PROCEEDINGS OF THE ROYAL SOCIETY B

Proc. R. Soc. B (2012) **279**, 2714–2724
doi:10.1098/rspb.2012.0515
Published online 25 April 2012

Perspective

What conservationists need to know about farming

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Farming is the basis of our civilization yet is more damaging to wild nature than any other sector of human activity. Here, we propose that in order to limit its impact into the future, conservation researchers and practitioners need to address several big topics—about the scale of future demand, about which crops and livestock to study, about whether low-yield or high-yield farming has the potential to be least harmful to nature, about the environmental performance of new and existing farming methods, and about the measures needed to enable promising approaches and techniques to deliver on their potential. Tackling these issues requires conservationists to explore the many consequences that decisions about agriculture have beyond the farm, to think broadly and imaginatively about the scale and scope of what is required to halt biodiversity loss, and to be brave enough to test and when necessary support counterintuitive measures.

Keywords: conservation; farming; ecosystem services; biodiversity

1. INTRODUCTION

Farming—to produce food crops, animal feed, meat, eggs, milk, fibres and biofuels—has transformed the Earth's capacity to support people but at the same time had a greater impact on the rest of biological diversity than any other human activity. Cropland and permanent pasture cover an estimated 12 per cent and 26 per cent of ice-free land, respectively [1], and affect a larger area still [2]. Agriculture is by far the leading cause of deforestation in the tropics [3] and has already replaced around 70 per cent of the world's grasslands, 50 per cent of savannahs and 45 per cent of temperate deciduous forest [1,4].

Beyond land conversion, inorganic inputs to farming through the Haber–Bosch process are the main reason why rates of nitrogen fixation have doubled in a century [5]. Agriculture is responsible for roughly 70 per cent of freshwater withdrawals and around one-third of greenhouse gas emissions [1], and threatens more species with extinction than any other sector [6]. Furthermore, despite some high profile mitigation attempts (not least as part of the European Union's programme of agri-environment payments, now worth approx. €5B per year; [7]), rising demand means these unintended impacts of farming are still growing. Thus, conversion of forest was the main source of new cropland in the tropics during the 1980s and 1990s [8,9], while in South Africa the recent expansion of just one minor but fashionable crop—rooibos tea—has been responsible for 112 plant taxa becoming threatened with extinction in just 12 years [10].

For all these reasons, conservation practitioners and researchers need to think seriously about the consequences of farming for biodiversity and ecosystem services. To generate clear insights, they also need to be explicit about what it is they want to conserve—whether that's particular species, communities or services, and whether their interest lies only in what happens on farmland *per se* or in the consequences of agricultural practices for species or ecosystems on non-farmed land as well. Some researchers working in this area focus on events on agricultural land [7,11,12]. In contrast, because farming is not a closed system our work (and this review) extends to the impact that farming decisions are likely to have on the conservation value of currently non-farmed land. Specifically, we are interested in how to retain (or indeed restore) as much of an entire region's native biodiversity and the services it provides as possible while simultaneously meeting demand for agricultural products. As such we are concerned not just with on-farm impacts, but with the consequences of choices about farming for as-yet unfarmed, relatively intact land. This in turn requires thinking about overall demand for farm products, and about how decisions that alter farm yields (i.e. production per unit area) influence the total area used for agriculture.

This study is an attempt to identify five major issues that arise when viewing farming through this lens, where we think a step-change in understanding is needed if the impact of farming on wild nature is to be mitigated. Present understanding is limited and will anyway need re-examining as climate, water availability and patterns of economic growth and demand alter. Our list deals in turn with the drivers underpinning farming, with the specific threats it poses, with an overarching framework for identifying how to limit negative impacts, with evaluating specific agricultural practices, and with developing farming policy (in its broadest sense) so as to enable promising approaches to flourish. In setting out these topics, we have considered them in the context of the cultivation of crops, livestock, animal feed and biofuels, but similar questions could usefully be asked for related activities such as production and harvesting of wood, fish and other natural products.

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† An invited Perspective to mark the election of the author to the fellowship of the Royal Society in 2011.

Received 6 March 2012
Accepted 5 April 2012

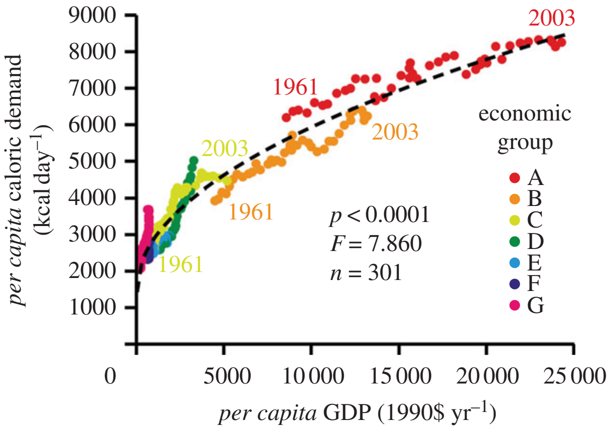

Figure 1. The relationship between *per capita* demand for crop calories and *per capita* gross domestic product (GDP) from 1961 to 2003, for groups of countries ordered from richest (A) to poorest (G). The curve is fitted to the square root of *per capita* GDP. From Tilman *et al.* [14].

2. TOPIC 1. UNDERSTANDING FUTURE DEMAND

The scale and diversity of the effects of farming on wild nature means that even if demand was unchanging it would be imperative for conservation researchers to explore ways to reduce its impact. However, food demand is clearly expanding. The United Nations' Food and Agriculture Organization (FAO) reckons, based on expert assessment of national and regional trends, that demand will rise by 70 per cent worldwide between 2005 and 2050 [13]. A recent global analysis combining statistically compelling relationships between observed trends in *per capita* demand and wealth with forecasts for economic and population growth suggests this may be a substantial underestimate, with demand for food calories and protein both predicted to increase by 100–110% over the same interval [14] (figure 1).

Of course much could be done to address the issue of food insecurity in developing countries without increasing production. Getting more (and more nutritious) food to the billion or more people who go to bed hungry or undernourished each night has more to do with governance, distribution, food prices and protecting local food production than it does with raising overall levels of farming output [13,15,16]. It is also important to take measures to limit over-consumption, and to recognize that some growth in global food demand could be met by efforts to reduce post-harvest waste, which runs at about 30–40% of production [1,17,18]. However, even if food security is improved, unnecessary demand curbed and waste reduced, it seems implausible that agricultural production will not rise very substantially over the next half century [14,19,20] (cf. [21]).

The main drivers of this scaling up are population growth and rapidly rising *per capita* demand—for non-food crops such as rubber and biofuels [22,23] and in particular the shift, as people become more prosperous, from largely vegetarian diets dominated by staple crops to far greater consumption of meat, dairy products and eggs. The world's human population looks likely to rise from just over 7 billion today to more than 9 billion by 2050 [24]. On the basis of recent trends, livestock numbers are likely to grow even faster: since 1961, worldwide chicken numbers have risen more than fourfold, and in China *per capita* meat consumption has increased from 4 to 54 kg per year (compared with 80 kg per person per year in the UK; [19,25,26]). These patterns look set to continue. For example, commercially motivated attempts to reverse lactose intolerance in China by carefully targeted marketing campaigns have the potential to radically increase demand for dairy products in the world's most populous nation [27].

These dietary changes have profound environmental implications because typically far more land, nutrients and water are needed, and more nitrous oxide and methane emitted when a unit of food energy or protein for human consumption is produced via an animal than direct from a plant [28,29]. Rearing livestock on crop residues or other waste products can reduce these costs and make a net contribution to global food supply [28,30]. Nevertheless, the current disproportionate growth in livestock numbers is being achieved in large part by using rangelands (at a cost, often, to native biodiversity [31]) and by using fertile croplands to produce animal feed [1]. Moreover, these effects of rising *per capita* demand for livestock products are compounded by increased production of non-staple crops such as coffee, tea, flowers and luxury vegetables (more of which tend to be grown as countries' yield of staples increases [32]).

