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Social-ecological and regional adaptation of agrobiodiversity management across a global set of research regions

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ABSTRACT

To examine management options for biodiversity in agricultural landscapes, eight research regions were classified into social-ecological domains, using a dataset of indicators of livelihood resources, i.e., capital assets. Potential interventions for biodiversity-based agriculture were then compared among landscapes and domains. The approach combined literature review with expert judgment by researchers working in each landscape. Each landscape was described for land use, rural livelihoods and attitudes of social actors toward biodiversity and intensification of agriculture. Principal components analysis of 40 indicators of natural, human, social, financial and physical capital for the eight landscapes showed a loss of biodiversity associated with high-input agricultural intensification. High levels of natural capital (e.g. indicators of wildland biodiversity conservation and agrobiodiversity for human needs) were positively associated with indicators of human capital, including knowledge of the flora and fauna and knowledge sharing among farmers. Three social-ecological domains were identified across the eight landscapes (Tropical Agriculture-Forest Matrix, Tropical Degrading Agroecosystem, and Temperate High-Input Commodity Agriculture) using hierarchical clustering of the indicator values. Each domain shared a set of interventions for biodiversity-based agriculture and ecological intensification that could also increase food security in the impoverished landscapes. Implementation of interventions differed greatly among the landscapes, e.g. financial capital for new farming practices in the Intensive Agriculture domain vs. developing market value chains in the other domains. This exploratory study suggests that indicators of knowledge systems should receive greater emphasis in the monitoring of biodiversity and ecosystem services, and that inventories of assets at the landscape level can inform adaptive management of agrobiodiversity-based interventions.

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1. Introduction

Agrobiodiversity includes biota on and around farms, and is natural capital that provides options for food security and other ecosystem services. At the field scale, agrobiodiversity sustains crop and livestock productivity, nutrient cycling, pathogen suppression, pest control and human nutrition (Jackson et al., 2007; Geiger et al., 2010; Jarvis et al., 2011; Letourneau et al., 2011; Remans et al., 2011). At the landscape scale, agrobiodiversity supports water quality and mitigation of greenhouse gas emissions (e.g. through nutrient and carbon storage by plants and soil biota), pollination and pest control (e.g. through ecological connectivity for flora and fauna), and protection of nearby wildland ecosystems (e.g. when biodiversity is used for ecological functions that reduce inputs and impacts of agricultural chemicals) (Jackson et al., 2007; Geiger et al., 2010; Tscharntke et al., 2005).

Agrobiodiversity is frequently lost when high agrochemical inputs (e.g. synthetic fertilizers, pesticides, and fossil fuels) are used to intensify agriculture and increase land and labor productivity (Matson and Vitousek, 2006; Perfecto and Vandermeer, 2010). The use of such non-renewable inputs has proven efficient on the short-term and feasible across many of the world's biomes, but raises major concerns about environmental quality and socioeconomic vulnerability. In contrast, ecological intensification promotes high and reliable agricultural production, but with a strong role for agrobiodiversity and biological processes (Doré et al., 2011). For example, in cacao production, moderate shading from a diverse tree canopy supports high yields and antagonists that control insect pest and diseases, thereby avoiding boom-and-bust cycles typical of cleared plantations (Tscharntke et al., 2011) and deforested lands (Rodrigues et al., 2009). Ecological intensification typically invokes a land-sharing or wildlife-friendly farming approach, rather than segregation of land for nature and production (land-sparing) (Phalan et al., 2011a,b). Land-sparing does not address the real-world complexity of socio-economic issues, externalities caused by high-input intensification (e.g. non-point source pollution), nor the provision of multiple ecosystem services (Tscharntke et al., 2012). The challenge of ecological intensification is to encourage innovations for biodiversity-rich farming systems that are resilient, sustainable, and thus improve the livelihood of farmers while supporting the conservation of wild species by limiting the adverse effects of agriculture on wildland habitats (Srivastava et al., 1996; Perrings et al., 2006).

