig. 1; Sparovek *et al.* 2010). Three of the six terrestrial biomes (Cerrado, Pampas and Caatinga) have lost at least 50% of their natural habitats (MMA 2012), and one of the forested biomes – the coastal Atlantic Forest – has lost 88% of its native vegetation (Ribeiro *et al.* 2009). Habitat degradation in the remaining areas (e.g. through unsustainable logging and fire) represents a significant, yet often overlooked threat to the integrity of all biomes (e.g. Asner *et al.* 2005; Leal *et al.* 2005; Overbeck *et al.* 2007; Sano *et al.* 2010; Santos *et al.* 2011).

Fig. 1. Conversion of natural vegetation to agriculture for each terrestrial Brazilian biome. We have no data for the island of Marajó at the mouth of the Amazon, which is classified as water. Source: Sparovek *et al.* 2010.

The expansion of agriculture across all Brazilian biomes has led to a consistent decline in native vegetation irrespective of differences in the legal requirement for protection of private lands as determined by the Forest Act (i.e. 80% set aside for rural properties in the Amazon; 35% in the Cerrado located in the Legal Amazon region and 20% in the Cerrado and all remaining biomes) (Fig. 2). Moreover, the protection of native vegetation in public reserves is consistently low outside the Amazon and below 5% for most biomes (Fig. 2). It is striking to note that the majority of native vegetation in each Brazilian biome is still found on private lands (Fig. 2), clearly demonstrating the importance of the Forest Act legislation.

IMPACTS OF AGRICULTURAL EXPANSION ON BIODIVERSITY

One of the most important ecological impacts of agricultural expansion is the loss and fragmentation of natural habitats, which leads to the reduction and isolation of native populations, increasing their risk of extinction (Ewers & Didham 2006). This trend has been consistently reported in studies from different Brazilian biomes (e.g. Carvalho, De Marco & Ferreira 2009; Peres *et al.* 2010) causing the local extinction of native species, a loss of alpha and gamma diversity, the expansion of generalist, edge-tolerant and exotic species, with consequent changes in biological interactions (e.g. pollination, seed dispersal) and key ecological processes (Tabarelli, Lopes & Peres 2008; Pardini *et al.* 2010). For instance, the reduction in area of the Atlantic forest and the Cerrado is estimated to have caused the loss of at least 20 thousand specialized herbivores that feed on endemic plants (Fonseca 2009).

Agriculture already consumes about 55% of the current water use in Brazil, even though $<10\%$ of the cultivated area is currently irrigated (ANA 2007; FAOSTAT 2012). Infrastructure projects have been proposed to address problems of water supply through dams and inter-basin water transfer, both of which can exacerbate biodiversity impacts. Conversion of riparian habitats has driven marked (yet poorly quantified) changes in aquatic biodiversity, causing population declines and local extinctions of fauna (Becker *et al.* 2007) and a widespread increase in generalist and/or alien species such as the guppy *Poecilia reticulata* (Casatti, de Ferreira & Carvalho 2009).

Local impacts on forest biodiversity can often be partially mitigated by retaining forest cover in plantations (Barlow *et al.* 2007; Fonseca *et al.* 2009) or agroforestry such as cocoa *Theobroma cacao* (Pardini *et al.* 2009). Nevertheless, efforts to retain biodiversity in modified landscapes are heavily dependent on the wider landscape context, ecological connectivity and the proximity of source populations (Pardini *et al.* 2010).

