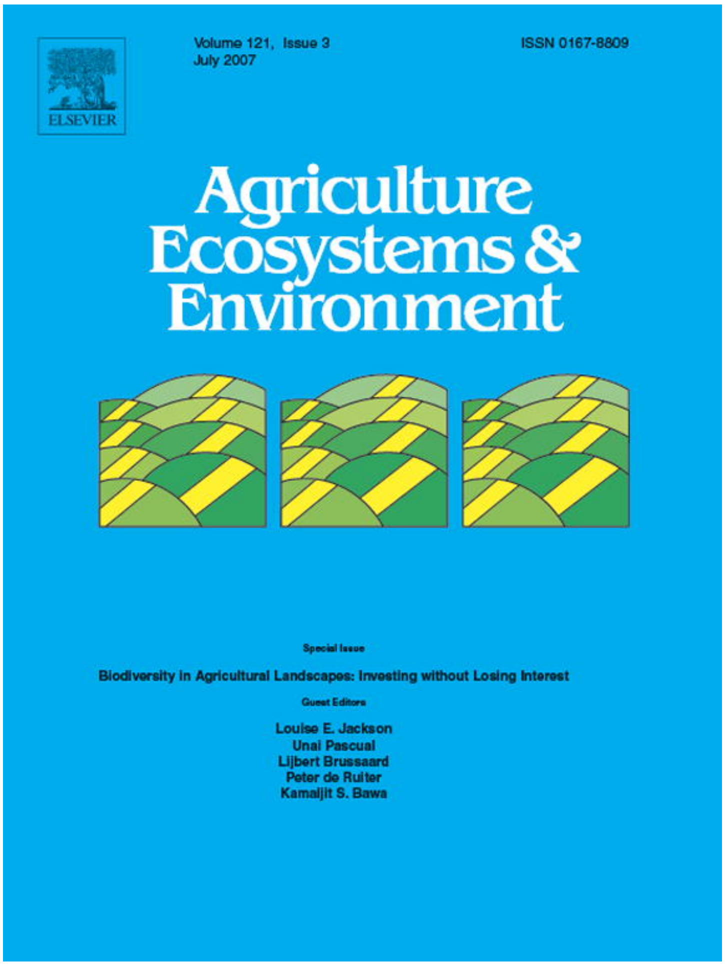
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Utilizing and conserving agrobiodiversity in agricultural landscapes☆

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Abstract

A biodiversity-based paradigm for sustainable agriculture is a potential solution for many of the problems associated with intensive, high input agriculture, and for greater resilience to the environmental and socioeconomic risks that may occur in the uncertain future. The challenge is to understand the combined ecological and social functions of agrobiodiversity, determine its contribution to ecosystem goods and services and value for society at large, and evaluate options for the sustainable use and conservation of biodiversity across the agricultural landscape. Agrobiodiversity is most likely to enhance agroecosystem functioning when assemblages of species are added whose presence results in unique or complementary effects on ecosystem functioning, e.g., by planting genotypes with genes for higher yield or pest resistance, mixing specific genotypes of crops, or including functional groups that increase nutrient inputs and cycling. Simply adding more species to most agroecosystems may have little effect on function, given the redundancy in many groups, especially for soil organisms. The adoption of biodiversity-based practices for agriculture, however, is only partially based on the provision of ecosystem goods and services, since individual farmers typically react to the private use value of biodiversity, not the 'external' benefits of conservation that accrue to the wider society. Evaluating the actual value associated with goods and services provided by agrobiodiversity requires better communication between ecologists and economists, and the realization of the consequences of either overrating its value based on 'received wisdom' about potential services, or underrating it by only acknowledging its future option or quasi-option value. Partnerships between researchers, farmers, and other stakeholders to integrate ecological and socioeconomic research help evaluate ecosystem services, the tradeoffs of different management scenarios, and the potential for recognition or rewards for provision of ecosystem services. This paper considers ways that scientists from different disciplines can collaborate to determine the functions and value of agrobiodiversity for agricultural production, but within the context of understanding how biodiversity can be conserved in landscape mosaics that contain mixtures of land use types.

Keywords: Agricultural intensification; Biodiversity; DIVERSITAS; Ecosystem services; Environmental services; Natural capital; Resilience; Social capital; Sustainable agriculture

1. Introduction

Recent increases in agricultural productivity can largely be attributed to dependence on high-yielding varieties, irrigation, and agrochemical inputs, yet many of the inputs and practices of intensive agriculture are detrimental to human health, environmental quality, and the maintenance of biodiversity (Conway, 1997; Evenson and Gollen, 2003; MEA, 2005; Mooney et al., 2005). As people confront population growth, increased food demand, climate change, and the globalization of agricultural markets during the next few decades, agricultural landscapes will undergo unprecedented transitions. Most (75%) of the world's poor people live in rural landscapes, and are especially vulnerable to the ecological and economic risks associated with such transitions (WRI, 2005).

New solutions are necessary for producing more food and fiber, protecting the resource base upon which agriculture

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depends, and promoting social well-being (MEA, 2005). Conservation of existing biodiversity in agricultural landscapes and the adoption of biodiversity-based practices have been proposed as ways of improving the sustainability of agricultural production through greater reliance on ecological goods and services, with less damaging effects on environmental quality and biodiversity (Collins and Qualset, 1999; McNeely and Scherr, 2003; MEA, 2005). For example, in the Millennium Ecosystem Assessment (MEA, 2005), biodiversity is viewed as an important coping strategy against agricultural risks in an uncertain future, but with the current state of knowledge, this may be viewed as 'received wisdom' rather than substantiated proof of process (Wood and Lenné, 2005).

Evaluating the potential for the utilization and conservation of biodiversity in agricultural landscapes requires new types of communication and cooperation, e.g., among agriculturalists, ecologists, and economists to identify and establish adequate assessment strategies (Robertson and Swinton, 2005), between anthropologists and ecologists to preserve ethnobiological species and functions (Brush, 2004), and between conservation biologists and agriculturalists to seek common ground for managing genetic, species and ecosystem diversity in agricultural landscapes (Banks, 2004). Bridging the natural and the social sciences also creates frameworks that engage farmers and other stakeholders in the search for biodiversity-based solutions for increasing agricultural production in a sustainable manner (Pretty and Smith, 2004). However, much still needs to be learned about biodiversity as natural capital for providing ecosystem goods and services for agriculture, the direct and indirect use value in economic terms that are derived from these goods and services, and the social forces that will promote or impede its sustained adoption (Daily, 1997; Swift et al., 2004; Wood and Lenné, 2005).