Unlike typical biodiversity conservation, for which the goal is to maintain or restore wildland ecosystems, biodiversity-based agriculture is oriented toward interventions that will improve land management and living standards, especially in situations with persistent poverty (Barrett et al., 2011). Reliance on biodiversity-based agriculture and ecological intensification requires investing in the five key livelihood resources: human, social, natural, physical, and financial assets (Scoones, 1998). Such sets of assets differ among different types of biomes, agricultural landscapes and social-ecological systems (Campbell et al., 2003), and may ultimately be useful for the design of global monitoring systems for agriculture and ecosystem services (Sachs et al., 2010).

In this paper, eight landscapes across five continents were analyzed to identify factors important for increasing agrobiodiversity and ecosystem services across an agricultural landscape. The objectives were to: (1) compare landscapes in terms of their past and current trajectories toward intensification, and the gain or loss of different types of ecosystem services; (2) assemble a set of indicators associated with assets at the landscape level related to adoption of biodiversity-based agriculture; (3) determine if landscapes can be classified into social-ecological domains, i.e., sets of landscapes with common sets of assets; and (4) examine biodiversity-based interventions for ecological intensification in different landscapes (Fig. 1). This analysis is based on literature review and interdisciplinary expert judgment, and was conducted to gain insights into ways that local decision-making can be better integrated into the global agenda for ecosystem services and land stewardship.

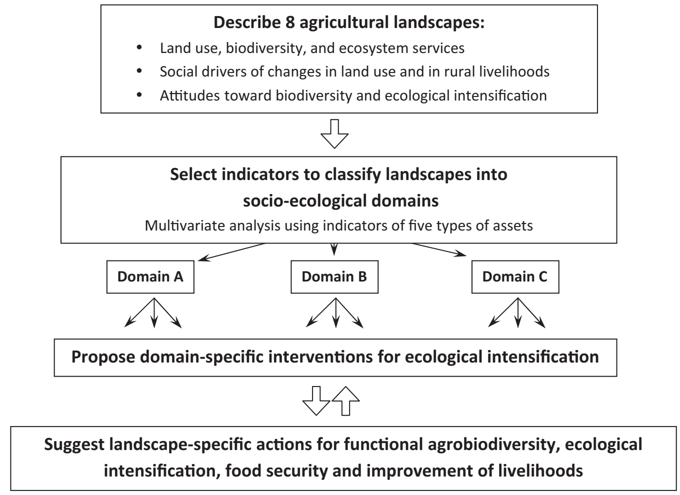

Fig. 1. Conceptual diagram of the framework of the paper, in which eight landscapes are used to explore pathways for biodiversity-based ecological intensification of agriculture.

2. Approach and methods

Participatory agrobiodiversity research has occurred for 5–20 years at the eight sites in the study (Table 1). Five of the sites occur in biodiversity 'hotspots' (Myers et al., 2000). The following biomes are represented: temperate broadleaf and mixed forest; Mediterranean forest, woodland and scrub; tropical/subtropical moist broadleaf forest; tropical/subtropical dry broadleaf forest; and tropical/subtropical grassland, savanna and shrubland (McGinley and Ellis, 2008). The types of agroecosystems and their management intensity, levels of deforestation, topography, propensity for soil erosion and water quality issues show marked differences among the sites, as do rural livelihoods and poverty levels. Landscape descriptions at each site provide an overview on: (1) land use, biodiversity and ecosystem services; (2) socio-economic drivers of changes in land use and rural livelihoods; and (3) attitudes of social actors toward biodiversity and ecological intensification.

The next two tasks used an interdisciplinary approach with expert knowledge and judgment from researchers, mixing expertise in ecology, conservation biology, agriculture and social sciences. Each site was represented by one to three researchers, and nearly all of the researchers had visited at least two of the sites. A team of three to five researchers worked on each task. After the researcher(s) from each site provided data relevant to each task, the task's team then checked for consistent scoring among landscapes by interviews with the researcher(s) from each site.

