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Reconciling biodiversity conservation and food security: scientific challenges for a new agriculture

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Production ecology and conservation biology have long focused on providing the knowledge base for intensive food production and biodiversity conservation, respectively. With increasing global food insecurity and continuing biodiversity decline, we show that the largely separate development of these fields is counterproductive. Scenario analyses suggest that feeding the world is possible without further encroachment of agriculture into natural ecosystems. Without ignoring the necessary demographic, socio-economic, institutional and governance requirements, we make the case for a science that develops the best ecological means to produce food in a way that has substantially less negative effects on biodiversity and associated ecosystem services and, indeed, should be able to contribute to their persistence and enhancement. Recent developments in trait-based ecology should soon make it possible to adapt and (re-)design agroecosystems to meet both goals of biodiversity conservation and food security. However, there are real tensions between, on the one hand, the opportunity costs of biodiversity conservation (for direct use and for conversion to agriculture) and on the other hand, the ecosystem service values and option values associated with biodiversity. We elaborate the management of plant genetic resources as a metaphor of the tensions between such values of biodiversity and ecosystem services in general. We conclude that significant changes in policies, institutions and practices are necessary to make advances in ecology work for reconciling biodiversity conservation and food security.

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Introduction

Agriculture as we know it today is founded on the natural capital of wild biodiversity and the outcome of interaction between human and natural selection. Increasing specialization and intensification of production systems has led to reduction in crop and livestock biodiversity, increasing genetic vulnerability and erosion [1,2]. Concurrently, wild biodiversity is still declining rapidly [3], in no small measure because of expansion of agricultural areas [4]. At the same time food insecurity is a major and growing problem with more than 1 billion people considered food insecure in 2009. Climate change aggravates the situation for both biodiversity conservation and food security by increased risks of crop failure and population extinctions because of the higher frequency of extreme events and progressive change in key climate variables [5].

With mounting pressures to both increase food security and stop biodiversity decline, it is counterproductive that agriculturalists and conservationists often find themselves in opposing camps. Hence, the urgent question is whether the following Millennium Development Goals on food security and biodiversity can simultaneously be met:

> Goal 1: Eradicate extreme poverty and hunger — target 3: Halve, between 1990 and 2015, the proportion of people who suffer from hunger, and

> Goal 7: Ensure environmental sustainability — target 2: Reduce biodiversity loss, achieving, by 2010, a significant reduction in the rate of loss.

We briefly outline different recent strategies [6•,7•] to increase food security and conserve biodiversity and we explore the possible role of science in closing the apparent gap between them.

Food production and food security

The most successful scientific endeavors to increase food production have been in *production ecology*. A fundamental scientific approach, in particular in crop ecophysiology, plant breeding, plant nutrition and crop protection, supported by technology development for mechanization, has made it possible to considerably increase the light, water and nutrient use efficiencies and cropping intensities in the major crops of the world [8], and to grow these well beyond their original distributional areas. The green revolution of the fifties and sixties of the last century was largely built on such research [9]. Research on livestock physiology, breeding, nutrition and disease control has led to similar developments [10], while research on fish and aquaculture follows suit [11].

In spite of the availability of knowledge and technologies provided by science, the potential increases in food production are far from being realized under field conditions in most countries. Major impediments are considered to be poor education and health systems, poorly functioning markets and other institutions, political instability/poor governance and lack of alternative livelihood opportunities for those who are not in a position to make the transition from subsistence-based to market-oriented agriculture [6•].