This paper focuses on determining the links between agrobiodiversity and ecosystem (or environmental) goods and services, their net benefits, and scenarios that promote sustainable agriculture. The main focus is agrobiodiversity for agricultural production, but within the context of understanding how biodiversity can be conserved in landscape mosaics that contain mixtures of land use types, e.g., that range from production agriculture to extraction of products from wildlands, as well as urbanized or later successional natural areas. It considers ways that scientists from different disciplines can collaborate to determine the functions and value of agrobiodiversity, and the involvement of farmers and stakeholders in this complex process.

2. Defining agrobiodiversity

In this paper, agrobiodiversity refers to the variety and variability of living organisms that contribute to food and agriculture in the broadest sense, and the knowledge associated with them (Qualset et al., 1995). Sometimes agrobiodiversity is considered to encompass a broader definition, to include the full diversity of organisms living in agricultural landscapes, including biota for which function, in the human utilitarian point of view, is still unknown. Under this definition, planned agrobiodiversity is the biodiversity of the crops and livestock chosen by the farmer, while associated agrobiodiversity refers to the biota, e.g., soil microbes and fauna, weeds, herbivores, carnivores, etc., colonizing the agroecosystem and surviving according to the local management and environment (Vandermeer and Perfecto, 1995). Included are croplands and fields, as well as habitats and species outside of farming systems that benefit agriculture and enhance ecosystem functions. Along an ecological hierarchy, examples are: (1) genetic and population characteristics, e.g., of traditional varieties and wild species for human adaptation to socioeconomic and environmental change; (2) community assemblages or guilds that influence crop and livestock production, e.g., that reduce the need for inputs of agrochemicals and off-farm impacts; (3) heterogeneity of biota in relation to biophysical processes within ecosystems, e.g., nutrient cycling and retention that are derived from spatial and temporal variation in biodiversity; and (4) landscape-level interactions between agricultural and non-agricultural ecosystems that enhance resources for agriculture, and potentially, resilience during environmental change.

Although agrobiodiversity has always formed the basis for human food production systems (Brush, 2004), and has provided cultural, spiritual, religious, and aesthetic value for human societies (Nabhan, 1989; Zimmerer, 1991), scientists know relatively little about the combined ecological and social functions of much of the world's agrobiodiversity, and ecological mechanisms underlying these functions. The need for different agricultural products at different times and agroecological conditions, however, is a clearly and commonly articulated reason for conserving crop diversity, and diversity in cropping systems within landscapes. For provisioning services (e.g., food, fuel, fiber, and fresh water production), functions of agrobiodiversity are better understood than for supporting (e.g., nutrient cycling and soil formation) and regulating (e.g., climate, flooding, disease regulation, or water purification) services that usually involve assemblages of species and guilds, each with a complex set of functions and interactions (Pearce and Moran, 1994; MEA, 2005; Pascual and Perrings, 2007; Fig. 1). The potential for biodiversity to provide ecological resilience, i.e., the capacity to recover from disruption of functions, and the mitigation of risks caused by disturbance (Holling, 1996; Swift et al., 2004) is compelling, but poorly documented. The functional significance of biodiversity is likely to be most profound at larger spatial and temporal scales, by providing insurance value, especially when dispersal abilities of organisms allow for immigration within the landscape (Loreau et al., 2003). This would also imply that the 'realized niche' of organisms may shift, such that they occupy greater or different habitats within the

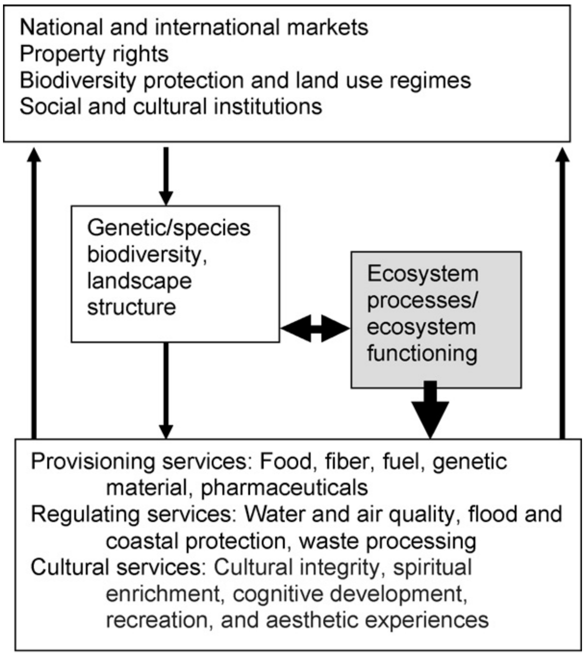

Fig. 1. Flow chart showing that knowledge of ecosystem processes and functions aid in the accurate assessment of the value of biodiversity in agricultural landscapes. Adapted from a diagram by C. Perrings (personal communication) and the MEA (2005).

landscape. The insurance hypothesis proposes that species or phenotypes that appear to be functionally redundant for a specific ecosystem process at a given time may actually diverge in response to environmental fluctuations, thereby stabilizing the aggregate ecosystem function through time. On the short-term, this may essentially be an expansion of the 'realized niche' through genotype × environment interactions, but selection for plasticity could be a likely evolutionary outcome if environmental fluctuations become the norm. Heterogeneous composition of ecosystems in agricultural landscapes may thus provide insurance value that is not detected by the local-scale experiments that are typical of most agricultural research. While some theoretical analysis of the economic relevance of the insurance value exist (e.g., Folke et al., 1996; Perrings, 1998; Baumgärtner, 2007), there are few empirical studies of the insurance value of agrobiodiversity (e.g., Smale et al., 1998; Di Falco and Perrings, 2003, 2005).

By maintaining landscape mosaics composed of different sets of ecosystems, the potential for resilience from biodiversity is expected to increase. Given that agricultural landscapes are prone to disturbance, succession can be more rapid when some indigenous plants remain, seed banks exist, and/or neighboring intact biodiversity-rich vegetation still serves as a source of dispersing organisms (Lamb et al., 2005). Thus, avoiding fragmentation of native vegetation is important for a range of supporting and regulating services, but also cultural and provisioning services, such as extraction of non-forest timber products (NFTP), and the germplasm of NFTP-producing species for domestication (Leakey et al., 2004).

The adoption of biodiversity-based practices for agriculture, however, is not solely based on services and value that society as a whole obtains from such functions. Individual farmers are ultimately the agents who decide how much natural capital to conserve and utilize based on their own objectives and needs, and the social, economic (e.g., markets and policies), and environmental conditions in which they operate. One key problem is that the private and social values of agrobiodiversity differ and the markets and policies do not align such values properly (Perrings et al., 1995; Pascual and Perrings, 2007). The privately perceived value is reflected by the financial benefits arising from positive effects on productivity and/or the savings generated when agrobiodiversity substitutes for costs of synthetic inputs, e.g., pesticides. The total or social economic value of agrobiodiversity includes the value of the ecological services that it provides to others than farmers, e.g., through environmental quality, recreation, and aesthetic values. Generally, individual farmers react to the private use-value of biodiversity and ecosystem services assigned in the marketplace and thus typically ignore the 'external' benefits of conservation that accrue to the wider society. For example, a farmer may benefit from intensive use of the land but generally does not bear all the consequences caused by leaching of excess nutrients and pesticides into ground or surface water, or loss of habitat for native species. This implies an over-exploitation of biodiversity, thus imposing excessive costs on society at large, since this will result in suboptimal or inadequate conservation levels.