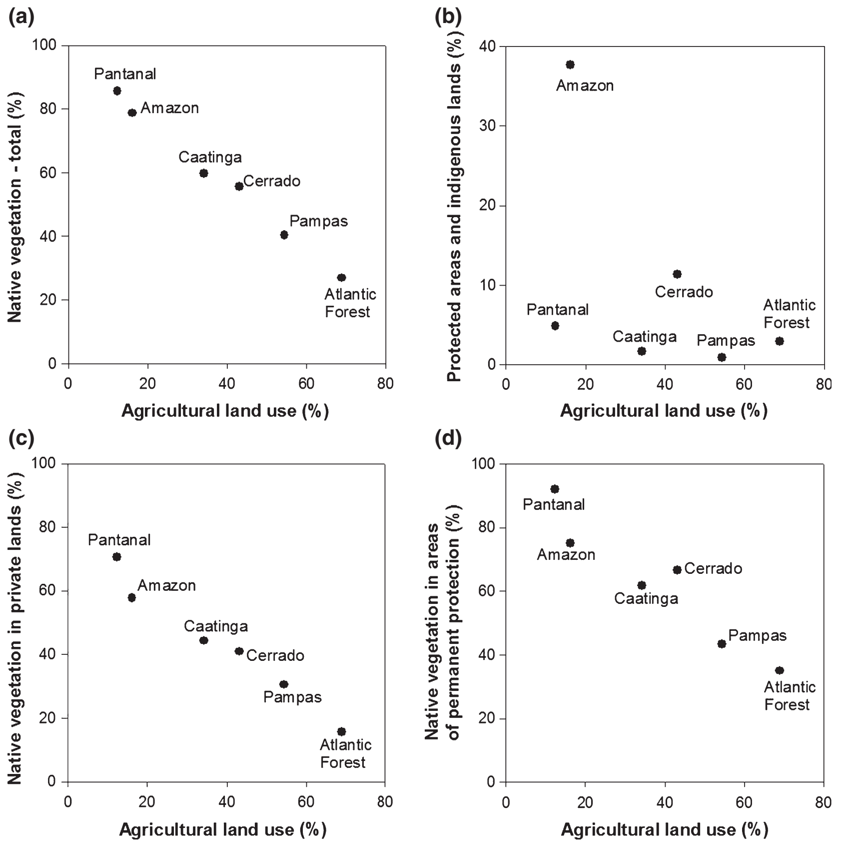

Fig. 2. Relationship between the proportion of agricultural land in each of Brazil's six terrestrial biomes and different conservation measures, including percentage of the total area of the biome covered by native vegetation (a); percentage of the total area of the biome covered by protected areas (IUCN categories I–VI) and indigenous lands (b); percentage of the private lands (excluding areas of permanent protection) covered by native vegetation (c); and percentage of the areas of permanent protection (APP, including riparian vegetation, slopes $> 45°$ and hilltops areas) covered by native vegetation (d).

Biological invasion is estimated to be the second most important cause of biodiversity loss worldwide (Sax, Stachowicz & Gaines 2005), and Brazil is no exception. By the end of the last millennium, at least 11,605 plant species had been introduced to Brazil, representing one-fifth of the native flora (Pimentel *et al.* 2001). Exotic, invasive species, commonly distributed by agricultural practices, are present throughout the country but are particularly widespread in the non-forest biomes. For example, a single unpalatable grass, *Eragrostis plana*, has invaded more than one million hectares of natural and managed grasslands in the Brazilian Pampas (Medeiros & Focht 2007). The a *priori* identification of invasion risks is important for controlling invasive species, and Brazil can learn from pioneering work undertaken elsewhere (e.g. Dehnen-Schmutz 2011; Essl *et al.* 2011). Encouragingly, a national initiative linked to the I3N Global Invasive Species Programme has started to provide information on both risk assessment and control protocols in Brazil (http://i3n.institutohorus.org.br/www/).

KNOWLEDGE GAPS

Whilst much has been learnt about general patterns of biodiversity response to agricultural expansion, important knowledge gaps remain. For example, insufficient work has been done on the impacts of air, soil and water pollution from pesticides, although such impacts can greatly exacerbate the effects of habitat loss and fragmentation (Laurance & Peres 2006). The impact of invasive species on native biodiversity has also largely been overlooked in Brazil (Almeida-Neto *et al.* 2010).