Taken together, the magnitude and rapidity of these changes in demand underscore the importance of conservation researchers and practitioners anticipating how agriculture is likely to change, examining where these changes are most likely to happen (especially in relation to priority areas for conservation—[33,34]), and having sufficiently broad understanding of farming to be able to devise ways to limit their impact. So which farm products should conservationists know most about?

3. TOPIC 2. TARGETING RESEARCH TO THE FARM PRODUCTS THAT MATTER MOST

Which crops are likely to have the largest impact on biodiversity conservation? An initial indication can be gained by identifying those crops that cover the greatest land area and those whose area is increasing most rapidly. (Note that it is harder to take this approach for livestock species because the area their feed comes from is not quantified in a consistent manner and they differ widely in diet and feed conversion rates.) FAO statistics suggest the top 10 crops defined in terms of area (including those grown for livestock feed, fibre and biofuels) are wheat, maize, rice, soybeans, barley, sorghum, millet, cotton, rapeseed and beans [35]; together, these account for two-thirds of global cropland. Except for barley, millet and cotton, these crops also have high annual rates of expansion of area grown, with rates for soybeans, maize, wheat and rapeseed being especially high.

To see if these are the crops that attract most attention from conservation scientists we conducted a literature search on Web of Knowledge to find papers in conservation journals that looked at the impact on biodiversity of any of these crops. As context, we also looked for studies on five other crops noted for their biodiversity impact (coffee, cocoa, oil palm, rubber and tea). This was not intended to be a comprehensive assessment of all studies of the conservation effects of cultivating these products (we looked at only a sample of the

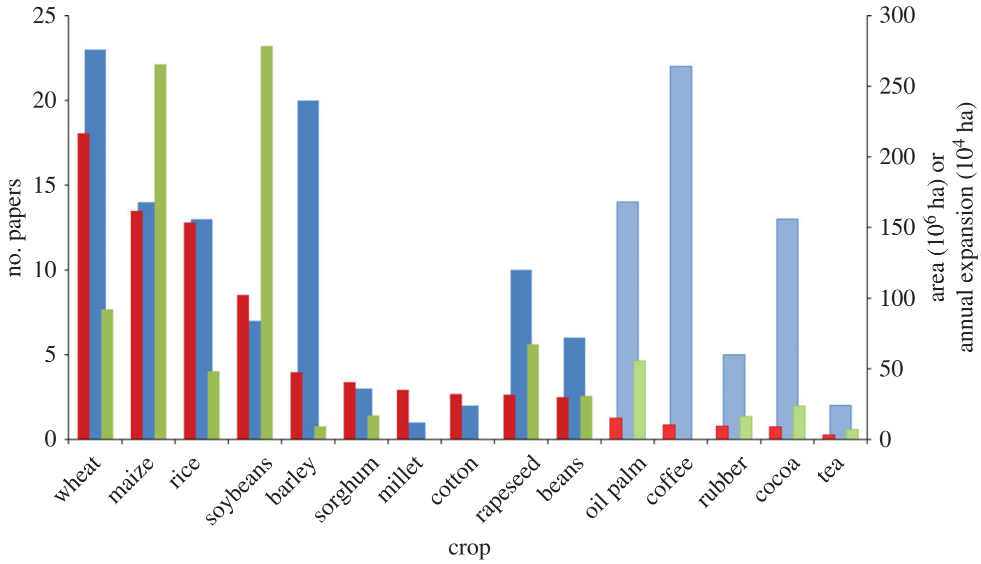

Figure 2. An indication of the relative number of papers in the conservation literature (blue bars; number of relevant papers) that address the biodiversity impacts of specific crops, based on a random sample of 20% of 1062 papers returned from a literature search. Also shown are the global harvested area in 2010 (red; area in 10^6 ha) and mean annual increment in area (green: expansion; 10^4 ha) based on linear regression of area from 1999 to 2010 [35]. The 10 crops on the left are the top 10 crops by harvested area, and the five on the right are additional crops noted for their biodiversity impact. The top 10 crops by annual increment is similar except that oil palm, sugar cane, vegetables and sunflower replace barley, sorghum, millet and cotton. The literature search was carried out in February 2012 on Web of Knowledge for papers published up to 2011 in 14 conservation journals, with search terms for crop names and for farmland*, arable* or cereal* entered in the topic field (which searches title, abstract and key words). Papers were counted if they were relevant to the impact on biodiversity of the extent or management of named crops; those focused only on conservation of crop genetic diversity, pest control or human–wildlife conflict were excluded.

papers retrieved, omitted non-conservation journals and completely ignored the grey literature, for example). However, we think our findings are broadly indicative of where conservation researchers interested in farming have focused their effort.

The results are striking (figure 2). Temperate arable crops such as wheat and barley are among the most well-studied (despite the fact that our search underestimates the number of papers relevant to these crops, because many relevant studies mention only ‘arable’ land or ‘cereals’). Among tropical crops, more research attention has been devoted to perennial crops typical of moist forest regions than to crops grown in more open or arid areas. This is understandable, given the rapid expansion of these perennial crops in areas of high biodiversity value [8,36,37]. However, there remains a serious knowledge gap about the effects on biodiversity of some crops grown over large areas, such as soybeans, sorghum, millet and cotton. Of these widespread crops with few publications, the area under soybeans is also rapidly increasing. Some of the crops that have tended to be overlooked are less widely traded than the crops conservationists have focused on (and so may be less amenable to international market-based interventions to limit their impact—L. Fishpool & H. Ducharme 2012, personal communication); nevertheless, continuing to know very little about their impacts would be unwise.

There appear to be similar gaps in the effort devoted to understanding the impacts of livestock. For instance, a literature search for conservation papers about chickens revealed more papers about prairie chickens (*Tympanuchus* spp.) than about the consequences for wild nature of producing tens of billions of domestic birds each year. Conserving two globally threatened species of grouse is undoubtedly important, but we suggest ameliorating the direct and indirect effects of the poultry industry on land use, fisheries, greenhouse gas emissions, water quality and wild animal health is likely to have more bearing on the fate of global biodiversity.

Our assessment of which farm products conservationists need to focus on is obviously simplistic (it misses out rooibos, flagged in §1, for example). More sophisticated approaches might include identifying those products associated with frontiers of habitat clearance, which are grown in areas of particular biodiversity value, and whose production is expected to increase substantially in the future. Beyond the products themselves, it is also vital to examine what farming approaches and methods are studied, and what exactly is measured in those studies (see §§4–6).

4. TOPIC 3. QUANTIFYING TRADE-OFFS AND SYNERGIES

Most analysts agree that agricultural production will increase dramatically over the next 50 years but that achieving this by increasing yields and converting wild lands to agriculture in the ways seen over the past half century is both impractical and likely to involve unacceptable environmental impacts. However, opinions are divided over the best strategic direction for instead limiting the negative effects of this growth [6]. One option is to further integrate conservation and food production: land sharing. This approach—which underpins much European agri-environment policy—aims to make existing farmland as hospitable to wild species as possible, by reducing inputs of pesticides and fertilizers and retaining on-farm habitat elements such as shade trees, hedgerows and ponds [11,38–41]. However, land sharing typically lowers or limits farm yields so that more farmed area is required to produce a given amount of food. An alternative approach, addressing this problem, is land sparing, in which yields on existing farmland are maintained or increased while as much unmodified habitat as possible is spared from future clearance [42–45]. Others suggest that an intermediate approach, or a mixture of land sharing and sparing at different spatial scales, may be most appropriate [46–48].