3. Rapid change in agricultural landscapes

At present, 10% of the global land area is under modern, intensive agricultural use, 17% is under extensive use associated with the use of far fewer artificial inputs, and 40% is grazed by domestic livestock (Wood et al., 2000; Mooney et al., 2005). The world's population of 6.3 billion people is projected to grow to 7.2 billion by the year 2015, 8.3 billion by 2030 and to 9.3 billion by 2050 (FAO, 2003). By 2050, food production must double to meet human needs. In order to meet this increasing demand for food and fiber, production systems are expected to become increasingly dependent on synthetic inputs of fertilizers and pesticides (Clay, 2004).

Both the expected expansion and intensification of agriculture will increase the human ecological footprint on the earth, which is already present on 80% of the terrestrial area (Sanderson et al., 2002). Efforts to increase or conserve biodiversity in agricultural landscapes seem to imply tradeoffs between food production and the provision of other services, but a bigger challenge is to find ways to meet both sets of needs in a sustainable fashion.

Modern intensive cropping systems have greatly increased the global food supply by relying on high-yielding genotypes that rely on intensive input application including fertilizers and agrochemicals for pest suppression (Matson et al., 1997; Evenson and Gollen, 2003), irrigation (Postel, 1999), and fossil fuels (Smith et al., 1998). Along with high off-farm synthetic inputs, intensification is accompanied by management strategies that are appealing at larger scales: "keep it simple", because "that's better and easier to manage". But the environmental costs have been high in terms of pollution, the loss of biodiversity in both agroecosystems and in wildlands, and the traditional knowledge associated with it (Dirzo and Raven, 2003; Tisdell, 2003; Altieri, 2004; Brush, 2004). At the same time, economic subsidies paid to modern intensive agriculture constitute a large percentage of the global value of agricultural products and have supported the overproduction of some crops and the associated overuse of agrichemicals (MEA, 2005).

Several long-term trends that are projected for human societies also impact agriculture and land use, and thus biodiversity in agricultural landscapes (Kates and Parris, 2003). Rural populations will decrease, and cities will expand to accommodate the growing urban population. Agroindustrialization, i.e., off-farm sources of inputs, food processing, and distribution; new farm technologies; and more vertical coordination between farms and markets, will increase (Reardon and Barrett, 2000). For many situations, it is predicted that agribusiness firms may increasingly dominate food production systems, with concomitant increases in large scale farming and marketing operations (Reardon and Timmer, 2005). But, on the other hand, many low-income countries are likely to retain stable or even increasing rural poulations, especially if higher energy prices for transport and lower communication costs provide incentives for less concentrated patterns of settlement.

4. Agrobiodiversity during agricultural transitions

Worldwide, many agricultural landscapes have already experienced some level of transition towards intensive agriculture, i.e., with high application of inputs based on non-renewable resources, substitution of human labor by machines and fossil fuels, and high capital invested per unit of land (Matson et al., 1997). In many areas where traditional farming systems still exist, mixed practices often co-exist with some use of fertilizers or mechanization combined with continued use of traditional livestock or crop varieties. The general trend towards further intensification based on uniformity and the increased use of external inputs raises real questions as to how agrobiodiversity can realistically be utilized to achieve similar or higher yields, support human livelihoods, and reverse the trend toward lower environmental quality (MEA, 2005). In other words, what research is necessary to determine where and how agrobiodiversity can make positive contributions to productivity, sustainability, and resilience of human livelihoods?

One example is the use of diverse traditional varieties of crops. In many agroecosystems throughout the world, particularly in developing countries, farmers continue to use traditional local varieties (or landraces) of both major and minor crops. It was expected that these would rapidly disappear in the face of new high yielding cultivars (Frankel and Soulé, 1981), but traditional varieties often continue to dominate production, even when modern cultivars are available and used by the community to some extent (Bellon, 1991; Brush, 1995; Louette et al., 1997). It has been suggested inter alia that traditional varieties provide yield stability, are resistant to biotic and abiotic stress, have good resilience, and are adapted to low input agriculture. Hence, they constitute a key component of the natural resources assets of the rural poor in many parts of the world (Altieri and Merrick, 1997; WRI, 2005). There has been increasing interest in the kinds of traditional varieties that are maintained by farmers, where and how this occurs, and who maintains such varieties and for what reasons (Jarvis et al., 2004; Smale and Drucker, 2007).

Understanding when, where, and why farmers continue to maintain high levels of agrobiodiversity is a complex process even when only one component, such as crops or livestock is considered (Brush, 1995). There is now considerable information available about the amounts of crop genetic and species diversity maintained in different production systems and the reasons for this (e.g., Bellon, 1996; Jarvis and Hodgkin, 1999; Teshome et al., 2001; Eyzaguirre and Linares, 2004; Smale, 2006). For example, in Nepal, traditional varieties of rice (*Oryza sativa* L.) continue to be important in many different agricultural landscapes. At high altitudes these are often the only varieties that can survive and in the mid-hill areas over 80% of the rice varieties grown can be local traditional varieties maintained by farmers themselves. Even in the lowland areas, where there is significant intensification, up to 20% of the area may be planted with local varieties (Jarvis et al., 2000; Khatiwada et al., 2000).

The numbers of rice varieties still grown in Nepal are extremely high. Communities of 10,000 people can maintain over 60 varieties in the areas richest in rice diversity. A small proportion of these varieties are usually grown by many farmers in quite small areas (Table 1). However, the largest proportion (75%) are grown by only a few farmers in rather small areas. There seem to be different reasons for the different groups of varieties. The first group, grown by many farmers in relatively large areas, satisfied general subsistence requirements. Other varieties are grown by many farmers in small areas and tend to be associated with specific needs or opportunities including low yielding but high value varieties (e.g., basmati type), those required for cultural purposes such as festivities, or those that were used in response to commonly occurring stresses, such as particular soil types. However, the largest proportion (often over 75%

Table 1
Numbers of rice varieties grown by farmers at a mid-hills ecosite, Kaski, Nepal (from a survey of over 150 farmers in 1998)

Area of farm using a specific variety	By many farmers (more than 10%)	By few farmers (less than 10%)
Large (more than average)	9	2
Small (less than average)	4	44

Classification according to whether varieties were grown by many farmers (over 10%) or few farmers, and whether the farmers planted larger or smaller areas to the specific varieties in their farms. The number of varieties grown by each farmer averaged 3.8 (from Khatiwada et al. (2000).

of the total number of varieties grown in an area) are grown by only a few farmers on small areas. The reasons for this are more difficult to identify and seem to be more mixed. However, this kind of distribution has been found in many other situations where traditional varieties continue to be widely grown (e.g., Zimmerer, 1991).