There is a critical lack of research on the ecological impacts of agriculture on aquatic systems, which has driven the loss and degradation of significant areas of instream habitat (Marques *et al.* 2004). Scientific guidance on acceptable limits for water diversion is currently based on hydrological criteria alone (ANA 2007), and attempts to improve guidelines with ecological information are limited by the scarcity of biotic data (e.g. Leal, Junqueira & Pompeu 2011).

There is a scarcity of work on the biodiversity impacts of different pasture systems and other short rotation crops, despite the fact that they dominate agricultural landscapes (but see Almeida *et al.* 2011). This lack of information is particularly worrying given the rapid advance of commodity crops such as soybeans *Glycine max* in the Cerrado and elsewhere (Carvalho, De Marco & Ferreira 2009; Feltran-Barbieri, Abramovay & Metzger 2011). Moreover, much more work is needed to assess the effectiveness of management practices that are claimed to be environmentally friendly.

We still have a very poor understanding of how biodiversity responds to landscape-scale changes, and biological flows across mosaics of habitat remnants and agricultural areas (Gardner *et al.* 2009). Recent work in tropical countries has suggested that in some situations higher yielding agriculture that requires less land for production (thereby 'sparing' land for conservation) can be more effective at conserving biodiversity than lower yielding, supposedly environmentally friendly production systems across larger areas (Green *et al.* 2005; Phalan *et al.* 2011). However, in both cases, a landscape ecology perspective, incorporating native forest remnants and corridors, is necessary to maintain ecological connectivity among conservation areas at a regional scale (Gardner *et al.* 2009). Understanding the potential of intensification and yield increases as a strategy for sustainable agricultural development is a key research challenge, especially in the light of the rapid expansion of more intensive farming systems across the country.

Another important knowledge gap relates to the scale of studies. Most studies of biodiversity in agricultural landscapes have focused on only one taxonomic group (most commonly birds, large mammals or trees), are largely limited to a small number of research sites and typically encompass only a small period of time (Gardner *et al.* 2009). In addition, the majority of biodiversity work in Brazilian ecosystems to date has been limited to relatively simple descriptions of biotic communities (e.g. species richness, composition and diversity), with far less work on biodiversity-mediated changes in ecological functions and processes. There has been a recent surge of global research interest on the importance of functional diversity, and its links with ecosystem processes (Cadotte, Carscadden & Mirotchnick 2011). Understanding these key biodiversity-ecosystem function relationships remains critical to assessments of the overall ecological resilience of modified systems and generation of scientifically credible best practice recommendations.

Finally, much more work is needed to improve our understanding of the interconnections between biodiversity loss, the degradation of ecosystem services and human well-being. Identifying socio-ecological feedbacks from land-use change is essential for understanding likely trajectories of different development pathways to appropriately inform policy decisions.

Linking ecological research and policy for sustainable agriculture in Brazil: The case of Brazilian environmental legislation on private lands

A primary function of applied ecological research is to contribute towards the development of policy frameworks that can guide more sustainable social and ecological systems (Carpenter & Folke 2006). A number of issues, however, are commonly identified as preventing the connection between science and practice (Pardini *et al.* In press). Here, we consider the interface between ecological research and application in the context of the Brazilian Forest Act, which is the foremost environmental legislation in Brazil responsible for regulating private land use. The Brazilian Forest Act dates from 1934, underwent a major revision in 1965 and was then submitted to successive changes in 1986, 1989, 1996, 2001 and 2005 (Sparovek *et al.* 2010). One of the most important changes relates to the amount of set aside area that is required on private land [Legal Reserve (LR)], including in 1996, when the LR area for properties in the Amazon region was increased from 50% to 80%, retrospectively placing a large number of properties outside limits for legal compliance.