Our view is that there are too few relevant quantitative data to decide which of these approaches is likely to be best. We therefore think that the way to progress this debate is to conduct wide-ranging, quantitative analyses of the consequences of these contrasting approaches across broad spatial scales (rather than simply on existing farmland), looking where necessary over the long-term and even across into other sectors besides farming [6,49,50]. We suggest that key externalities (such as the generation of pollutants or the conversion of natural habitat to farmland) should be expressed per unit of product generated (rather than per unit of farm area) so as not to underestimate the overall effects of meeting demand through low-yielding agriculture. Assessing how far high-yield farming actually spares land (the so-called Borlaug effect; [51]) is crucial, as is quantifying the real-world effects of land sharing on biodiversity; [52]. Where leakage (i.e. the spatial displacement of impacts) is especially far-reaching (as is likely to be the case with EU policy on biofuels, for example—[53]), it may be necessary to assess the consequences of agricultural decisions internationally or even globally. Taking such a broad perspective is demanding—but it can also yield important and counterintuitive insights.

In considering which approach to agriculture is better for biodiversity, for example, several studies looking at the species richness of different taxa on low-intensity farmland have concluded that because this can typically support 40–60% of the species found in nearby forest, maintaining this sort of countryside (i.e. land sharing) is beneficial for biodiversity conservation [38,54–57] (but see [58]). While it is important to consider the conservation value of farmland, the observation that some species persist in it does not mean that it should be conserved at all costs. Consideration also needs to be given to what sorts of species (rather than simply how many) are found where, to the abundance of each species (because presence alone gives limited information about population viability), to agricultural yields (because this influences how much land is needed for farming), and to intact habitats and high- as well as low-yielding farm land (for detailed discussion of these points, see Phalan *et al.* [50]; see also [6,59–62]). Together, this information can then be used to estimate how each species' density changes across the full spectrum of agricultural yield, with the shape of its resulting density–yield curve predicting whether its population size might be greatest under land sharing, land sparing or some intermediate approach [6].

The only published studies that have addressed all these requirements—in Ghana and India—have found higher species richness in low- than in high-yield farmland, consistent with previous studies, but have come to markedly different conclusions [63]. In both areas and for both birds and trees, while some (typically wide-ranging) species had higher population densities on farmland compared with intact habitat, more species had lower densities on farmland, and most of these so-called 'loser' species (and nearly all narrowly distributed or threatened species) were so dependent on forest that they would have bigger populations under a system of high-yield farming coupled with habitat protection (i.e. land sparing) than under land sharing or intermediate-yield farming [63].

Similarly, broad-scale studies incorporating the effects of land-use change have generated novel conclusions about the consequences for greenhouse gas emissions of different approaches to farming. For example, assessments (such as [64]) that look only at the growth, refinement and use of biofuel crops typically report they have lower emissions than fossil fuels. However, analyses that take into account emissions incurred when natural habitats are converted to make way for biofuel crops (or the food crops they displace) consistently conclude that switching from fossil fuels to biofuels made from farmed crops will cause a net increase in emissions lasting 50 years or longer [65–67].

What about greenhouse gas emissions in the context of the land sparing/sharing debate? While there is well-justified concern over the emissions per unit area typically associated with high-yielding agriculture [68], comparisons of approaches must include the consequences that differences in yield are likely to have on the area of farmland needed and hence on emissions incurred during habitat conversion [69]. A recent global analysis illustrates why [70]. When the estimated cumulative emissions from farming since 1961 were compared with those likely if yields had not increased, it was found as expected that the yield growth seen over the following 45 years was linked to greatly increased emissions from soils and fertilizer production. However, had low-yield farming instead been maintained, these greenhouse gas savings would have been dwarfed by emissions from the extra land conversion needed to meet rising demand, even if *per capita* demand also stayed at 1961 levels [70] (figure 3). The authors thus conclude that investment in high-yield farming has delivered cost-effective climate mitigation through land sparing—though they also point out that much more needs to be done to reduce emissions from conventional intensive production.

But despite these findings on greenhouse gases and Indian and Ghanaian birds and trees, the evidence that land sparing outperforms land sharing is still patchy. Even if (as discussed in §§5 and 6) yield increases are achieved and are used as part of a strategy to save land from conversion (or free it up for restoration), there are still important gaps in our understanding. In the context of biodiversity, the density–yield curve technique needs to be elaborated to incorporate key aspects of the spatial dynamics of populations and the externalities that farming imposes on populations living on non-farmed land [6,50,63]. Empirical data collection needs to be extended to other regions and taxa. In particular, more data are needed for non-forested biomes and for areas which have been repeatedly exposed to substantial natural disturbances such as glacial–interglacial cycles, as these might have long been purged of their disturbance-sensitive biota [63,71]. An important challenge here will be in establishing baselines against which the effects of

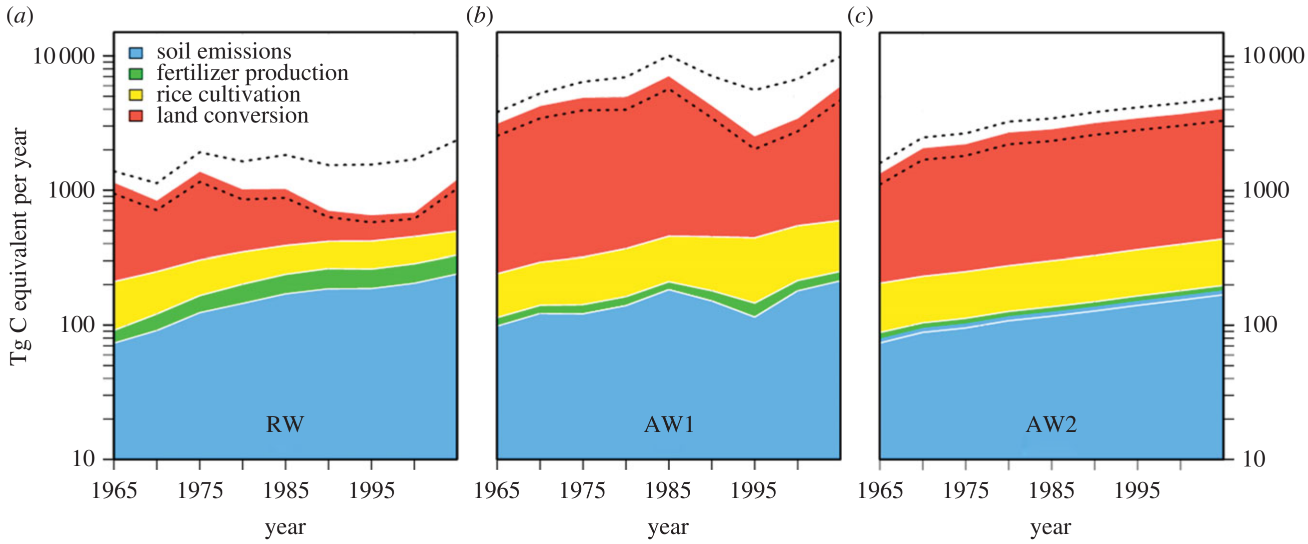

Figure 3. (*a*) Estimated annual greenhouse gas emissions from agriculture between 1961 and 2005 assuming observed increases in yield, *per capita* demand and population (RW) and (*b*) two alternative world scenarios in which yield remained at 1961 levels but *per capita* demand grew as in RW (AW1) or (*c*) both yield and *per capita* demand were unchanged from 1961 (AW2). The dotted lines represent uncertainty (±20%) in the change in carbon stock owing to land conversion. Note the logarithmic *y*-axis. From Burney *et al.* [70].

different farming regimes can be judged. More broadly, there is a pressing need to measure not just how biodiversity and greenhouse gas fluxes vary with farm yields but to consider other ecosystem services—and then to develop methods for how best to limit the costs of farming across a suite of benefits of importance to society [72]. Last, as well as improving our understanding of how contrasting farming approaches might perform in principle, we need to know much more about how they might be delivered in practice.