Other drivers for diversity levels within these Nepalese communities were age and wealth. Larger numbers of traditional varieties were maintained at the household level by richer and older farmers. Smale and Drucker (2007) concluded that the overriding determinants of crop biodiversity levels on farms are geographical location, cultural cohesion, and environmental heterogeneity. They suggest that another common feature is relative isolation from physical markets, but this is more complex than sheer physical distance. Public policy in support of agrobiodiversity is also important, and only recently has this on-farm conservation of genetic resources been recognized by central government agencies in Nepal (Sthapit et al., 2003).

Formal scientific evidence that traditional varieties actually possess some of the attributes claimed for them, such as greater yield stability, resilience and adaptation to stressful production conditions, is actually quite limited, although good case studies do exist, e.g., for barley landraces in Syria (Ceccarelli, 1996). Methodologies for testing the relationship of genetic or species diversity to productivity, vulnerability, and efficiency and to a range of non-provisioning ecosystem services are needed. Farmers customarily consider a complex of reasons in challenging production situations that are often not assessed or mimicked by researchers. Diversity indices developed for scientific research are often far removed from farmer decision-making processes. Farmers themselves commonly identify a set of multiple adaptations which include the local abiotic environment, resistances to various stresses, specific agromorphological traits (maturity period, height, etc.) and meeting various uses (e.g., Smale, 2006). They value various dimensions of diversity which are often not well captured by current measures.

Recent studies (e.g., Smale and Drucker, 2007) suggest that the marginal commercial value from an individual genetic resource in agricultural use will not be high enough to fund national innovation or conservation efforts at levels desirable for society. The total use value of the genetic resource, however, may be much higher than the commercial value due to incomplete markets. Also, there are socioeconomic benefits in terms of the improved environmental quality that is typically associated with farming systems that utilize traditional varieties that require low amounts of off-farm fertilizers and pesticides. In the short-term, at the level of the farm, village, or region, crop diversity will probably continue to persist in marginal environments, even when economic development increases. At a global scale, there is ample evidence that continuing releases of improved varieties, based on conserved genetic resources, have generated economic returns that far outweigh the costs of investment (Qualset and Shands, 2005).

5. Understanding the functions of agrobiodiversity

In examining roles for agrobiodiversity as a contributing force to sustainable agriculture, understanding its functions becomes a high priority. Agrobiodiversity is most likely to enhance ecosystem functioning when a unique or complementary effect is added to an ecosystem, e.g., by planting genotypes with specific genes for higher yield or pest resistance (Qualset and Shands, 2005), mixing specific genotypes of crops (Zhu et al., 2000), using cover crops (Jackson et al., 2004) or intercropping (Vandermeer et al., 2002), supporting more parasitoids or insect enemies with specific roles in controlling pests (Altieri and Nicholls, 2003; Tscharntke et al., 2005), or including a plant functional group, such as a legume, that increases nitrogen inputs and cycling (Drinkwater et al., 1998). Current evidence suggests that merely adding more species to most agroecosystems has little effect on function, given the redundancy in many groups, especially for some members of the soil biota (Swift et al., 2004), e.g., organic matter decomposition or N-mineralization, that are carried out by a large variety of bacterial and fungal species (Schimel and Bennett, 2004).

More is known about the functions of genetic and population diversity in agriculture because farmers and society see a direct result from investment in research that supplies goods with market value. The functions of community and ecosystem-level agrobiodiversity are less studied, although this has recently become an important theme in research geared to improving the sustainability of modern, intensive agriculture (Thrupp, 1998; Wolters et al., 2000). Another factor that has influenced research priorities is that farmers and policy makers often base their decisions to utilize and conserve agrobiodiversity on easily measurable attributes, such as goods in the form of harvested yield, rather than on other functions, or on option or existence value, which are more difficult to measure (Edwards and Abivardi, 1998). Some observations on current knowledge of agrobiodiversity functions at different hierarchical levels are given below.

5.1. Genetic and population diversity and their ecological functions

Genetic and population diversity provides the essential basis for continuing crop and livestock improvement. Breeding programs have exploited landraces and crop wild relatives for genes for increased pest resistance, yield and quality (Briggs and Knowles, 1967; Cooper et al., 2001; Tisdell, 2003). In most cases, crop breeders have selected for morphological and developmental traits, rather than increased rates of photosynthesis or other physiological processes (Jackson and Koch, 1997; Sinclair et al., 2004). Readily available genetic sequence information, and genetic and physical maps open new possibilities for introgressing traits for stress tolerance and disease resistance (Engels et al., 2002), further increasing the potential utilization of agrobiodiversity at the genetic and population levels.

In modern production systems, the focus has been on traits that increase yield, keep up with the treadmill of rapidly changing virulence of specific diseases, meet the demand for resistance to an increased range of biotic and abiotic stresses, or increase the temporal and spatial production of commodities, destined for different uses or planted at different times of the year (Cassman et al., 2003). Spatial diversity with many varieties grown within a single agroecosystem has been to some extent replaced by temporal diversity with the production of a continuous flow of new varieties. Within traditional production systems different needs exist and farmers and communities opt to maintain a number of traditional varieties because they: (1) meet their multiple needs more closely than modern ones, such as legumes (e.g., *Phaseolus* spp.) that provide both food and forage (Singh et al., 1997); (2) perform better under low levels of external inputs such as pesticides and herbicides (Finckh and Wolfe, 1997; Zhu et al., 2000); (3) are less sensitive to abiotic stress, e.g., bean landraces (*Phaseolus vulgaris* L.) for drought resistance in the Mexican Highlands (Acosta-Gallegos and White, 1995; Teran and Singh, 2002); or (4) are composed of genotypic mixtures that minimize risk in different types of seasons, e.g., barley (*Hordeum vulgare* L.) in terminal drought environments in Syria (Ceccarelli, 1996).

Largely due to research based on on-farm participatory approaches and interdisciplinary studies, genotypic attributes, cultural practices, and economic risk aversion have been shown to be closely tied to local biotic and socioeconomic conditions (Smale, 2002; Jarvis et al., 2006). For example, the maintenance of traditional varieties depends on the continued functioning of informal seed exchange networks which can account for up to 90% of seed exchange in some developing countries (Hodgkin et al., 2006). Seed networks constitute part of a complex set of social institutions within rural communities which seem to support the maintenance of common and widespread varieties as metapopulations, although this has yet to be fully established (Brush, 2004).