Biodiversity conservation

The most successful scientific endeavors to conserve biodiversity have been in *conservation biology*. Research on the habitat requirements and management needs of emblematic and Red List species continues to contribute considerably to the establishment and conservation of species and the management of habitats, including protected areas [12]. In addition, much scientific focus is now on methods by which to prioritize conservation action, such as on biodiversity hotspots that is areas with many species or high levels of endemism [13], and on means by which to measure and monitor conservation progress through biodiversity indicators. Yet, although more than 130 000 protected areas now cover almost 14% of the earth's surface [14] — but much less of its waters — the rapid decline in biodiversity has not stopped. One reason is that not all the habitat requirements for the persistence of biodiversity generally can be fulfilled within the boundaries of protected areas. Among causes of biodiversity loss are the fragmentation and degradation of habitat, overexploitation of natural resources, pollution, climate change and invasive species. These can be the result of poor management and/or the expansion of commercial interests, be they in conversion of forests for plantations or commercial wildlife trade. Finally, many countries are reluctant to set aside (more) land solely dedicated for biodiversity conservation, particularly in areas with high population pressure on the land.

Intensive agriculture approach

There are broadly two approaches to improve the appalling situation of persistent hunger and equally persistent biodiversity loss. One approach holds that increased use efficiencies of light, water and nutrients, and mechanization will double the world food production, while drastically reducing negative effects on the environment per unit of product (ecological intensification *sensu* [15,16]). Under this approach, if production falls short of its potential or if land is being (further) degraded, then the constraints, be they social, technological and/or political, need to be identified and incentives put in place to overcome the impediments. If production would be concentrated on those soils, it would be possible to increase the area allocated to biodiversity conservation, at the same time protecting the resource base for agricultural germplasm that may be needed in future. Biodiversity often happens to be highest on agriculturally marginal soils, which renders a win-win situation, if agriculture is concentrated on the most fertile soils [17]. This has been referred to as *the intensive agriculture approach*. This approach is built upon the notion that there are tradeoffs between agricultural productivity and biodiversity, but the approach largely fails to recognize the potential synergies between productivity and biodiversity.

Ecoagriculture approach

In the second approach to overcome persistent hunger and biodiversity loss, agriculture's role is expanded well beyond efficient food production. This approach assumes that biodiversity at the landscape level is pivotal to sustain both agricultural production and the provision of ecosystem services. This has been referred to as *the ecoagriculture approach* [18••]. In this approach, the land provides a wide array of ecosystem services, all having a bearing on social welfare, from the well-being of local people (e.g. regulation of availability and purification of water) to that of the world community (e.g. carbon sequestration). Improvement, adaptation or re-design of existing agricultural landscapes would be in order with a focus on crop, livestock and landscape diversification instead of the specialization implied by the first approach [19•]; on extensive instead of intensive production [20]; on the multifunctionality of agriculture [21]; and on regionalization instead of globalization [22].

Directions of change in either approach

In the context of industrialized agriculture (which usually results from the first approach), diversification would benefit biodiversity directly, restore the association between biodiversity and ecosystem services, and reduce the economic risks because of crop or livestock failure or the vicissitudes of the market. When practiced with the best ecological means, this type of agriculture would also increase the use efficiencies of fertilizers; reduce greenhouse gas emissions; and reduce the dependence on external inputs such as fertilizers, pesticides and fossil fuels [23]. Regionalization would be a way to make farmers less dependent on expensive transport and the power of retailers; foster the re-introduction of unused or underutilized crops/varieties and livestock/breeds and, thereby, use genetic resources to better cope with environmental stress [24•]. All measures would help restore the farmers' *license to produce* in society [25].

In the context where agriculture is already extensive and biodiverse (which would make it conducive to the second approach), such as in most developing countries or 'marginal' lands, intensification is feasible through precision agriculture, multiple cropping, agroforestry and landscape-scale planning and management of services provided by adjacent natural, semi-natural or restored ecosystems.

Investments in new knowledge and multistakeholder partnerships and the development of new technologies and institutions to provide appropriate incentives will be necessary in either approach.

What role for science?

Both approaches are based upon demographic, social, technological, institutional and governance transformations foreseen or proposed and the predictions of their impacts would benefit from scientific scrutiny. Ironically, the people suffering most from hunger or malnutrition are often the people in agricultural societies, which points to lack of an enabling environment for agriculture to drive poverty alleviation [6•,7•]. Much political will is needed to facilitate the transition to new forms of agriculture, irrespective of which of the two approaches one subscribes to. The intensive agriculture approach hypothesizes that both food production and conservation of biodiversity are best served by keeping them rigorously separate (land sparing *sensu* [26]). The ecoagriculture approach hypothesizes that the two can go together [27]. The tacit assumption of both is that expansion of agriculture into protected areas will not be needed to feed the world.