Since July 2010, the Forest Act has been subjected to a major and controversial revision. At the time of writing, it is in the final stages of such reform in the Brazilian congress (Metzger *et al.* 2010; Nazareno 2012) – a process that has raised serious concerns regarding the future of Brazilian ecosystems with reforms having the potential to remove legal protection from an additional 220,000 km^2 of forest in private farmland (Sparovek *et al.* 2010).

Considering the impact of the proposed changes in the Forest Act, we evaluated the role that applied ecology has played in helping to guide the decision-making process thus far. Despite the Forest Act representing an active political issue since the 1980s, prior to 2010 few publications have explicitly focused on the environmental consequences of this legislation. Whilst some spatial modelling studies have assessed the implications of different approaches to achieving (or failing to achieve) legal compliance (e.g. Lourival *et al.* 2008; Sparovek *et al.* 2010), very little primary research has directly assessed the ecological implications of such choices. By comparison, there has been a wealth of studies on topics that are broadly relevant to conservation in managed landscapes, such as the management of forest corridors, landscape connectivity and fragmentation. These findings were reviewed by Metzger (2010), who showed for the first time how existing research could be used to support or refute different aspects of the legislation.

Following Metzger (2010), Brazil's academic community attempted to inform the debate through a series of publications in a special edition of the Brazilian *Biota Neotropica* journal (e.g. Develey & Pongiluppi 2010 and a series of other articles in this special issue). The Brazilian Society for Progress of Science (SBPC) and Brazilian Science Academy (ABC) produced a review outlining the ecological consequences of the proposed changes shortly before voting on the Forest Act in parliament (Silva *et al.* 2011).

Despite these efforts, most scientists in Brazil believe that scientific evidence has been largely ignored during the revision of the Forest Act (SBPC/ABC 2011), providing a conclusive example of the disconnection between Brazilian science and policy (see also Scarano & Martinelli 2010) similar to that reported elsewhere (Knight *et al.* 2008). The debate around the Forest Act is only one example of this disconnection in Brazil. The largest research network ever developed in the country – the 'Large-Scale Biosphere Atmosphere experiment in Amazonia, LBA' – has also had relatively little impact on environmental policy decisions (Lahsen 2009). We found no record of the programme having directly influenced national decision-making processes, despite producing over 2000 scientific articles, more than 200 PhDs and nearly 300 master degrees

(Artaxo 2012). However, the LBA may have had an important impact by increasing both scientific capacity and the public awareness of Amazonian environmental issues in Brazil and internationally (Lahsen & Nobre 2007).

These examples demonstrate the value of improving the engagement and communication between scientists and policy makers (Forbes 2011). A second synthesis document on the Forest Act debate produced by the SBPC/ABC (2011) responded to this by providing clearer and more accessible recommendations to legislators on specific questions regarding the Act. Whilst the first SBPC/ABC publication (Silva *et al.* 2011) provided a very detailed scientific review of related themes, the second report was more strictly focused on providing scientific evidence and associated recommendations regarding each one of the proposed changes in the legislation reform. Although the impact of these recommendations on the final structuring of the law has thus far been minimal, this failure is best explained by the flawed political process that led to evidence being disregarded from the final stages of negotiations rather than a lack of scientific evidence *per se*.

Although ecological research has so far contributed little to the Forest Act, there are more positive examples. At a national level, the process of creating conservation reserves has included significant input from the science community on environmental and social criteria in planning the expansion of the protected area network (http://www.mma.gov.br). In a similar way, the BIOTA-FAPESP programme on biodiversity conservation research in the state of São Paulo has had an important influence on state environmental legislation – with research underpinning four governmental decrees and 11 resolutions (Joly *et al.* 2010). BIOTA's success has been ascribed to the networks' efforts to synthesize data for public-policy-making and state-level demand, as well as the political will to take notice of scientific based conservation evidence (Joly *et al.* 2010). Guaranteeing the persistence of Brazil's rich ecological heritage urgently requires more examples like this, with engagement at the local, state and federal levels from the start of the process, including in the initial process of selecting applied research questions (Sutherland *et al.* 2011).