5.2. Agrobiodiversity within communities and ecosystems and its ecological functions

Recent ecological research has shown that increased plant species richness may have the largest effects on ecosystem processes at relatively low levels (Loreau et al., 2002). This can be attributed to niche complementarity, i.e., differential resource use, positive interactions between organisms, and greater resource capture than in species-poor communities (Tilman et al., 2001; Loreau et al., 2002). These findings suggest that in agricultural communities composed of only a few species, small increases in biodiversity may have a large effect on ecosystem functions such as productivity. This simplistic conclusion, however, is complicated by multitrophic interactions. Species assemblages must be carefully chosen through a set of feedback loops that maintain functions within acceptable bounds for agricultural productivity (Lewis et al., 1997).

The role of agrobiodiversity in pest control strategies shows the need for an ecosystem approach, rather than a reductionist focus on specific organismal interactions. Toxin biosynthesis or other plant defenses against herbivore attack, crop mixtures, release of natural enemies, and pest suppression by a complex soil food web, are examples of using agrobiodiversity for pest control, but these must be manipulated with management practices that are pertinent to specific cropping systems (Lewis et al., 1997; Dicke et al., 2004). Ideally, species assemblages will provide a set of multi-functions, but these raise issues about tradeoffs (Gurr et al., 2003). For example, weeds can favor natural enemies of insect pests by providing non-host foods such as pollen, nectar, alternative hosts and prey, and shelter. Thus, weed management, e.g., with herbicides, must be evaluated in terms of a range of different biota and functions, which are unique to specific agroecosystems. Another issue is scale. Insectary strips of trap crops can provide habitat for natural enemies of insect pests (Colley and Luna, 2000; Hossain et al., 2002). Yet the small scale of most research trials does not portray the true composition of the pest and natural enemy communities and interactions at the actual farm ecosystem or landscape scale (Coll and Bottrell, 1994).

Changes in community structure often occur with a simultaneous change in other inputs, making it hard to differentiate the effects of biodiversity. For example, higher biodiversity, for instance, numbers of species of weeds, carabid beetles, staphylinids, spiders, and soil microbial functional groups, can occur with long-term organic management, compared to conventional management, but changes in ecosystem function cannot be simply attributed to biodiversity, because other inputs also vary substantially, e.g., fertilizers, manures, and legume-based crop rotations (Mäder et al., 2002). Likewise, no-till or conservation tillage systems increase the biodiversity and complexity of the soil food web, supporting more gastropods, earthworms, and arthropods, but functions cannot be solely attributed to the soil biota, because they are accompanied by changes in physical and chemical properties, such as soil carbon accumulation and stratification, and nutrient cycling, that also affect functions (Holland, 2004).

Species interactions can be complicated, and are not always repeatable. Increased nutrition in cereals in a rotation following a grain legume resulted in higher attacks by insect borers, but also improved crop yield (Chabi-Olaye et al., 2005), implying trade-offs that might vary between locations. For soil biota, it is especially difficult to attribute ecosystem functions to biodiversity, since numerous species, many of which are unidentifiable, contribute to soil activity and aboveground responses (Swift et al., 2004; Wardle et al., 2004). Thus, idiosyncratic effects on soil biota can occur, even with the same plant species, or same plant community, or a similar soil type (Wardle et al., 2004; Steenwerth et al., 2006).

Based on these considerations, assessing species diversity and community assemblages for multi-functionality, along with gauging inputs to maximize economic benefit and environmental quality, is important for sustainable agriculture. This requires interdisciplinary research, an ecosystem approach, and often site-specific analyses across different types of gradients (Lewis et al., 1997; Gurr et al., 2003).

5.3. Biodiversity in the agricultural landscape and its ecological functions

The insurance hypothesis of biodiversity, i.e., that higher numbers of species increase resilience and reorganization after disturbance, may be most relevant at the landscape-level (Loreau et al., 2003; Swift et al., 2004; Tscharntke et al., 2005). Agricultural landscapes that are composed of a mosaic of well-connected early and late successional habitats may also be more likely to harbor biota that contribute to regulating and supporting services for agriculture, compared to simple landscapes (Bengtsson et al., 2003; Elmqvist et al., 2003; Swift et al., 2004). In Europe, however, where direct payments to farmers through agri-environmental schemes support the modification of their farming practices to provide environmental benefits, the species richness of birds and vascular plants increased slightly or not at all, although more consistent increases occurred for arthropods (Kleijn et al., 2001; Kleijn and Sutherland, 2003). One problem is that comparisons lack truly paired replicates, so that they constitute an incomplete research design. Another issue may be the low frequency of natural and semi-natural areas in these agricultural landscapes, and few opportunities for dispersal of species and functional groups of insects from relatively undisturbed habitats into agricultural production areas (Duelli and Obrist, 2003).

Assessing landscape-level biodiversity requires close association with farmers and other land managers, as well as involvement with stakeholders engaged with the social forces that affect boundaries between agricultural and non-agricultural ecosystems. This is necessary for both the conservation of undisturbed natural ecosystems, as well as traditional human land use systems (Bawa et al., 2004). Setting up landscape-level biodiversity research poses some major issues related to scale. For example, agroforestry research in Southeast Asia has emphasized both local and regional data collection, combined with modeling, to assess tradeoffs between different types of services provided under landscape scenarios that vary in fallowing frequency and intensification (Murdiyarso et al., 2002; van Noordwijk, 2002; Gillison et al., 2004).

The issue of cropland expansion versus intensification in agricultural landscapes as a means to enhance ecosystem services and biodiversity of wild species has usually been considered in the context of two scenarios (Donald, 2004; Green et al., 2005; Mooney et al., 2005): (1) expansion of less-intensive, often low-yielding, cultivation systems into wildlands, or (2) intensifying agriculture with agrichemical inputs, monocultures, and loss of traditional farming system with little change in the area of cultivated lands. These extremes are too simplistic. For one reason, high input, modern agriculture can quickly dominate an agricultural landscape, often due to economies of scale, so that wildland areas are unlikely to remain. Another issue is the potential for sustainable agricultural intensification, i.e., where plans are devised to utilize biodiversity and renewable resources for higher production and profitability, with lower impact on wild species and their services (McNeely and Scherr, 2003). This scenario requires strong investment by society in research and landscape management.

The economic assessment of services provided by agrobiodiversity at the landscape level is affected by the juxtaposition of different types of agricultural and non-agricultural ecosystems. Simple calculations have shown that pollination services contributed by wild bees increase yields and thus profitability on a farm field, with upscaling to assess impact at larger scales (Kremen et al., 2002; Ricketts et al., 2004). Yet this approach does not show the costs of leaving land out of agricultural production so that the bees' nearby undisturbed habitats are protected. Modelling approaches can show the tradeoffs between various aspects of environmental quality, economics, and social welfare that change when biodiversity-based practices are adopted, e.g., use of open ditches that support biodiversity versus subsurface drains that reduce nutrient losses and erosion (Hietala-Kiovu et al., 2004). Trade-offs at the landscape level, however, are complex and depend strongly on scale (van Noordwijk, 2002).