One task was a comparative analysis to determine if the eight sites could be grouped into social-ecological domains (Fig. 1). Forty indicator attributes were assigned to one of five categories of landscape-level capital assets (financial, physical, natural, human and social/institutional capital) related to rural livelihood resources (Table 2). Balanced sets consisting of eight variables associated with each of the five capital assets were identified among the entire group. The data on each asset component consisted of a simple high-medium-low ranking system. Multivariate analysis used principal components analysis. The hierarchical clustering of sites was performed with the divisive analysis

Table 1
General characteristics of each landscape, arranged alphabetically. Attributes are related to agricultural livelihoods, land use and biodiversity.

Site	Agroecosystem list	Major agriculture–livelihood–biodiversity issues	Topography	Native vegetation types	External inputs	Soil erosion/water quality	Deforestation
Hoeksche Waard, The Netherlands	Mostly arable rainfed rotation of monocrops (sugar beet, potato, wheat and open field horticulture) Some cattle/sheep on cultivated grasslands	Field margins and non-productive landscape elements along dykes and ditches as a source of biodiversity and associated environmental services for intensive agronomic crop production and recreation. Low poverty	Flat polder, reclaimed from sea	Broad-leaved temperate forest	High	Erosion low, water quality moderate	Forests gone; some restoration of semi-natural woodland along rivers
Jambi transect, Sumatra, Indonesia	Rubber agroforest Rubber monoculture Oil palm monoculture Upland and irrigated rice	Conservation of highly biodiverse rubber agroforests vs. conversion to intensive rubber or oil palm monocrop plantations. High poverty	Peneplain and piedmont	Dipterocarp rainforest	Low	Low erosion, water quality moderate	Moderate
Koubri, Central Plateau, Burkina Faso	Rainfed sorghum and millet Irrigated vegetables and rice Livestock on uncultivated grassland in savanna Shea/Karité (*Vitellaria paradoxa*) fruits for local and export, néré fruits and seeds (*Parkia biglobosa*)	Restoration of soil quality for crops for local consumption (food security) and for irrigated cash crops, and restoration of savanna trees for firewood, medicines, and other non-timber forest products for local human well-being, as well as export. High poverty	Plains, river flood plains	Open dry tropical savanna	Low	High soil erosion, Moderate water quality	High
Pacajá, Pará, E. Amazon, Brazil	Upland rice, cassava, beans Cocoa agroforestry Home gardens Pastures for beef cattle Some illegal logging activities	Keeping options open for small-holder agriculture by maintaining and restoring forest cover for cocoa (high value cash-crop), sustaining production for household use, improve access to markets. High poverty	Rolling hills, river plains, and some steep terrain	Rainforest	Low	Erosion high (steep terrain) or low (plains), Water quality high	Moderate
Sierra Madre, Chiapas, Mexico	Rainfed annual maize–sorghum–beans (mainly monocrops) Cattle grazing in cultivated pastures and browsing at forest margins	Participatory development of agroforestry and silvopastoral systems to reduce deforestation and soil erosion on steep slopes with overgrazed pastures and maize fields. Inequality in income and land-ownership. Moderate poverty	Steep mountains and narrow valleys	Tropical deciduous forest Oak-pine forest Montane cloud forest	Moderate	High erosion and water quality	High
Sacramento Valley, USA	Intensive vegetables (organic and conventional) Intensive grain monocultures Cattle grazing on uncultivated annual grassland	Crop diversification and restoration of native vegetation in farm margins to increase soil and water quality and the options for response to climate change, and to support small- to mid-sized operations, farmworkers and local food systems and migrant farmworkers. Low poverty	Rolling hills and alluvial plain	Grassland Riparian deciduous forest Tule marsh	High	High erosion, low water quality	Woodlands nearly gone except in uplands
Western Ghats, India	Rainfed finger millet–maize–beans–amaranthus in mixture Coffee agroforest Forest products, e.g. gooseberry, honey, lichen	Sustainable livelihoods from products from forest–agriculture ecotones to reduce pressure on biodiversity in protected forests. High poverty	Rolling hills and steep hills	Dry scrub Dry and moist deciduous forest Rainforest patches	Low	High erosion, water quality moderate	Low