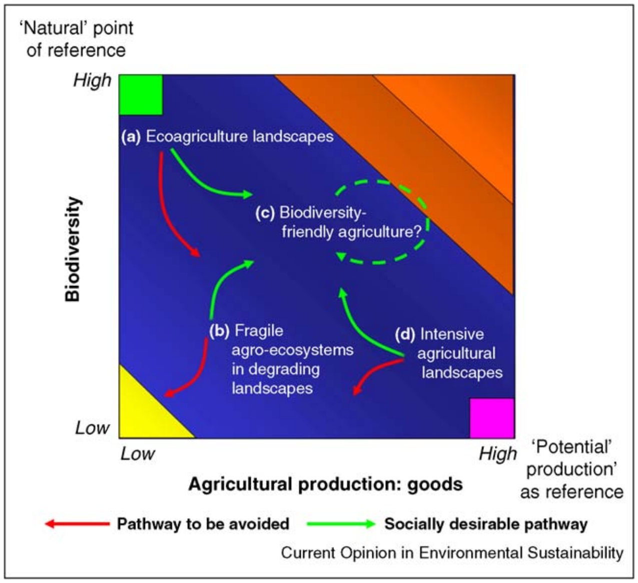
Current research in line with the intensive agriculture approach represents the dominant paradigm in the agricultural sciences and naturally follows up on the green revolution it generated. This does not mean that it is *science as usual*. Major side-effects on the environment, caused by air, water and soil contamination with nutrients and pesticides, and by water extraction for irrigation from rivers and aquifers are now addressed by research aimed at increasing not just the use efficiencies of added fertilizer and water, but higher overall use efficiencies, that is encompassing environmental aspects [8]. As a result, there is a movement away from very high inputs to avoid overuse, and towards reliance on biological mechanisms to the extent that they can be restored or newly applied in intensive agriculture. This development is based on increased ecological literacy. For example, soybean production in Brazil almost entirely relies on biological nitrogen fixation instead of N fertilizers, which is the result of selection and subsequent mass inoculation of efficient strains of N_2-fixing bacteria [28]. Other examples are biological control of pests in glasshouses and, increasingly, in the field instead of pesticide applications [29•]; the use of 'green' and 'gray' water to prevent overuse of water from rivers and aquifers [30•] and conservation agriculture [31••]. A common feature of most such practices is that they are not only environmentally benign but also productive and cost-effective at the farm enterprise level.

As areas under intensive agriculture are increasingly confronted with inevitable constraints and restrictions, research partly shifts to, for example, drought or salinity stress of plants, while the focus remains on modifications at the (sub)individual to cropping or crop/livestock system levels [32•]. These modifications are largely grounded in research on trait-based G×M×E (genotype–management–environment) interactions, on the assumption that the highest potential for increased production still lies there. Crop and livestock biodiversity have increasingly become a matter of concern in the intensive agriculture approach, as apparent from efforts towards *ex situ* conservation and *in situ* protection of the areas of origin of the major crops and livestock of the world.

A system-level approach aimed at changing water and nutrient availability and erosion risks is increasingly applied, as are participatory approaches, multistakeholder involvement and agent-based modeling. Hence, although it is not often explicitly acknowledged or emphasized, also the intensive agriculture approach recognizes that even an industrial farmer has always been, and will always be, more than just a producer of food or other commodities and that farmers are not the only stakeholders in agriculture. However, this approach assumes that the impediments to an enabling environment for intensive agriculture can be overcome to realize its full potential and that it can contribute to improvement of environmental quality to the extent that it will also take pressure away from natural areas. Critics of this approach state that they have seen large-scale intensification of agriculture, but that this has not led to notable reduction of expansion of agriculture into natural areas [33••].