6. Ecosystem services provided by agrobiodiversity

With the recent publication of the Millennium Ecosystem Assessment (MEA, 2005), great optimism has been placed on the potential for biodiversity to supply ecosystem services, i.e., biophysical functions and ecological processes that support human life and welfare:

"...where agriculture already dominates landscapes, the maintenance of biodiversity within these areas is an important component of total biodiversity conservation efforts, and, if managed appropriately, can also contribute to agricultural productivity and sustainability through the ecosystem services that biodiversity provides (such as through pest control, pollination, soil fertility, protection of water courses against soil erosion, and the removal of excessive nutrients)." (MEA, 2005, p. 13)

There are risks associated with overrating the value of biodiversity for agriculture production, without understanding the direct and indirect links between species richness, community composition, and impacts on flows and rates of delivered services for human well-being. It has been argued that there is a tendency to adopt the 'received wisdom' that biodiversity is essential for ecosystem services and thus for human well-being (Wood and Lenné, 2005). Instead, the focus must be on determining, and quantifying wherever possible, the links between biodiversity and ecosystem services, their strengths and values for society, and outcomes under various scenarios. The various short- and long-term tradeoffs associated with biodiversity-based practices will require predictive models.

One example is the search for biodiversity-based solutions that contribute to sustainable and highly productive agriculture, and also reduce the agricultural impact on wild species and habitats that provide a broader set of ecosystem services (McNeely and Scherr, 2003; Buck et al., 2004). 'Ecoagriculture' is a term that has been coined to reflect this type of strategy. Although some clear examples exist whereby agricultural management, pollution reduction, erosion control, or habitat networks can work to achieve productive food systems and save wild biodiversity and its services (McNeely and Scherr, 2003), more ecological research is needed to provide a foundation for valuation, management and education of conservation practitioners, and as justification for policy-makers to support ecoagriculture (Table 2).

6.1. *The value of agrobiodiversity*

Evaluating the actual value associated with agrobiodiversity or the opportunity costs that would result from conserving it, is a complex undertaking (Gollin and Smale, 1999). There is a lack of adequate knowledge of how the ecological functions that are provided by agrobiodiversity translate into tangible benefits for society. For example, forested riparian corridors in agricultural landscapes clearly improve water quality for irrigation and reduced sediment load due to erosion, but ecologists have a limited understanding of how species richness in riparian zone pays off in terms of these ecosystem services (Naiman et al., 1993; Cavalcanti and Lockaby, 2005). Furthermore, management decisions are hampered by the difficulty of assigning an accurate social value to the services attributable to the diversity of tree species, rather than to the stock of tree biomass or to the ecosystem as a whole.

The social benefits that accrue from biodiversity conservation require assessment of the amount of 'interest' that would otherwise be foregone due to agrobiodiversity loss (Gollin and Smale, 1999; Perrings et al., 2006). Given that so little is known about much of it, such agrobiodiversity might only be credited with its option/quasi option value, or its existence value, i.e., its aesthetic, ethical and spiritual value, rather than its value in providing directly goods and services (direct and indirect use value). Direct use value, or the benefit derived from the direct 'consumption' of biodiversity, is the most tangible, as it can be measured in the form of raw materials used in production of food, fiber and fuel. Option value is a value approximating an individual's willingness to pay to safeguard an asset for the option of using it at a future date. As an example of option value, genebanks created for genetic resource conservation (Fowler and Hodgkin, 2004) have provided a steady stream of materials over the last 20–30 years which have been used both in research (Dudnik et al., 2001) and in breeding and crop improvement (Smale and Day-Rubenstein, 2002; Hodgkin et al., 2003). Some of these materials have provided enormous economic value in terms of crop or livestock breeding (Qualset and Shands, 2005) and the potential for much greater use clearly exists in a number of crops (Duvick, 2002). Quasi option value can also be attributed to genebanks. This is the notion that, as the information on the value of economic services of biodiversity increases with time, i.e., as further ecological knowledge about how biodiversity translates into tangible services for society is gathered, there is a value for conserving biodiversity that otherwise would have irreversibly been lost. Investment decisions in bioprospecting also rest on quasi option value. For agrobiodiversity, there is only a limited amount of economic analysis available on its indirect use value, e.g., provision of supporting and regulating services either on- or off-site (Pascual and Perrings, 2007).

For farmers, decisions to improve land stewardship through agrobiodiversity-based practices may be based upon a mixture of private (instrumental) benefit-cost financial calculation over a period of time and non-use (spiritual and emotional) values (Verhoog et al., 2003). Given that the latter is more difficult to assess, it may be used as a supplementary way to justify conservation of biodiversity, when the instrumental value of biodiversity is not deemed sufficient to conserve it (Dasgupta, 2000), especially if such non-use values enhance legitimacy, trust, and support for conservation policies (Cobb et al., 1999). Conservation biologists, however, often react strongly to such an approach, and believe that species have rights to existence that override economic value (Ehrenfeld, 1988; Gollin and Smale, 1999). The wider set of societal values provided by agrobiodiversity, such as bequest and existence values, have been largely ignored by most of the agricultural research community. Yet both traditional and urban societies derive a mixture of instrumental, existence, and bequest values from

Table 2
Ecological science needed to develop ecoagriculture concepts, i.e., strategies to increase agricultural productivity and save the biodiversity of wild species and their ecosystem services, since farmers and farming communities seeking to protect, manage or restore biodiversity resources in their dynamically changing and fragmented agricultural landscapes, as well as their conservation partners, are often handicapped by the lack of ecological knowledge; adapted from S. Scherr (personal communication)