Table 1 (*Continued*)

Site	Agroecosystem list	Major agriculture–livelihood–biodiversity issues	Topography	Native vegetation types	External inputs	Soil erosion/water quality	Deforestation
Zona da Mata, Minas Gerais, Brazil	Sun coffee monoculture or intercropped with maize–beans–cassava; agroforestry coffee Cattle/cultivated grassland Sugarcane Vegetable gardens	Strong social movements among groups of farmers to develop agroforestry systems that utilize and conserve biodiversity and sustain soil quality, and to integrate with markets. Moderate poverty	Rolling hills	Atlantic coastal rainforest (seasonal semi-deciduous forest)	Moderate	High erosion and moderate water quality	High

clustering (diana) routine available in the R package 'cluster' (R Development Core Team, 2006), using several distance metrics for the dissimilarity matrix that were compared. Minimum-variance clustering with Ward's method (also known as Orloci's method) was chosen to minimize heterogeneity within groups, hence favoring clusters with approximately equal size.

A second task then used local expert judgment to identify viable biodiversity-based interventions and actions to shift current agricultural practices toward ecological intensification (Fig. 1). Viable is used here to refer to both actually observed as well as potentially successful interventions which might arise from adaptive management of actual interventions. Local experiences of the individual researchers, their ongoing participatory projects with various types of stakeholders in their respective research sites, scientific literature and other published materials prepared by government agencies and non-governmental organizations (NGOs) associated with the eight sites formed the basis for this exercise. Both field-scale and landscape-scale interventions were identified. The researcher(s) from each landscape then evaluated each intervention for feasibility and potential impact locally, and suggested specific actions deemed most important for implementation.

3. Results

3.1. Descriptions of agricultural landscapes

The following descriptions of the eight agricultural landscapes deal with historical and cultural factors that affect the trajectories toward biodiversity-based agriculture and ecosystem services. The order reflects the relative positions of the eight landscapes along a gradient of increasing biodiversity use and conservation, i.e., along axis 1 of the PCA bi-plot described below (Fig. 2).

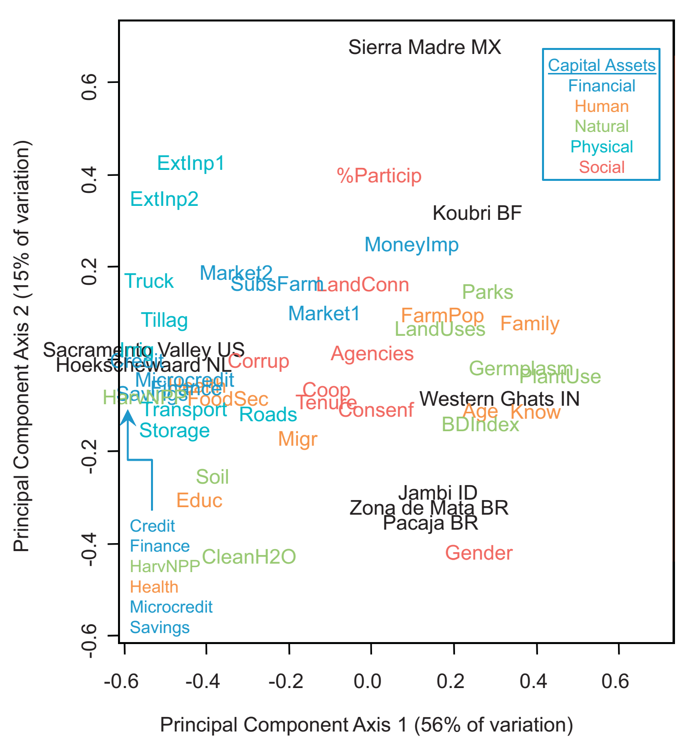

Fig. 2. Multivariate analysis of indicators of five forms of capital and the eight landscapes using principal components analysis. Indicator values are shown as abbreviations that are explained in Table 2. The same data are used for the hierarchical clustering of sites in Fig. 3.