In the ecoagriculture approach, a landscape is characterized by both agricultural crop and livestock diversity and wild (be it planned or unplanned) biodiversity in a certain spatial configuration. Landscape composition and con-

Figure 1



Possible tradeoffs between agricultural production and biodiversity. Modified after original drawing in [34].

figuration determine to what extent agriculture *benefits from* biodiversity and the associated ecosystem services and, vice versa, to what extent agriculture *contributes to* biodiversity and ecosystem services. In contrast to the intensive agriculture approach, the ecoagriculture approach emphasizes biodiversity as an asset for both production and ecosystem services. The farmer should be rewarded as both a producer and an environmental steward. In Figure 1 various situations along the agricultural production and biodiversity axes are conceptually represented.

This figure suggests that research should be directed at moving systems towards the upper-right of the diagram to benefit both production and biodiversity.

We suggest that trait-based ecology will be(come) extremely helpful in this respect [36••]. In trait-based ecology, organisms are characterized in terms of their multiple biological attributes such as physiological, morphological or life-history traits. A trait is a well-defined property of organisms, usually measured at the individual level and used comparatively across species. The conceptual foundation consists of trait distributions (initially derived from the pool of possible traits of individual organisms — see upper level in Figure 2) and performance filters (i.e. environmental filters eliminating traits with inadequate local fitness — see middle level in Figure 2), resulting in associated community composition and ecosystem functioning (see lower level in Figure 2). This framework can be used to analyze the dependence of the functioning of existing agroecosystems on the existence of traits and trait filters, using a procedure developed by [37••]. We suggest that, as trait-based ecology theory develops towards projection of performance filters across environmental gradients to make predictions, it can be applied and further developed to (re-)design agroecosystems at the landscape scale in ways that are conducive to wild biodiversity and to the use of as yet un-/underutilized crops/varieties and livestock/breeds that enhance food security, as well as to environmental health and social well-being.

At the agroecosystem level, this branch of ecology complements (and may re-direct) the trait-based approach from gene to plant to cropping system level, that is now commonly practiced in production ecology.

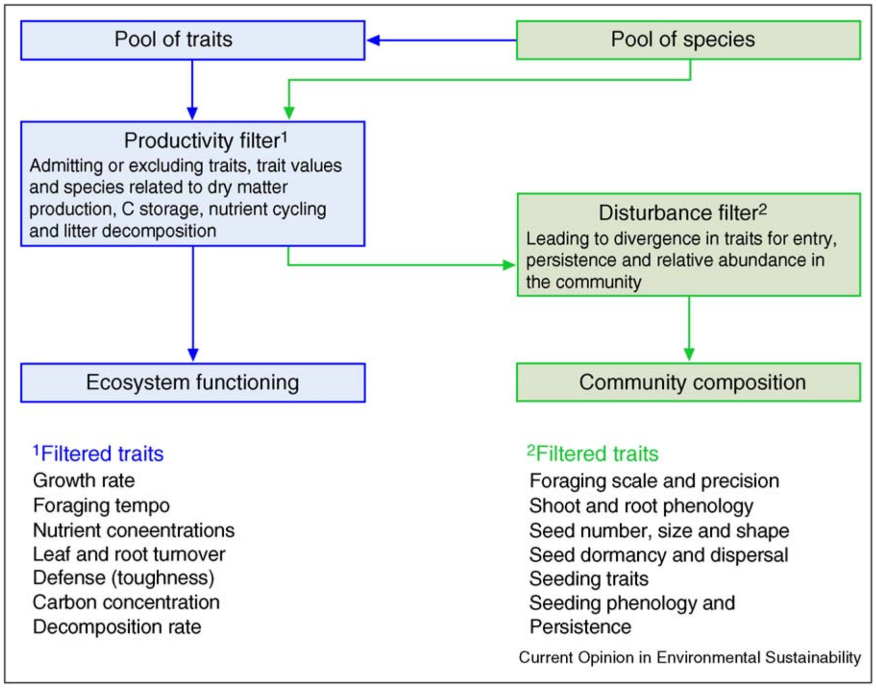
This approach should be supportive to already existing analytical and design-oriented research of the *matrix landscape*, in which apparent ecological interactions between productive and non-productive landscape components are studied (e.g. [38,39•]) to optimize the mimicking of nature.