5. TOPIC 4. ASSESSING WHICH FARMING METHODS HAVE GREATEST POTENTIAL

Given current evidence of growth in demand for agricultural products, on how far we might meet that through waste reduction, and on the relative merits of land sparing versus sharing, we agree with calls for the sustainable intensification of farming [14,19,20,25]. We understand this to mean increasing developing world yields at least cost in terms of environmental externalities, and lowering the environmental costs of maintaining high yields in the developed world. Others may consider that land sharing is preferable, or even that increased farm production is unnecessary. But whichever of these views one takes, it seems there is a need to develop, test and promote methods that lower the negative impacts of farming on biodiversity and ecosystem services per unit of agricultural production.

The encouraging news is that very many potential methods for achieving these aims are either in use already or in development [18,19,20,73]. Simply widening the adoption of existing farming techniques could do much to close yield gaps (differences between what farmers currently achieve and what best practice can deliver in the same area; [1]). There is particular scope for improvement in sub-Saharan Africa, where adoption of practices widespread elsewhere—applying even modest amounts of inorganic fertilizer, using improved seed varieties, mulching, spacing plants appropriately and so on—has been shown to double or even treble yields in just a few years [18,69,74–76].

In terms of crop improvement a diverse array of sophisticated plant-science technologies using both marker-assisted 'conventional' breeding and genetic modification (GM) are at various stages of development—with possibilities of raising yields and/or lowering externalities by, among other things, enhancing nutrient and water uptake and efficiency, increasing resistance to pests, boosting drought tolerance and photosynthetic efficiency, and converting annual crops into perennials [19,77]. The potential for improving largely neglected tropical crops such as cassava, plantains and yams through such approaches is especially marked [18], though concerns about the extent to which GM and other sophisticated technologies place power over the food system in the hands of a few corporations need to be taken seriously.

There are also many different methods for reducing the inputs to farming—including organic techniques, drip irrigation and co-culture systems (such as a 1200-year-old south Chinese rice and fish co-culture method, in which carp eat insect pests and then defaecate in the paddy, thereby decreasing the need for pesticides and fertilizers while maintaining rice yields and providing a protein harvest [78]). Precision agriculture involving fine-tuning fertilizer and pesticide inputs based on near real-time, fine-scale measurements of soil, plant and pest conditions can also increase resource efficiency and reduce pollution inputs in developed-world agriculture [79]. Elsewhere, if labour is abundant precision agriculture can be achieved by farmers' detailed knowledge of soil properties at a fine scale, and their ability to tend even to individual plants [76].

One other particularly promising area is the development of integrated pest management and the use of companion crops. In push–pull agriculture, yields are increased by using companion crops grown within the main crop to repel pests and others grown around field

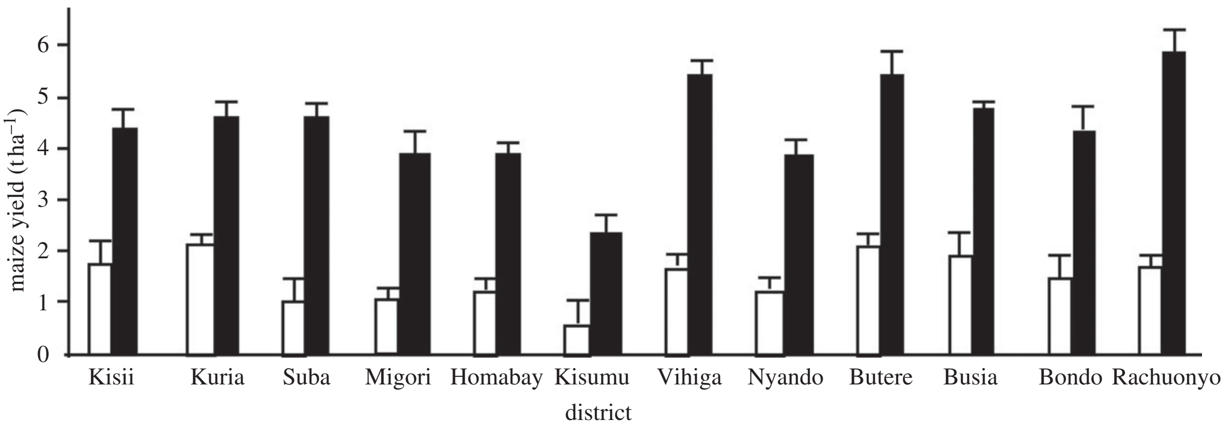

Figure 4. Mean (±s.e.) maize yield in monocrop plots (open bars) and push–pull plots (filled bars) in different districts of western Kenya. Means are from 30 fields and three growing seasons in each district, and in every district differ between monocrop and push–pull plots at $p < 0.0001$. From Khan *et al.* [82].

margins to attract them. The most advanced such system to date—known as *vuta sukuma* ('pull–push') in Kiswahili—involves combating stemborer damage in African maize farming by intercropping with *Desmodium uncinatum* and growing a trap crop of Napier grass (*Pennisetum purpureum*) around the edge of the field [80,81] (figure 4). The *Desmodium* produces volatile semiochemicals which repel female stemborers but attract their parasitoids, whereas the Napier grass produces semiochemicals which attract the ovipositing pests, plus a sticky exudate which kills their larvae. As well as greatly reducing stemborer damage, both companion plants can be harvested for animal feed, while the *Desmodium* has the added advantages of fixing atmospheric nitrogen, and of inducing suicidal germination by parasitic witchweed (*Striga hermonthica*), which itself causes heavy yield losses across more than 40 per cent of sub-Saharan Africa's arable land. The system increases maize yields from less than 1 to 3.5 t per hectare per year, and because it builds on existing intercropping practices, uses locally available plants and requires very limited external inputs it has already been adopted by over 30 000 smallholder farmers across around the eastern shore of Lake Victoria. Efforts are now underway to apply similar push–pull principles to other tropical crops, as well as to insect pests of livestock, and even to aquaculture ([81]; J. Pickett 2012, personal communication).

The key challenge for conservationists is to quantify the relative merits of the most promising of these and other methods in terms of their on- and off-farm consequences for biodiversity and ecosystem services. Very few such tests have been conducted to date, and we suspect that outcomes will vary across biomes and farming systems. Such evaluation should be expressed per unit of production, should include all externalities, and should explicitly consider the impact a technique may have on land conversion—through its effects on yield, profitability, the availability of capital or labour, or the range of environments in which particular crops can be grown [51]. Data collection must take proper account of potentially confounding variables. For example, comparing the output of farmers who are helped to adopt a new method with that of less well-supported growers continuing previous practices may say less about the innovation of interest than about the importance of agricultural extension work (for an example, see [83,84]; for a clear account of how to tackle the problem, see [85]). It is also important to assess promising techniques in a social context, and in particular to consider factors which might influence a method's adoption, such as profits and other effects on livelihoods, equity and gender considerations, the need for training or capital, and how well the practice fits local cultural conditions [86]. Above all, we think it essential that this assessment of ways forward is not bound by dogma: we need to consider all options, from GM through to organic farming, and identify likely winners based on data, not ideology [1,19,20,25].