Table 2
40 Indicator variables for the five types of capital assets evaluated for each landscape and the units for assigning scores by expert judgment. The abbreviations are used in Fig. 2.

Indicator categorized by form of capital asset	Abbreviation	Units
Human capital		
Farmers vs. total population	FarmPop	High > 60%, medium = 10–60%, low < 10%
Average age of farmer (willingness to innovate/invest)	Age	High < 35 yrs, medium 35–55 yrs, low > 55 yrs
Farmer knowledge of flora and fauna	Know	High = mostly adept, medium = uneven, low = mostly marginal
Education of farm families	Educ	% Beyond primary education, low < 20%, medium = 20–70%, high > 70%
Migration from rural to urban	Migr	Important, medium, not important
Family structure of farms	Family	% of farms operated by extended family, high > 70%, medium = 20–70%, low < 20%
Under five mortality rate per 1000 births[a]	Health	No. of deaths/1000 births, high > 50, medium = 10–50, low < 10
Food security	FoodSec	Months with food shortage, absent = 0; frequent = 1–3 months, severe > 3 months
Social/institutional capital		
Gender dominating farming and biodiversity mgmt	Gender	High = men and women, medium = mainly women, low = mainly men
Corruption/lack of trust	Corrup	High = bribing frequently, medium = sometimes, low = almost never
Proportion of land owners involved in project	%Particip	High > 20%, medium = 5–20%, low < 5%
Land tenure	Tenure	High = most farmers 'own' land (>80%), medium = 20–80% own land, low < 20% own land
Agencies supporting local agrobiodiversity use	Agencies	High > 8 agencies, medium = 3–8 agencies, low < 3 agencies
Marketing cooperatives	Coop	%Farmers in cooperatives, high > 50%, medium = 10–50%, low < 10%
Level of conservation enforcement by government	Consenf	High = frequently enforced, medium = sometimes enforced, low = rarely enforced or no reserve
Connection to the land	LandConn	%Farmers on land > 50 yrs, high = 60–100%, medium = 30–60%, low = 0–30%
Financial capital		
Savings as liquid assets	Savings	% Earned income as savings in liquid assets, high > 50%, medium = 10–50%, low < 10%
Formal financial institutions	Finance	Main institutions used, high = banks, medium = family borrowing, low = petty lenders
Use of microcredit by impoverished farmers	Microcredit	%Farmers with microcredit, high > 50%, medium = 10–50%, low < 10%
Government subsidies to % of farmers	SubsFarm	%Farmers who get subsidies, high > 50%, medium 20–50%, low < 20%
Credit for investment	Credit	%Farmers capable of obtaining loans, high > 75%, medium = 50–75%, low < 50%
Remittance of $ from out of region	MoneyImp	%Farmers who receive money from out of region, high > 50%, medium = 20–50%, low < 20%
Market integration as % of farmers	Market1	%Farmers selling products in the market, high > 50%, medium = 20–50%, low < 20%
Market integration as % of products	Market2	%Farm products sold in markets, high > 75%, medium = 25–75%, low < 25%
Natural capital		
Net Primary Productivity: harvested portion	HarvNPP	Harvested portions of the NPP, high > 25%, medium = 5–25%, low < 5%
BD index[b]	BDIndex	Rankings of high, medium and low for each group of taxa
Water quality	CleanH2O	%Population with clean drinking water, high > 80%, medium = 50–80%, low < 50%
Soil fertility	Soil	%Farmers on naturally fertile soils, high > 50%, medium = 20–50%, low < 20%
Land in parks/preservation areas	Parks	%Land, high > 20%, medium = 5–20%, low < 5%
Richness of landuse categories in the landscape[c]	LandUses	No. land use categories, low < 5, medium = 5–8, high > 8
Source of germplasm of crops and domestic animals	Germplasm	Mainly traditional varieties, both, improved varieties
Utilization of endemic plants for food and medicine	PlantUse	High > 20 species, medium = 5–20 species, low < 5 species
Physical capital		
Mechanization/tillage	Tillag	Level of tillage/mechanization in most cases: machinery, animal traction, hand-labor
Farmer ownership of car or truck	Truck	%Farmers, high > 60%, medium = 20–60%, low < 20%
Irrigation availability	Irrig	%Farmers with available irrigation, high > 60%, medium = 20–60%, low < 20%
External inputs (e.g. fertilizers, pesticides) by farmers	ExtInp1	%Farmers using external inputs, high > 60%, medium = 20–60%, low < 20%
External inputs (fertilizers, pesticides) as % of inputs	ExtInp2	%External inputs used on farm, high > 60%, medium = 20–60%, low < 20%
Postharvest storage availability	Storage	%Commodities with storage capacity, high > 60%, medium = 20–60%, low < 20%
Internal access to markets (road network)	Roads	Availability of roads in the landscape: high, medium, low
Infrastructure for external markets (airport, harbor, rail)	Transport	Availability of external transport: high, medium, low