Ecoagriculture challenge	Critical Issues Requiring Scientific Research
How to assess the importance of ecoagriculture	
Determine geographic priorities for investment in biodiversity conservation	Mapping and documenting existing species populations, distribution and behavior within agricultural landscapes
	Conservation of biodiversity resources in landscapes where ecosystems are especially productive and most converted to agriculture
Analyze the tradeoffs and synergies involved in managing for agriculture productivity vs. for biodiversity conservation	Valuation of biodiversity in agricultural landscapes from biophysical and socioeconomic perspectives on short- and long-term time scales
How to keep natural areas in agricultural landscapes	
Design networks of natural areas in agricultural landscapes to achieve effective habitat and biodiversity functions	Habitat requirements for wild species within different types of ecosystems within agricultural landscapes, especially in response to agricultural intensification
	Flows of genes, diseases, and other associated biota between wild and domesticated species
Assess progress towards achieving biodiversity conservation objectives in agricultural landscapes	Methods for measuring biodiversity within dynamic, highly fragmented landscapes (including interaction effects with key types of agricultural patches)
Determine minimum size, type and configuration of natural areas required to achieve conservation of different species and ecological communities within agricultural landscapes	Degree and type of ecological disturbances that can be tolerated by different species and ecological communities
Achieve sustainable harvest of wild species from natural areas	Species tolerance and viability under diverse types of management and harvest
How to manage agriculturally productive areas for biodiversity conservation	
Mobilize resources for habitat protection through ecosystem service payments to farmers and farming communities	Contribution of wild and domestic biological resources to maintaining or increasing agricultural productivity, resilience and sustainability
	Substitution of off-farm inputs with agrobiodiversity-derived ecosystem services
Determine where reduction of agrochemicals are especially important for biodiversity conservation	Tolerance of wild species and ecological communities to agrochemical exposure
Decide where changes in crop, tree and livestock management are especially important for biodiversity conservation	Response of wild species to agricultural management practices (e.g., cultivation, timing of practices, soil management)
	Interaction of wild species with different types of agricultural crops and livestock
Maintain adequate levels of both livestock and wildlife health	Interrelationships of disease vectors for domestic stock and wildlife
Develop best management practices to conserve wild species critical for agricultural production	Species population dynamics, behavior and interactions with agricultural species and landscapes for soil microorganisms, crop pollinators, etc.
Determine parameters for irrigation system design and management to minimize threats to wild species and habitats	Impact of hydrological regimes on species and habitats

agrobiodiversity (Perrings et al., 1995; Pascual and Perrings, 2007).

6.2. Communication between ecologists and economists

Ecologists and economists need to speak the same language so that the latter can advance in assessing the social worth of ecosystem services derived from biodiversity. One issue is clarification of definitions and types of biodiversity and functional groups. For economists, the notion of biodiversity often refers to native, wild biodiversity and its supposed functions (Nunes and van den Bergh, 2001). But an adequate description of the diversity of a system must also reflect not only the total number of taxa (species or genotypes) present, but also their distribution and proportion, their ranges of variation and its adaptive significance.

Furthermore, many economists generally refer to biodiversity as a much wider set of biological resources, which may somewhat overlap. Hence, the difference between land use change and changes in higher organization levels of biodiversity is often not clear in the economics of biodiversity. This practice may be a direct consequence of the lack of information flowing from ecologists on specific ecosystem services. Thus, economists search for a pragmatic solution to assess the value of natural resources in the broadest sense. For instance, they tend to relate biodiversity values to entire natural habitats (e.g., forest or wetland), and thus assess biodiversity values from the goods and services derived from all the ecological functions of that habitat. Even when there is a close association between organisms and their physical habitat, e.g., soil microbes in physical contact with soil particles, ecologists recognize the need to separate functions due to organismal biodiversity, and those due to physical processes. Hence, most economic analyses assume that functions of a given land use type are attributable to its biodiversity, without clear distinction between functions provided by biodiversity versus other natural resources in that land use type, i.e., soil and hydrological resources (Pearce and Moran, 1994; Stocking, 2003).

Therefore, by assuming a direct connection between biodiversity and the provision of goods and services, economists may over-simplify the benefits of biodiversity (Fig. 1). The various valuation tools employed by economists are specific to different aspects and functions of biodiversity, and to ecological processes that vary spatially and temporally. Likewise, ecologists will assess a more appropriate set of environmental services when they are aware of the socioeconomic situations and types of decision-making that is involved in changing agricultural management practices or land use regimes (Lambin et al., 2003). Involving farmers and stakeholders will identify values that researchers do not easily see, and can demonstrate the pros and cons that will be part of any negotiation process.

7. Agrobiodiversity utilization and conservation: the human dimension

An array of issues for agrobiodiversity research has been described above, and the emphasis has been on moving toward sustainability through interdisciplinary research between biophysical and social sciences. This fits within the concept of integrated natural resource management (iNRM), which invokes an approach that examines tradeoffs between enhanced productivity, human well-being, and ecosystem resilience (Tomich et al., 2004, 2007; Sayer and Campbell, 2003). Partnerships and participatory approaches between researchers, farmers, and other stakeholders to integrate ecological and socioeconomic research are instrumental in understanding ecosystem services and the tradeoffs of different management scenarios. On-farm research and adaptive management also encourages the adoption of biodiversity-based practices, with multifunctionality of biodiversity as a central theme (FAO, 2003).

Such partnerships are not always easy to set up or to sustain. The deliberate search for win–win–win environmental, social, and economic benefits that provide agricultural productivity, improved human livelihoods, and biodiversity conservation is a lofty goal, yet it can be too simplistic (Adams et al., 2004; Foley et al., 2005). For instance, the recent popular approach known as ‘integrated conservation and development projects’, or ICDP, has often failed due to over-optimistic goals and tenuous assumptions, i.e., that rational planning and an initial injection of seed money would allow nature conservation to co-exist with economic development, and that the benefits would be equally distributed among local people (McShane and Wells, 2004). At the local scale, packaging projects as win–win situations masks the incompatibilities among stakeholders' goals, something that may be further exacerbated by poverty (Adams et al., 2004). Instead, it is now considered more effective to focus research on how ecological and socioeconomic processes underpin distinct types of local relationships between poverty reduction and conservation (WRI, 2005). Priority should thus be given to understanding the protection of key biodiversity assets that provide goods and services that are fundamental to the well-being of the poor. In addition, research on ways to decentralize, and create local or regional authority and accountability may be more effective in reducing poverty through greater dependence of rural communities and households on income derived from biodiversity and ecosystem services. In the long-run, this may result in greater sustainability of this natural capital.

Especially for agricultural landscapes without high poverty levels, conserving and enhancing agrobiodiversity is often perceived as an aspect of land stewardship, even when direct use values are not clearly known. When people are well connected in groups and networks, and their combined knowledge is used in planning and implementation of conservation activities, sustained stewardship of natural resources is more likely to occur over the long term (Pretty and Smith, 2004). Social capital encompasses elements of social structure and organization that allow individuals to accomplish their personal aims and interests regarding nature and their environment. Key features of social capital are: (1) relations of trust; (2) reciprocity and exchanges; (3) common rules; and (4) connectedness to networks and groups (Pretty and Ward, 2001). Research that shows the processes that link social and natural capital for agrobiodiversity conservation is a high priority (Katz, 2000; Uphoff and Wijayaratna, 2000; Pretty and Smith, 2004; Rodríguez and Pascual, 2004).