6. TOPIC 5. LEARNING HOW TO BETTER INTEGRATE CONSERVATION AND AGRICULTURAL POLICY

Alongside identifying on-farm techniques capable of lowering the impacts of agriculture on wild nature, we also need to develop those economic and policy instruments needed for them to fulfil their potential to mitigate environmental damage. For example, under a land sparing approach, farming methods that increase yields will not help the conservation of biodiversity at all unless natural habitat that might otherwise have been cleared for agriculture is spared (or farmland is restored to nature). The evidence to date suggests that although yield increases are sometimes associated with reduced land conversion, the Borlaug effect is patchy and partial [32,51,87–90]. Without explicit policy interventions linking yield growth to land sparing, high yields can act as an incentive for agricultural expansion [91], and land spared from farming might be put to other uses than conservation. Clearly, for high-yield farming to consistently benefit wild nature, we need to devise ways of simultaneously encouraging the setting aside or restoration of other land for conservation (usually away from the farm itself [92]). (Note that the same argument also holds in reverse: the long-term conservation of intact habitats threatened by conversion to agriculture is often likely to depend—practically and, some would argue, ethically—not just on enhanced protection but on alleviating pressure by increasing yields on farmland elsewhere [93].)

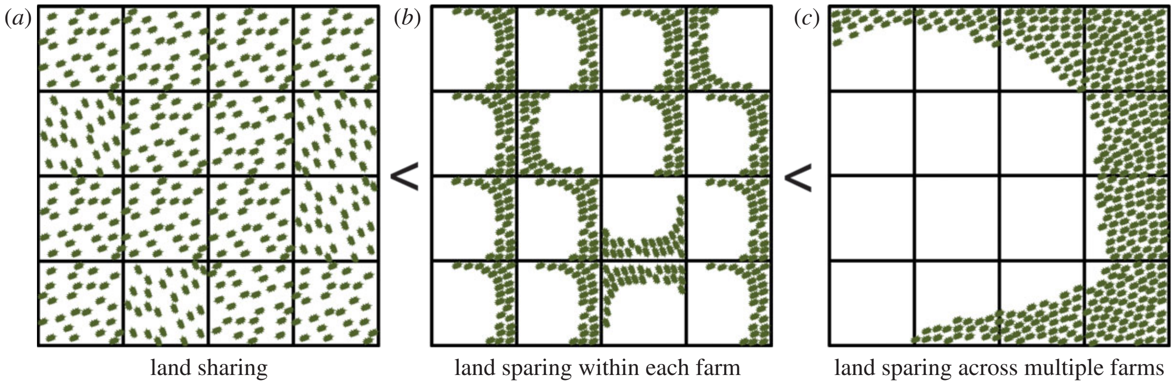

Figure 5. Schematic summarizing what some 'biodiversity-friendly' certification schemes currently endorse (*a*) compared with landscapes that involve land sparing within large farms (*b*) or across a group of farms (*c*). In each landscape, the same total area (denoted by the green shapes) is given over to wild nature, but recent evidence suggests that its value for other species and for ecosystem services might increase from left to right, raising the question of whether certification could be realigned towards incentivizing high-yield farmers to collectively set aside adjacent areas of land for conservation. Developed from ideas in Edwards *et al.* [92] and Komar [97].

India offers two local examples where conservation efforts have generated both yield increases and land sparing. In the remote Spiti Valley of the Trans-Himalaya, herders who lost on average one-eighth of their livestock each year to snow leopards (*Uncia uncia*) have joined an insurance programme that covers their losses but also provides financial incentives for better shepherding. At the same time, the villagers have set aside roughly 2000 hectares from which livestock are excluded. This has enabled the recovery of native ungulate prey, which in conjunction with improved herding practices has caused depredation of livestock by snow leopards to fall by two-thirds [94]. Meanwhile, in the western Ghats, villagers around Bandipur National Park who have typically offset crop losses to elephants (*Elephas maximus*) and wild boar (*Sus scrofa*) by illegally grazing their cattle inside the park have been given financial support to fence their farms. This has boosted yields but also made entering Bandipur no longer the most productive use of these farmers' time, so degradation of the park has slowed [95].

Developing instruments that can help yield growth and deliver land sparing at larger scales is challenging but there are several possibilities. One obvious route is through greater government regulation and land-use planning. For example, increased enforcement to reduce deforestation is thought to be partly responsible for a recent shift in the source of soybean production gains in Mato Grosso, which are now being achieved less through conversion of forest and more from yield growth and expansion into pasture [96]. In many countries, there may also be considerable scope for re-shaping government subsidy schemes, with the suggestion, for instance, that high-yielding farmers could become eligible for agri-environment payments if they invest in large-scale habitat restoration [61]. Payment schemes for securing or enhancing the provision of ecosystem services could have a role too: where expansion of low-yield farming is a major threat, conditional payments for reducing habitat loss could be used to support farmers to produce higher yields on a smaller area. Such an approach could play an especially important part in the implementation of REDD (the UN-backed proposal for reducing emissions from deforestation and forest degradation; [93]). One other promising area for linking yield growth to land sparing is through the market—for example, pressure from environmental organizations and consumers is thought to have been an additional factor in the dramatic slowdown in forest conversion for soybean farming in Mato Grosso state [96]. There are also suggestions that certification schemes might be realigned away from rewarding low-yield farming towards incentivising producers who instead—either individually or collectively—set aside significant areas of land for conservation [97] (figure 5).

Although most attention in the literature (and in this section) has focused on the problems of achieving land sparing, the practical implementation of land sharing has proved at least as difficult. Despite billions of euros of investment each year in European agri-environment schemes, for instance, biodiversity gains have often been minimal [7,98,99]. Problems have included poor design, poor execution, limited monitoring and a lack of adaptive management. Elsewhere, there is a growing catalogue of instances where promotion of low-yield farming has had the unintended consequence of causing the conversion or degradation of intact, previously non-farmed habitat [89,100,101]. This reinforces the point that whether they are intended to enhance delivery of benefits from land sharing or land sparing, any promising policy innovations need to be tested carefully, looking well beyond the boundaries of the farms involved, and controlling as much as possible for potentially confounding factors [85,102].

7. CLOSING REMARKS

The list of topics set out here is inevitably eclectic. Others would doubtless have different suggestions. Nevertheless, we believe that the efforts of conservationists, whether working at local or global scales, would benefit from being framed in the context of broad-reaching challenges such as these. Burgeoning demand, growing worries about food security and diverse advances in agricultural technology mean farming and its impact on nature will change very considerably over next the next 50 years. Conservation has generally dealt with agricultural change reactively—detecting major problems (such as the side effects of DDT, the loss of winter stubbles or the rapid expansion of biofuels) only after they have become widespread. We think such responses, though necessary and understandable, are insufficient in an era of accelerating agricultural change. Likewise, conservationists have typically had limited ambitions in their approach to agriculture—looking only to influence activities which have harmful on-farm effects, rather than thinking strategically about the impacts that different approaches to farming have on overall patterns of land-use, water availability, air quality and so on. We suggest instead that there is a pressing need for conservation researchers and practitioners to proactively and ambitiously engage with farmers, plant breeders, nutrition experts, retailers and consumers, and to work open-mindedly, quantitatively, and—over large scales and broad timeframes—to identify least-cost ways so as to feed and fuel humanity into the future. Few other conservation activities will have as great an influence on the fate of wild nature.

For stimulating discussions on farming and conservation, we are grateful to Ian Bateman, David Baulcombe, Tim Benton, Toby Bruce, Ariel Brunner, Paul Donald, Graziela Dotta, Claire Feniuk, Toby Gardner, M.D. Madhusudan, Malvika Onial, John Pickett, Jorn Scharlemann and David Williams. We thank Paul Donald, Claire Feniuk and two anonymous referees for their helpful comments on an earlier draft. B.P.'s input to this work has been supported by The Isaac Newton Trust, RSPB, and a Raymond and Beverly Sackler Junior Research Fellowship at Churchill College.