[a] World Bank list of economies (December 2010) (http://siteresources.worldbank.org/DATASTATISTICS/Resources/CLASS.XLS).
[b] Mean rankings of scores for biodiversity in the region: birds: high > 300 spp., medium = 100–300 spp., low < 100 spp.; butterflies: high > 100 spp., medium = 50–100 spp., low < 50 spp.; plants: high > 1000 spp., medium = 200–1000 spp., low < 200 spp.; amphibians: high > 15 spp., medium = 5–15 spp., low < 5 spp.; mammals: high > 60 spp., medium = 30–60 spp., low < 30 spp.
[c] Agroforestry, perennial cropping/orchard/fruits, annual cropping, pastures, home-gardens, forest plantation, secondary forest/"bush", fallow/abandoned land, primary forest, irrigated land, silvo-pastoral, swamp/water bodies, urban/industrial.

3.1.1. *Western Ghats, India*

The Biligiri Rangaswamy Temple Wildlife Sanctuary belongs to the Western Ghats global biodiversity hotspot (Myers et al., 2000). The hilly landscape encompasses a large rainfall gradient and supports several types of vegetation: scrub forest, dry deciduous forest, and evergreen forest interspersed with grasslands (Bawa et al., 2002). The area is inhabited by rich variety of plant (Setty and Mandal, 2007), bird (Aravind et al., 2001), and butterfly (Aravind and Rao, 2002) species. Approximately 150 taxa (e.g. native plant species and local varieties of beans, millet, banana and vegetables) are grown in agricultural fields (Setty and Mandal, 2007), but some of these traditional crops are being replaced by cash crops such as coffee and pepper. Non-timber forest products provide 30–60% of the income of local people. The forests also provide pollination, water resources, tourism and cultural services from the temples and religious deities that are enshrined there. The agricultural activities of the different social groups are important for food security but threaten the rich forest biodiversity.