Prospects for synergy

We acknowledge that most agriculturalists and conservationists are genuinely dedicated to the cause of hunger reduction and biodiversity conservation, respectively [32•,40•]. While neither of them will deny the urgency of either goal, in seeking their respective objectives they may overlook or neglect the needs of the other. However, there are signs of recognition and acceptance of the need for integration. The intensive agriculture community is already responding to new opportunities that ecosystem service provision could offer for agriculture, through environmental labeling or payment for ecosystem service programs [2]. In addition, focusing more on the use of renewable resources, embracing that biodiversity and associated ecosystem services are important production factors, and recognizing that non-use values gain in importance to keep the *license to produce*, would pave the way for *eco-efficiency* in agriculture *sensu* [41•]. The biodiversity conservation community is also recognizing that a complete focus on protected areas for biodiversity on the other hand, denies that much biodiversity resides in agricultural landscapes and that the world has to be fed. The ecoagriculture approach already considers agricultural landscapes as conducive to the persistence of much, though by far not all, biodiversity. In addition, the necessity of external inputs (such as fertilizers and water), wherever the natural conditions are too poor to allow acceptable yield levels, should not be excluded. However, such inputs should be a necessary supplement to the reinforcement of natural processes by applying trait-based ecology in (re-)design and optimization of the management of agricultural and non-productive landscape components.

Is there evidence that reconciling food security and biodiversity conservation is possible in practice? Indeed, the odds are against us. For example, in Agrimonde, a

Figure 2



Environmental filters of plant functional traits, which may be used in the (re-)design of agricultural landscapes. After [35].

foresight study of the French agronomic research institutes INRA and CIRAD, aiming at identifying possible ways to achieve food security at the global level in 2050 using re-analysis of 1961–2003 FAO data, the Agrimonde 'global orchestration' scenario, adapted from [4], is based on the following hypothesis: if food crop yields per ha grow by more than 1% per year (increasing yields in 2050 by 45%) and if no major shifts occur in consumption patterns, an increase of arable land by 18% would be required. An alternative scenario, Agrimonde 1 (adapted from [42]), based on average world and regional consumptions of 3000 kcal/inhabitant/day (as opposed to current trends towards 3600) and on a yield increase of 5.5% in 40 years, even requires an increase of arable land by about 40% [43••]. But in contrast to the 'global orchestration' scenario, the increase would occur by converting grazing lands and pastures into cropped areas. The encroachment on grazing lands, and not on forests, means that the total area under production would not increase, but effects on biodiversity will have to be considered as they depend on future land use [44]. While livestock and mixed farming systems may also support biodiversity [45], alternative strategies will have to be found for livestock producer livelihoods, wherever transformation to cropland is considered necessary. The opportunity costs of biodiversity conservation are demonstrated by such work, albeit that environmental consequences of such changes will highly vary from place to place depending on specific local production patterns and technologies and governance. The extra land area needed for agriculture may become less if serious efforts are made to minimize the loss of energy in food in the chain from harvest to processing, consumption and waste recycling; if the *slow food*, *fair trade*, *animal rights* and *healthy life-style* movements catch on; and if 'demand' were replaced by 'requirement' and 'supply' by 'capacity of ecosystems to produce'. Yet, the Agrimonde results underline that, while food security will remain the world's number one priority, food production must be reconciled *in any scenario* with broader societal goals, such as biodiversity conservation and the provision of the ecosystem services upon which agriculture also relies.