Institutions can create, deliver, and monitor better incentives to promote the sustainable use and conservation of biodiversity in agroecosystems, that otherwise would not be provided through farmers' private incentives (Article 11

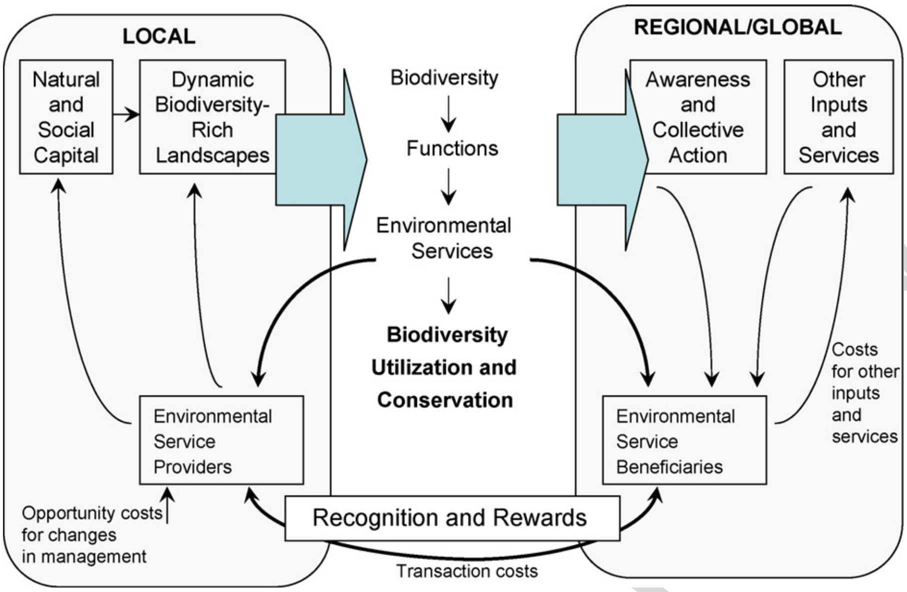

Fig. 2. Linkages between providers and beneficiaries of environmental services derived from dynamic biodiversity-rich landscapes, each supporting biodiversity utilization and conservation by different mechanisms. Adapted from van Noordwijk et al. (2004).

of the Convention on Biological Diversity). Market-based mechanisms may be necessary to conserve biodiversity (MEA, 2005; Pascual and Perrings, 2007). For instance, the idea of 'payment (or more generally 'rewards') for environmental services', P(R)ES, is gaining interest from governmental and non-governmental organizations (NGOs), but requires a clear understanding of the long-term value of agrobiodiversity's services, and negotiation frameworks. NGOs, working with the funds of external donors, could play an important role in developing and maintaining programs to utilize and conserve agrobiodiversity, e.g., bridging between farmers and agencies who pay for environmental services, or facilitating the production of 'added value' products that come from farming systems that utilize and conserve biodiversity (Pagiola et al., 2004; Rodríguez and Pascual, 2004; van Noordwijk et al., 2004). Also, stakeholders outside agriculture, e.g., tourist industry or fishers, may be induced to pay for conservation measures that offset the loss of biodiversity in agricultural landscapes that reduces their income and livelihood security. Social capital may become increasingly important as P(R)ES becomes more prevalent, since relations of trust that are forged by institutionalized groups encourage long-term individual investments for the common good, and generate economies of scale that bring greater economic and ecological benefits (Pretty and Smith, 2004; Rosa et al., 2004). As suggested by Fig. 2 (van Noordwijk et al., 2004), recognition and/or rewards for environmental services from beneficiaries in adjacent or even distant areas can generate finances and incentives for environmental service providers to maintain biodiversity-rich agricultural landscapes.

The international program of biodiversity science, DIVERSITAS (http://www.diversitas-international.org), has identified a scientific agenda for biodiversity use in agricultural landscapes that identifies three key research objectives that integrate biological and social sciences (Jackson et al., 2005; Perrings et al., 2006). Following the general core project structure of DIVERSITAS, there are three main themes of this agroBIODIVERSITY Science Plan: (1) to assess biodiversity in agricultural landscapes and the anthropogenic drivers of biodiversity change (bioDISCOVERY); (2) to identify the goods and services provided by agrobiodiversity at various levels of biological organization,

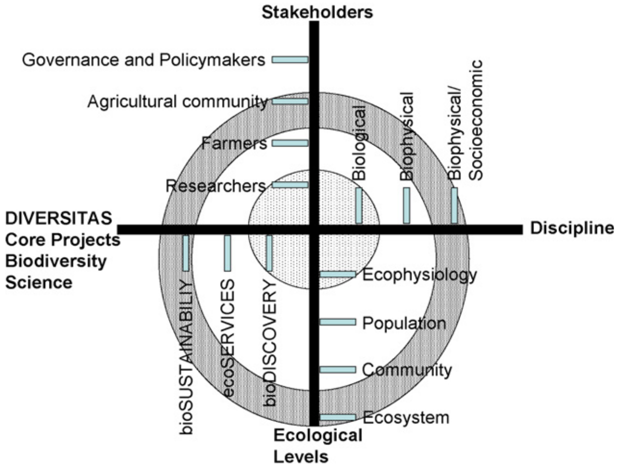

Fig. 3. Overlapping strategies for accomplishing cross-cutting research on agrobiodiversity. Two possibilities are shown. The interior circle shows a narrow research approach that is confined to biological processes that explain the ecophysiological responses of organism(s), and which act as drivers for their distribution in the landscape (bioDISCOVERY). The outer circle represents a research approach that involves biophysical and socio-economic disciplines to understand ecosystem functions that affect decisions by farmers and other members of the agricultural community, and which can lead to conservation and sustainable use of biodiversity (bioSUSTAINABILTY). Many other permutations are possible.

e.g., genes, species, communities, ecosystems and landscapes (ecoSERVICES); and (3) to evaluate the options for the sustainable use and conservation of biodiversity in agricultural landscapes (bioSUSTAINABILITY). Combining elements from each of the three themes, i.e., cross-cutting these themes, will provide biophysical and social scientific information on viable agrobiodiversity options for decision-making (Fig. 3). Cross-cutting disciplinary boundaries and among stakeholder groups is also necessary to achieve an information base that is broad enough to ensure relevance to long-term land use decisions and policy (Bawa, 2006). While no single research project may have the scope to cross-cut full sets of these different types of components, there are many potential approaches that can address a broader range of issues (ecological principles, interdisciplinarity, stakeholder involvement, and biodiversity science; Fig. 3), than are typically now used in research on sustainable agriculture.

8. Conclusions

This paper has emphasized the need for more research on agrobiodiversity and its ecosystem services, both to justify agrobiodiversity conservation in traditional agricultural systems, and as a potential source of innovation for sustainable agriculture. Although a growing number of ecologists, economists, and NGOs are making the case that conservation measures for agrobiodiversity must be deployed immediately, precisely because of the current lack of scientific understanding of the totality of ecosystem services provided by agrobiodiversity, a much stronger case can be made for conservation if there is definitive information on its ecosystem services. For this reason, society will need to invest more heavily in agrobiodiversity research, as well as conservation for the sake of option and quasi-option value, not only of genetic resources (Goeschl and Swanson, 2002), but of the much broader set of organisms and habitats that occupy the range of ecosystems in agricultural landscapes.

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