Traditionally, the indigenous Soligas people practiced swidden agriculture (shifting cultivation) and hunting until 1974, when the area was declared a wildlife sanctuary (Setty et al., 2008). Many Soliga settlements were moved to the edge of the sanctuary, limiting their access to forest resources. The collection of non-timber products was banned in 2004, but the Forest Right Act of

2006 acknowledged the right of access of forest dwellers to its resources. Less than 30% of the Soliga households have tenure, and then only to up one ha of land. Currently under the Forest Right Act, Soligas have received individual rights to cultivate land, and 25 Soliga villages have community rights, such as grazing and use of forest resources for their livelihoods, conservation and management. Recently, the designation of the sanctuary as a Tiger Reserve implies that the Soligas will be asked to settle outside the reserve, even though they have co-existed with tigers for many years. Co-management is likely to conserve more biodiversity than would alienation and conflict between the Soligas and the State.

Local movements striving to maintain cultural identities, researchers, and conservationists now recognize that successful conservation approaches have to consider land rights, traditional ecological knowledge, and local cultures (Chatterjee, 2008). NGOs are working with the Soligas to maintain and enhance agrobiodiversity (e.g. by planting native species in home gardens). Participatory approaches have been employed to map and monitor wild biodiversity and cultural diversity; establish seed banks to conserve native crop seeds as well as decentralized nurseries; and facilitate access to credit and markets for selling traditional products (Setty and Mandal, 2007).

3.1.2. Jambi, Sumatra, Indonesia

The Dipterocarp tropical forests of the Sumatra Lowland, situated in the Sundaland global biodiversity hotspot (Myers et al., 2000), are being rapidly transformed to rubber, oil palm and pulpwood plantations for global markets. These changes threaten the food security of the local people and the environmental services provided by rubber agroforests (e.g. terrestrial C stocks, watershed functions and cause loss of endemic species of local and global cultural value (Murdiyarso et al., 2002; Tomich et al., 2004; van Noordwijk et al., 2012)). Dramatic biodiversity loss has been shown for ferns (Beukema and van Noordwijk, 2004), termites (Jones et al., 2003) and birds (Beukema et al., 2007).

A century ago, rubber agroforests emerged as a unique biodiversity-rich land use type, combining human population densities of 30–80 km^{-2}, above-average income, retention of 70% of forest diversity and production of a large range of fruits, medicines, timber and firewood (van Noordwijk et al., 2012). In the 1970s, migration, commercial logging, improved infrastructure and demographic pressure caused major shifts in land use, labor and power relations (Murdiyarso et al., 2002; Feintrenie and Levang, 2009; Miyamoto, 2006; Williams et al., 2001). This led to increased rubber monoculture with higher production and slightly higher returns to labor, but loss of environmental quality and higher risk for livelihoods and associated social costs (Michon et al., 2005; van Noordwijk et al., 2012). Similarly, oil palm monocultures expanded due to strong policy support (Feintrenie and Levang, 2009).

In parts of the area, NGOs and research organizations have helped to raise local awareness of drawbacks of the intensification of rubber, oil palm, and pulpwood production. Despite strong arguments for payments or rewards to conserve the multiple ecosystem services generated by agroforestry (Tomich et al., 2004; van Noordwijk et al., 2012), external support has been hard to acquire. Conservation agencies and researchers tend to focus on biodiversity conservation in the natural forest remnants rather than outside protected areas. Domestication of native fruit and timber trees within agroforests has made little progress, partly because policy does not support legalization of on-farm timber harvests.

Interest is increasing for ecocertification of rubber agroforests with high biodiversity value and locally for micro-hydropower generation which helps to internalize environmental benefits from forests (van Noordwijk et al., 2006). Participatory efforts have enhanced the negotiation of local conservation perspectives in district level policies and land use plans. However, economic drivers, and local and national government policies do not support the transformation of forest plantations to agroforests in more than a fraction of the landscape.

3.1.3. Pacajá, Pará, Eastern Amazonia, Brazil

This site is a recently deforested Amazonian lowland landscape, located along a trail (travessão 338S) that branches off of the TransAmazon highway near Pacajá in the State of Pará. The landscape has a ‘fishbone-like’ pattern, with most of the deforested area near access trails, and the remaining primary and secondary forest further away. Locally important ecosystem services include abundant clean water, and alternative sources of food and medicines (Merry et al., 2008). The agricultural land provides food for home consumption and some families grow marketable products for cash (e.g. agroforestry cocoa and tree plantations). Family agriculture dominates and it relies on swidden agriculture cropping of cassava, rice, maize and beans, followed by low-productivity pastures and livestock breeding (Ozório de Almeida and Campari, 1995).