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REFERENCES

1 Foley, J. A. *et al.* 2011 Solutions for a cultivated planet. *Nature* **478**, 337–342. (doi:10.1038/nature10452)

2 Ellis, E. C. & Ramankutty, N. 2008 Putting people in the map: anthropogenic biomes of the world. *Front. Ecol. Environ.* **6**, 439–447. (doi:10.1890/070062).

3 Geist, H. J. & Lambin, E. F. 2002 Proximate causes and underlying driving forces of tropical deforestation. *BioScience* **52**, 143–150. (doi:10.1641/0006-3568(2002)052[0143:PCAUDF]2.0.CO;2)

4 Ramankutty, N., Evan, A. T., Monfreda, C. & Foley, J. A. 2008 Farming the planet. 1. Geographic distribution of global agricultural lands in the year 2000. *Glob. Biogeochem. Cycles* **22**, GB1003. (doi:10.1029/2007GB002952)

5 Sutton, M. A., Oenema, O., Erisman, J. W., Leip, A., van Grinsven, H. & Winiwarter, W. 2011 Too much of a good thing. *Nature* **472**, 159–161. (doi:10.1038/472159a)

6 Green, R. E., Cornell, S. J., Scharlemann, J. P. W. & Balmford, A. 2005 Farming and the fate of wild nature. *Science* **307**, 550–555. (doi:10.1126/science.1106049)

7 Kleijn, D., Rundlöf, M., Scheper, J., Smith, H. G. & Tscharntke, T. 2011 Does conservation on farmland contribute to halting the biodiversity decline? *Trends Ecol. Evol.* **26**, 474–481. (doi:10.16/j.tree.2011.05.009)

8 Koh, L. P. & Wilcove, D. S. 2008 Is oil palm agriculture really destroying tropical biodiversity? *Conserv. Lett.* **1**, 60–64.

9 Gibbs, H. K., Ruesch, A. S., Achard, F., Clayton, M. K., Holmgren, P., Ramankutty, N. & Foley, J. A. 2010 Tropical forests were the primary sources of new agricultural land in the 1980s and 1990s. *Proc. Natl Acad. Sci. USA* **107**, 16 732–16 737. (doi:10.1073/pnas.0910275107)

10 Raimondo, D. & von Staden, L. 2009 Patterns and trends in the red list of South African plants. *Strelitzia* **25**, 19–40.

11 Bengtsson, J., Ahnström, J. & Weibull, A.-C. 2005 The effects of organic agriculture on biodiversity and abundance: a meta-analysis. *J. Appl. Ecol.* **42**, 261–269. (doi:10.1111/j.1365-2664.2005.01005.x)

12 Clough, Y. *et al.* 2011 Combining high biodiversity with high yields in tropical agroforests. *Proc. Natl Acad. Sci. USA* **108**, 8311–8316. (doi:10.1073/pnas.1016799108)

13 Food and Agriculture Organization of the United Nations (FAO). 2009 *State of Food Insecurity in the World 2009*. Rome, Italy: FAO.

14 Tilman, D., Balzer, C., Hill, J. & Befort, B. L. 2011 Global food demand and the sustainable intensification of agriculture. *Proc. Natl Acad. Sci. USA* **108**, 20 260–20 264. (doi:10.1073/pnas.1116437108)

15 Sen, A. 1983 *Poverty and famines: an essay on entitlement and deprivation*. Oxford, UK: Clarendon Press.

16 Swinnen, J. & Squicciarini, P. 2012 Mixed messages on prices and food security. *Science* **335**, 405–406. (doi:10.1126/science.1210806)

17 Parfitt, J., Barthel, M. & Macnaughton, S. 2010 Food waste within food supply chains: quantification and potential for change to 2050. *Phil. Trans. R. Soc. B* **365**, 3065–3081. (doi:10.1098/rstb.2010.0126)