Meanwhile, people living in unacceptable poverty and hunger desire to access the natural assets in support of their own well-being, be that the intensification of vegetable growing, livestock rearing or cotton production; the clearing of woodlands for new families; or the '*mining of woodlands*' for firewood selling [46]. Failing local income sources, individual family members migrate out and remit funds (that are often reinvested in intensified production, often not food crops). In addition, pressures on the wildlands and shifts to intensified production are not purely driven by local people — the global demand for products can see vast areas cleared for commercial agriculture, as is the case for oil palm in Kalimantan [47]. Approaches based on payments for ecosystem services (PES) hold some promise, but emphasize utilitarian, anthropocentric perspectives, and leave intrinsic values and option values poorly represented. Water service payments are the most common [48,49], but current markets and other institutions rarely offer incentives to promote management systems that support biodiversity as a public good, for example, for its option value for improving provisioning and regulating services in the future [50].

Management of crop genetic resources: an example of reconciling biodiversity conservation and food security

We illustrate the tradeoffs or synergies between biodiversity and food security using the case of crop genetic resources, where there is a tension between direct use values and option values. Lipper and Cooper [51] group the benefits of agricultural biodiversity into three main categories:

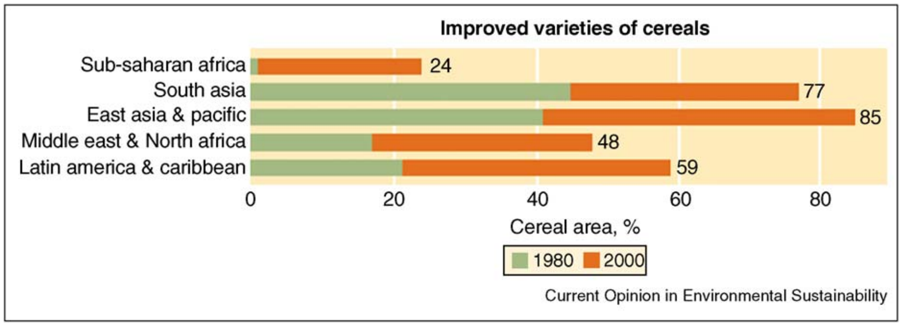
- Private benefits to farmers via the consumption and production values that they derive from crops, which are shaped not only by their own preferences and constraints, but also by policies affecting the demand and supply of crop genetic resources;
- Local or regional benefits to farmers and, ultimately, consumers, when the choices make farming more resilient to biotic and abiotic stress;
- Global benefits to future farmers, plant breeders and consumers, when the choices they make protect against genetic erosion. This benefit is also a quasi-public good at the global scale in that saving genetic resources and the evolutionary processes that generate them, both known and unknown, can benefit future generations of farmers, and help adapt to unforeseen changes. Genetic resilience and conservation of option values are important facets of coping with, and adapting to climate change.

Tradeoffs have occurred between these three categories of benefits. Essentially, use patterns to capture private farm benefits have involved the adoption of modern varieties in replacement of landraces or traditional varieties, as well as a reduction in the number of crops and varieties grown. These factors are considered major causes of loss of crop genetic diversity and associated increases in vulnerability at varying temporal and spatial scales. In recent decades, the development of improved or modern crop varieties for major commodity crops has had a significant impact on improving food security and reducing poverty [49,50]. The impacts have been both direct and indirect: high yields not only generating higher incomes, but also generating employment opportunities and lower food prices [52,54]. In a study looking across 11 food crops in four regions over the period 1964–2000 [9], it was concluded, however, that the contribution of modern varieties to productivity increases was a 'global success, but for a number of countries a local failure.'

The tension between direct use values and option values of biodiversity is particularly poignant in Sub-Saharan Africa, where adoption of improved varieties of cereal crops was very low during initial phases of the green revolution, and only began to reach significant levels in the late 1990s (Figure 3).