Future prospects for applied ecology in Brazil

Reconciling agricultural production and environmental conservation is one of the greatest challenges currently facing Brazil, and we believe that effective applied ecological science can play a key role in achieving this goal. The debate around the reform of the Forest Act has set the stage for a more critical and constructive evaluation of the role played by ecologists in the environmental policy process. To develop a truly applied ecology, we need to tailor efforts to the most important environmental challenges facing the country.

A wealth of opportunities has been created by massive government investments in Brazilian universities and research programmes during the last two decades (Regalado 2010). Ecological science is not an exception: there has been an exponential increase in the number of graduate courses in Ecology (from three in 1976 to 37 in 2010; Capes 2011), as well as in the number, and to a lesser extent, the impact of ecological papers published by Brazilian researchers in scientific journals indexed in Thomson ISI© (New York, NY, USA). Brazilian research in Ecology and Environment is ranked 14th in number of papers and 20th in number of citations among nations (Scarano 2008; Capes 2011). The recent creation of Professional MSc courses in applied ecology and natural resource management across the country is a particularly encouraging indicator of genuine efforts to improve the connection between ecological knowledge and environmental decision-making (Pardini *et al.* in press). Different from Academic MSc courses, these Professional courses focus on the training of people who already work, or intend to work, as practitioners and decision-makers in public and private institutions and companies. In doing so, these courses improve the connection between high-quality scientific knowledge and decision-making and bring practical conservation and management problems to classrooms and universities (Scarano & Oliveira 2005; Pardini *et al.* in press). Some progress has also been made to include public outreach and societal engagement in the evaluation of graduate courses and researcher performance in general (Pardini *et al.* in press), as well as through the creation of research networks, such as the National Institutes of Science and Technology Program launched by the Brazilian National Science Council in 2008.

These opportunities must be set in the context of the immense challenges faced by Brazil, which include the limited baseline and historical data on ecosystems, the lag period necessary to expand the cohort of scientists trained in the application of research to policy, and the inadequate communication of this knowledge to other societal sectors. These challenges are not surprising given the size of the country, the varied, rich and complex ecosystems it harbours, and the relatively young age of Brazilian ecological research (the first graduate course was established 36 years ago).

The ability of the Brazilian ecological research community to tackle these challenges effectively and contribute towards environmental policy will be improved if the research process is able to deal with the multifaceted nature of political issues (Carpenter *et al.* 2009), to be more targeted towards real-world problems (Sutherland *et al.* 2011), as well as better synthesized (Pullin, Knight & Watkinson 2009) and communicated (Pardini *et al.* in press). Experiences involving the use of scientific knowledge to guide environmental policy and decision-making in Brazil are few and recent and often assume a unidirectional transfer from academia to decision-makers. Future attempts to incorporate science in Brazilian decision-making should aim to be more interactive, engaging earlier with multiple stakeholders and the end-users of the science. This could be achieved by encouraging collaborations among students, researchers and decision-makers and helping educate students about both scientific and practical knowledge (e.g. Pardini *et al.* in press).

Conclusion

Reconciling agricultural production and environmental conservation is one of the most critical and urgent issues currently facing ecological science in Brazil. We have identified important knowledge gaps that urgently need to be addressed if we are to provide a thorough assessment of the ecological implications of agricultural expansion and better orient policy decisions. Furthermore, we show how existing ecological knowledge could make an important contribution to guiding policy and planning if appropriately synthesized and presented. However, there is little evidence of such contributions having been made at a national level, which is mainly owing to a lack of adequate engagement from both ecologists and policy makers. To capitalize on recent Brazilian government investments in research, both individuals and institutions need to engage actively in the identification, assessment and communication of environmental issues and solutions. Hopefully, the concerted efforts to engage in the debates around the reform of the Forest Act during the last 2 years provide a clear indication that a new form of science-policy dialogue around the future of sustainable agriculture in Brazil is possible.

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