18 Clay, J. 2011 Freeze the footprint of food. *Nature* **475**, 287–289. (doi:10.1038/475287a)

19 Royal Society. 2009 *Reaping the benefits: science and the sustainable intensification of global agriculture*.
20 Godfray, H. C. J. *et al.* 2010 Food security: the challenge of feeding 9 billion people. *Science* **327**, 812–818. (doi:10.1126/science.1185383)
21 Tomlinson, I. 2011 Doubling food production to feed the 9 billion: a critical perspective on a key discourse of food security in the UK. *J. Rural Stud.* (doi:10.1016/j.jrurstud.2011.09.001)
22 Ghazoul, J., Koh, L. P. & Butler, R. A. 2010 A REDD light for wildlife-friendly farming. *Conserv. Biol.* **24**, 644–645. (doi:10.1111/j.1523-1739.2010.01502.x)
23 OECD/FAO. 2011 *OECD-FAO Agricultural Outlook 2011–2020: biofuels*. Paris, France: OECD and Rome, Italy: FAO.
24 United Nations Population Division. 2011 World population prospects: the 2010 revision. New York: United Nations.
25 Pretty, J. 2008 Agricultural sustainability: concepts, principles and evidence. *Phil. Trans. R. Soc. B* **363**, 447–465. (doi:10.1098/rstb.2007.2163)
26 Thornton, P. K. 2010 Livestock production: recent trends, future prospects. *Phil. Trans. R. Soc. B* **365**, 2853–2867. (doi:10.1098/rstb.2010.0134)
27 Roberts, P. 2008 *The end of food*. London, UK: Bloomsbury.
28 Fairlie, S. 2010 *Meat: a benign extravagance*, 1st edn. Hampshire, UK: Permanent Publications.
29 Pelletier, N. & Tyedmers, P. 2010 Forecasting potential global environmental costs of livestock production 2000–2050. *Proc. Natl Acad. Sci. USA* **107**, 18 371–18 374. (doi:10.1073/pnas.1004659107)
30 Steinfeld, H. & Gerber, P. 2010 Livestock production and the global environment: consume less or produce better? *Proc. Natl Acad. Sci. USA* **107**, 18 237–18 238. (doi:10.1073/pnas.1012541107)
31 Soulé, M. E. 2010 Conservation relevance of ecological cascades. In *Trophic cascades: predators, prey, and the changing dynamics of nature* (eds J. Terborgh & J. A. Estes), pp. 337–352. Washington, DC: Island Press.
32 Ewers, R. M., Scharlemann, J. P. W., Balmford, A. & Green, R. E. 2009 Do increases in agricultural yield spare land for nature? *Glob. Change Biol.* **15**, 1716–1726. (doi:10.1111/j.1365-2486.2009.01849.x)
33 Scharlemann, J. P. W., Green, R. E. & Balmford, A. 2004 Land-use trends in endemic bird areas: global expansion of agriculture in areas of high conservation value. *Glob. Change Biol.* **10**, 2046–2051. (doi:10.1111/j.1365-2486.2004.00860.x)
34 Dobrovolski, R., Diniz-Filho, J. A. F., Loyola, R. D. & Marco Júnior, P. 2011 Agricultural expansion and the fate of global conservation priorities. *Biodivers. Conserv.* **20**, 2445–2459. (doi:10.1007/s10531-011-9997-z)
35 FAO. 2011 FAOSTAT Statistical databases. Rome, Italy: Food and Agriculture Organization of the United Nations.
36 O'Brien, T. G. & Kinnaird, M. F. 2003 Caffeine and conservation. *Science* **300**, 587. (doi:10.1126/science.1082328)
37 Clough, Y., Faust, H. & Tscharntke, T. 2009 Cacao boom and bust: sustainability of agroforests and opportunities for biodiversity conservation. *Conserv. Lett.* **2**, 197–205. (doi:10.1111/j.1755-263X.2009.00072.x)
38 Daily, G. C., Ehrlich, P. R. & Sanchez-Azofeifa, G. A. 2001 Countryside biogeography: use of human-dominated habitats by the avifauna of southern Costa Rica. *Ecol. Appl.* **11**, 1–13. (doi:10.1890/1051-0761(2001)011[0001:CBUOHD]2.0.CO;2)
39 Rosenzweig, M. L. 2003 Reconciliation ecology and the future of species diversity. *Oryx* **37**, 194–205. (doi:10.1017/S0030605303000371)
40 Perfecto, I. & Vandermeer, J. 2008 Biodiversity conservation in tropical agroecosystems: a new conservation paradigm. *Ann. N.Y. Acad. Sci.* **1134**, 173–200. (doi:10.1196/annals.1439.011)
41 Tscharntke, T. *et al.* 2012 Global food security, biodiversity conservation and the future of agricultural intensification. *Biol. Conserv.* (doi:10.1016/j.biocon.2012.01.068)
42 Goklany, I. M. 1998 Saving habitat and conserving biodiversity on a crowded planet. *BioScience* **48**, 941–953. (doi:10.2307/1313298)
43 Waggoner, P. E. 1995 How much land can ten billion people spare for nature? Does technology make a difference? *Technol. Soc.* **17**, 17–34. (doi:10.1016/0160-791X(94)00024-8)
44 Borlaug, N. E. 2002 Feeding a world of 10 billion people: the miracle ahead. *In Vitro Cell. Dev. Biol. Plant.* **38**, 221–228. (doi:10.1079/IVP2001279)
45 Tilman, D., Cassman, K. G., Matson, P. A., Naylor, R. & Polasky, S. 2002 Agricultural sustainability and intensive production practices. *Nature* **418**, 671–677. (doi:10.1038/nature01014)
46 Scherr, S. J. & McNeely, J. A. 2007 *Farming with nature*. Washington, DC: Island Press.
47 Fischer, J. *et al.* 2008 Should agricultural policies encourage land sparing or wildlife-friendly farming? *Front. Ecol. Environ.* **6**, 380–385. (doi:10.1890/070019)
48 Adams, W. M. In press. Feeding the next billion: hunger and conservation. *Oryx*.
49 Mattison, E. H. A. & Norris, K. 2005 Bridging the gaps between agricultural policy, land-use and biodiversity. *Trends Ecol. Evol.* **20**, 610–616. (doi:10.1016/j.tree.2005.08.011)
50 Phalan, B., Balmford, A., Green, R. E. & Scharlemann, J. P. W. 2011 Minimising the harm to biodiversity of producing more food globally. *Food Policy* **36**, S62–S71. (doi:10.1016/j.foodpol.2010.11.008)
51 Angelsen, A. & Kaimowitz, D. 2001 *Agricultural technologies and tropical deforestation*. Wallingford, Oxon, UK: CABI Publishing.
52 Matson, P. A. & Vitousek, P. M. 2006 Agricultural intensification: will land spared from farming be land spared for nature? *Conserv. Biol.* **20**, 709–710. (doi:10.1111/j.1523-1739.2006.00442.x)
53 Hellmann, F. & Verburg, P. H. 2010 Impact assessment of the European biofuel directive on land use and biodiversity. *J. Environ. Manage.* **91**, 1389–1396. (doi:10.1016/j.jenvman.2010.02.022)
54 Hughes, J. B., Daily, G. C. & Ehrlich, P. R. 2002 Conservation of tropical forest birds in countryside habitats. *Ecol. Lett.* **5**, 121–129. (doi:10.1046/j.1461-0248.2002.00294.x)
55 Daily, G. C., Ceballos, G., Pacheco, J., Suzan, G. & Sanchez-Azofeifa, A. 2003 Countryside biogeography of Neotropical mammals: conservation opportunities in agricultural landscapes of Costa Rica. *Conserv. Biol.* **17**, 1814–1826. (doi:10.1111/j.1523-1739.2003.00298.x)
56 Steffan-Dewenter, I. *et al.* 2007 Tradeoffs between income, biodiversity, and ecosystem functioning during tropical rainforest conversion and agroforestry intensification. *Proc. Natl Acad. Sci. USA* **104**, 4973–4978. (doi:10.1073/pnas.0608409104)
57 Ranganathan, J., Daniels, R. J. R., Chandran, M. D. S., Ehrlich, P. R. & Daily, G. C. 2008 Sustaining biodiversity in ancient tropical countryside. *Proc. Natl Acad. Sci. USA* **105**, 17 852–17 854.
58 Mahood, S. P., Lees, A. C. & Peres, C. A. 2011 Amazonian countryside habitats provide limited avian conservation value. *Biodivers. Conserv.* **21**, 385–405. (doi:10.1007/s10531-011-0188-8)