In terms of direct use value, key shortcomings cited have been the lack of adaptation of improved varieties to heterogeneous and marginal production areas [48]; emphasis on wide rather than local adaptation; and the failure of many centralized plant breeding programs to breed for traits of concern to small-scale and resource-poor farmers. On the environmental side, increases in pesticide and fertilizer use accompanying high-yielding varieties have, in some cases, generated serious damage to land, water and even human health. Diminishing returns to high input use and the increasing scarcity of water, land and labor, have resulted in a shift in plant breeding away from an exclusive focus on high yields per unit area towards varieties for more knowledge-intensive production systems with reduced input costs [52,54]. Those diminishing returns can be transferred into increasing returns when production ecological insights and approaches are used. That holds for well-endowed and less-endowed lands, but agricultural research and plant

Figure 3



Adoption of improved cereal varieties by region: 1980 and 2000 (the total bar length represents the cumulative total). *Source*: [6•].

breeding for 'less favored' agroecosystems increasingly recognizes the unsuitability of intensive monocropping for such areas and the importance of conserving natural resources through reducing external inputs [52,55]. While new varieties clearly have an important role to play in these systems, the types of technologies focused upon need to be different from those required for high potential, high input systems [55]. This is important in the context of poverty reduction, since the incidence of poverty in these regions is as high, or higher than in high potential production areas.

Improving farmers' access to the crop genetic resources they need to increase the productivity and resilience of their production systems is a key component of strategies to improve food security. Increasing the range of varieties and traits available and affordable to farmers and with sufficient information on their potential performance at the farm level will improve access. At the same time increasing the diversity of genetic resources on offer to farmers can generate positive incentives for *in situ* conservation.

The results of various case studies [56] suggest that, aside from interventions to improve the access and flow of diverse genetic resources in local markets, specific interventions to promote genetic resilience and conservation will be needed. These may or may not involve market interactions. Publicly funded *in situ* conservation programs could work to develop niche markets to enhance the value of genetically important resources, or directly fund farmers to maintain such varieties in production.

We suggest that, just as crop genetic erosion undermines food security, biodiversity loss in general undermines the provision of the ecosystem services agriculture itself depends on. Many examples can be given, in which the balance in the spectrum between short-term benefits at private and local level versus long-term benefits at public and global level tipped over to environmental degradation and out-migration in rural areas. However, there is also a plethora of literature showing that rural communities have opted for conservation and restoration of the resource base, with concomitant reduced out-migration and, indeed, re-ruralization, reconnecting people, land and nature [57] and linking agriculture, conservation and food sovereignty [39•].

Research needs

These areas of failure and success are field laboratories for the research we recommend. They so far suggest that, in regions where rural people cannot independently meet the MDGs of food security and biodiversity, we will need (cf. [58•,59]):

- Understanding of properties and functions of biodiversity as it relates to delivery of ecosystem services in agricultural landscapes and the perception of value amongst stakeholders.
- Enlightened landscape planning and management that allows for multiple functions in landscapes and enables the balancing of development and environmental goals.
- Development of sound agricultural policies that recognize and value the role of biodiversity in agricultural development and food security.
- Markets and institutions for ecosystem services, and payments or governance for ecosystem service systems that work for farmers and poor rural people, implying clear tenure and resource access regimes, fair and equitable contractual arrangements, systems for efficiently transferring funds or advantages from buyers to sellers, and good verification and sanction systems so that stakeholders are satisfied.
- Understanding of synergies and tradeoffs between different policy and management solutions to support choices.

Conclusions

We need to revisit the idea that there are two extreme options, intensive agriculture or ecoagriculture. We need scientific scrutiny and creativity to establish the best ecological means to be applied in both well-endowed and less-endowed areas, to reach the ultimate goal of sustainable development and food security. The challenge of meeting the MDGs on biodiversity and food security and reversing the degradation of ecosystems while meeting increasing demands for their services involves significant changes in policies, institutions and practices. The science we advocate should empower stakeholders from local to global levels with formal knowledge, supplementing informal knowledge, and further inform the decision-making process by developing alternative scenarios for reconciling agricultural production with biodiversity conservation.

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