59 Komar, O. 2006 Ecology and conservation of birds in coffee plantations: a critical review. *Bird Conserv. Int.* **16**, 1. (doi:10.1017/S0959270906000074)
60 Sridhar, H. 2009 Are arecanut plantations really suitable for biodiversity conservation? *Proc. Natl Acad. Sci. USA* **106**, E34. (doi:10.1073/pnas.0812897106)
61 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. (doi:10.1111/j.1461-0248.2010.01528.x)
62 Phalan, B., Onial, M., Balmford, A. & Green, R. E. 2011 Conservation: response. *Science* **334**, 594–595. (doi:10.1126/science.334.6056.594-a)
63 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. (doi:10.1126/science.1208742)
64 Farrell, A. E., Plevin, R. J., Turner, B. T., Jones, A. D., O'Hare, M. & Kammen, D. M. 2006 Ethanol can contribute to energy and environmental goals. *Science* **311**, 506–508. (doi:10.1126/science.1121416)
65 Fargione, J., Hill, J., Tilman, D., Polasky, S. & Hawthorne, P. 2008 Land clearing and the biofuel carbon debt. *Science* **319**, 1235–1238. (doi:10.1126/science.1152747)
66 Searchinger, T., Heimlich, R., Houghton, R. A., Dong, F., Elobeid, A., Fabiosa, J., Tokgoz, S., Hayes, D. & Yu, T.-H. 2008 Use of U.S. croplands for biofuels increases greenhouse gases through emissions from land use change. *Science* **319**, 1238–1240. (doi:10.1126/science.1151861)
67 Danielsen, F. *et al.* 2009 Biofuel plantations on forested lands: double jeopardy for biodiversity and climate. *Conserv. Biol.* **23**, 348–358. (doi:10.1111/j.1523-1739.2008.01096.x)
68 Crutzen, P. J., Mosier, A. R., Smith, K. A. & Winiwarter, W. 2008 N_2O release from agro-biofuel production negates global warming reduction by replacing fossil fuels. *Atmos. Chem. Phys. Discuss.* **8**, 389–395.
69 Gockowski, J. & Sonwa, D. 2011 Cocoa intensification scenarios and their predicted impact on CO_2 emissions, biodiversity conservation, and rural livelihoods in the Guinea rain forest of West Africa. *Environ. Manage.* **48**, 307–321. (doi:10.1007/s00267-010-9602-3)
70 Burney, J. A., Davis, S. J. & Lobell, D. B. 2010 Greenhouse gas mitigation by agricultural intensification. *Proc. Natl Acad. Sci. USA* **107**, 12 052–12 057.
71 Balmford, A. 1996 Extinction filters and current resilience: the significance of past selection pressures for conservation biology. *Trends Ecol. Evol.* **11**, 193–196. (doi:10.1016/0169-5347(96)10026-4)
72 Glendining, M. J., Dailey, A. G., Williams, A. G., van Evert, F. K., Goulding, K. W. T. & Whitmore, A. P. 2009 Is it possible to increase the sustainability of arable and ruminant agriculture by reducing inputs? *Agric. Syst.* **99**, 117–125. (doi:10.1016/j.agsy.2008.11.001)
73 Fedoroff, N. V. *et al.* 2010 Radically rethinking agriculture for the 21st century. *Science* **327**, 833–834. (doi:10.1126/science.1186834)
74 Denning, G. *et al.* 2009 Input subsidies to improve smallholder maize productivity in Malawi: toward an African Green Revolution. *PLoS Biol.* **7**, e1000023. (doi:10.1371/journal.pbio.1000023)
75 Sánchez, P. A. 2010 Tripling crop yields in tropical Africa. *Nat. Geosci.* **3**, 299–300. (doi:10.1038/ngeo853)
76 Twomlow, S. *et al.* 2008 Micro-dosing as a pathway to Africa's Green Revolution: evidence from broad-scale on-farm trials. *Nutrient Cycling Agroecosyst.* **88**, 3–15. (doi:10.1007/s10705-008-9200-4)
77 Bruce, T. J. A. 2012 GM as a route for delivery of sustainable crop protection. *J. Exp. Bot.* **63**, 537–541.
78 Xie, J. *et al.* 2011 Ecological mechanisms underlying the sustainability of the agricultural heritage rice–fish coculture system. *Proc. Natl Acad. Sci. USA* **108**, E1381–E1387. (doi:10.1073/pnas.1111043108)
79 Cassman, K. G. 1999 Ecological intensification of cereal production systems: yield potential, soil quality, and precision agriculture. *Proc. Natl Acad. Sci. USA* **96**, 5952–5959. (doi:10.1073/pnas.96.11.5952)
80 Khan, Z. R., Midega, C. A. O., Bruce, T. J. A., Hooper, A. M. & Pickett, J. A. 2010 Exploiting phytochemicals for developing a 'push–pull' crop protection strategy for cereal farmers in Africa. *J. Exp. Bot.* **61**, 4185–4196.
81 Hassanali, A., Herren, H., Khan, Z. R., Pickett, J. A. & Woodcock, C. M. 2008 Integrated pest management: the push–pull approach for controlling insect pests and weeds of cereals, and its potential for other agricultural systems including animal husbandry. *Phil. Trans. R. Soc. B* **363**, 611–621. (doi:10.1098/rstb.2007.2173)
82 Khan, Z. R., Midega, C. A. O., Bruce, T. J. A., Hooper, A. M. & Pickett, J. A. 2010 Exploiting phytochemicals for developing a 'push–pull' crop protection strategy for cereal farmers in Africa RID B-8523–2009. *J. Exp. Bot.* **61**, 4185–4196. (doi:10.1093/jxb/erq229)
83 Badgley, C., Moghtader, J., Quintero, E., Zakem, E., Chappell, M. J., Aviles-Vazquez, K., Samulon, A. & Perfecto, I. 2007 Organic agriculture and the global food supply. *Renewable Agric. Food Syst.* **22**, 86–108. (doi:10.1017/S1742170507001640)
84 Cassman, K. G. 2007 Editorial response by Kenneth Cassman: can organic agriculture feed the world—science to the rescue? *Renewable Agric. Food Syst.* **22**, 83–84.
85 Blackman, A. & Rivera, J. 2011 Producer-level benefits of sustainability certification. *Conserv. Biol.* **25**, 1176–1185. (doi:10.1111/j.1523-1739.2011.01774.x)
86 Khan, Z., Midega, C., Pittchar, J., Pickett, J. & Bruce, T. 2011 Push–pull technology: a conservation agriculture approach for integrated management of insect pests, weeds and soil health in Africa. *Int. J. Agric. Sustain.* **9**, 162–170. (doi:10.3763/ijas.2010.0558)
87 Brown, J. C., Koeppe, M., Coles, B. & Price, K. P. 2005 Soybean production and conversion of tropical forest in the Brazilian Amazon: the case of Vilhena, Rondônia. *Ambio* **34**, 462–469. (doi:10.1579/0044-7447-34.6.462)
88 Morton, D. C., DeFries, R. S., Shimabukuro, Y. E., Anderson, L. O., Arai, E., del Bon Espirito-Santo, F., Freitas, R. & Morisette, J. 2006 Cropland expansion changes deforestation dynamics in the southern Brazilian Amazon. *Proc. Natl Acad. Sci. USA* **103**, 14 637–14 641.
89 Grau, H. R., Gasparri, N. I. & Aide, T. M. 2008 Balancing food production and nature conservation in the Neotropical dry forests of northern Argentina. *Glob. Change Biol.* **14**, 985–997. (doi:10.1111/j.1365-2486.2008.01554.x)
90 Rudel, T. K., Defries, R., Asner, G. P. & Laurance, W. F. 2009 Changing drivers of deforestation and new opportunities for conservation. *Conserv. Biol.* **23**, 1396–1405. (doi:10.1111/j.1523-1739.2009.01332.x)
91 Gutiérrez-Vélez, V. H. *et al.* 2011 High-yield oil palm expansion spares land at the expense of forests in the Peruvian Amazon. *Environ. Res. Lett.* **6**, 0440129 (doi:10.1088/1748-9326/6/6/044029)
92 Edwards, D. P., Hodgson, J. A., Hamer, K. C., Mitchell, S. L., Ahmad, A. H., Cornell, S. J. & Wilcove, D. S. 2010 Wildlife-friendly oil palm plantations fail

to protect biodiversity effectively. *Conserv. Lett.* **3**, 236–242. (doi:10.1111/j.1755-263X.2010.00107.x)

93 Fisher, B., Lewis, S. L., Burgess, N. D., Malimbwi, R. E., Munishi, P. K., Swetnam, R. D., Kerry Turner, R., Willcock, S. & Balmford, A. 2011 Implementation and opportunity costs of reducing deforestation and forest degradation in Tanzania. *Nat. Clim. Change* **1**, 161–164. (doi:10.1038/nclimate1119)

94 Mishra, C., Allen, P., McCarthy, T., Madhusudan, M. D., Bayarjargal, A. & Prins, H. H. T. 2003 The role of incentive programs in conserving the snow leopard. *Conserv. Biol.* **17**, 1512–1520.

95 Sankaran, P. & Madhusudan, M. D. 2010 Desperate neighbours: endangered wildlife and the rural poor. *The Hindu survey of the environment 2010*, pp. 113–118. Chennai, India: The Hindu.

96 Macedo, M. N., DeFries, R. S., Morton, D. C., Stickler, C. M., Galford, G. L. & Shimabukuro, Y. E. 2012 Decoupling of deforestation and soy production in the southern Amazon during the late 2000s. *Proc. Natl Acad. Sci. USA* **109**, 1341–1346 (doi:10.1073/pnas.1111374109)

97 Komar, O. 2006 Ecology and conservation of birds in coffee plantations of El Salvador, Central America. Unpublished PhD thesis, University of Kansas, Lawrence, KS, USA.

98 Kleijn, D., Berendse, F., Smit, R. & Gilissen, N. 2001 Agri-environment schemes do not effectively protect biodiversity in Dutch agricultural landscapes. *Nature* **413**, 723–725. (doi:10.1126/science.1082328)

99 Kleijn, D. & Sutherland, W. J. 2003 How effective are European agri-environment schemes in conserving and promoting biodiversity? *J. Appl. Ecol.* **40**, 947–969.

100 Madhusudan, M. D. 2005 The global village: linkages between international coffee markets and grazing by livestock in a south Indian wildlife reserve. *Conserv. Biol.* **19**, 411–420. (doi:10.1111/j.1523-1739.2005.00330.x)

101 Tejeda-Cruz, C., Silva-Rivera, E., Barton, J. R. & Sutherland, W. J. 2010 Why shade coffee does not guarantee biodiversity conservation. *Ecol. Soc.* **15**, 13. (doi:10.1111/j.1365-2664.2003.00868.x)

102 Ferraro, P. J. & Pattanayak, S. K. 2006 Money for nothing? A call for empirical evaluation of biodiversity conservation investments. *PLoS Biol.* **4**, e105.