Colonization started in the 1970s through an official government program giving 100 ha lots with formal settlement, but informal settlement grew during the 1990s (Merry et al., 2008). Timber extraction then increased as did annual crops and pastures. In 2007, 70% remained in forest in various stages of conservation, but deforestation and land use transitions are leading to rapid biodiversity loss. Soil ecosystem services are still relatively viable although low soil fertility and erosion are problematic and soil compaction in pastures is reducing infiltration and water storage.

Farmers lack technical assistance and access to markets. Electricity only arrived in 2010 and health care is locally absent. The University of Altamira, 200 km away, has begun to organize technical assistance and research in the area. To optimize the use of cleared land, there is a need for sustainable intensification of perennial food crops, better access to improved crop and animal genetic resources and improved rice, cocoa and pasture management. The road network is the greatest challenge for sustainable land use options, together with uncertain property rights (Merry et al., 2008). Forest-based activities in the Amazon are not considered to be a ‘productive’ use according to Brazilian law and therefore do not advance tenure or land value, creating a disincentive to protect tropical forests.

3.1.4. Zona da Mata, Minas Gerais, Brazil

Zona da Mata is situated in the biodiversity hotspot of the Atlantic Coastal Rainforest (Myers et al., 2000), in the state of Minas Gerais. Only 7% of the natural forest remains, mainly in small fragments or protected areas (Freitas et al., 2006). The most important forest is in the Serra do Brigadeiro Natural Park, which is characterized by high altitudes, deeply weathered soils and harbors the rivers, Rio Doce and Paraiba do Sul. The forest is of importance for climate regulation and water resources (Schessl et al., 2008).

In the mid-1800s, forests started being replaced by full-sun coffee, the main cash crop, and later by pasture, mainly managed by smallholders, most of whom are landowners with properties $\leq$20 ha (IBGE, 2006; Valverde, 1958). Other crops such as maize, beans, sugarcane and cassava occupy smaller areas (Cardoso et al., 2001). In the 1970s, Green-Revolution technologies were introduced in the region with strong government support, which aggravated social and environmental problems. In the 1980s, during the process of re-democratization of Brazil, a strong grassroots movement for alternative agriculture formed.

Supported by grassroot movements, farmer unions, NGOs and researchers, farmers started experimenting with biodiversity-friendly technologies such as agroforestry (Cardoso et al., 2001).

Agroforestry systems were implemented by farmers from several municipalities, mainly in the buffer zone of the Serra do Brigadeiro Natural Park. In the process of experimentation with agroforestry, farmers selected local and some exotic multipurpose tree species suitable for intercropping with coffee (de Souza et al., 2010). Native species were used mainly for soil quality restoration, and exotic species for fruit production. More than 15 years of on-farm experience with agroforestry has shown that full-sun coffee and monoculture pasture can be converted to a more diverse matrix, thereby combining biodiversity conservation, environmental protection and production functions of the landscape (de Souza et al., 2012a). Another important benefit is the diversification of production on farms. Shaded coffee also secures future coffee production in the area, large parts of which will become too warm for full-sun coffee with climate change (de Souza et al., 2012a).

3.1.5. Sierra Madre de Chiapas, Chiapas, Mexico

The upper watershed of the Tablón River in the subhumid tropical mountains of the Sierra Madre de Chiapas comprises the largest part of the core and buffer zones of the La Sepultura Man and the Biosphere (MAB) Reserve. The altitude ranges from 800 to 2550 masl. The watershed belongs to the Mesoamerican biodiversity hotspot (Myers et al., 2000) and includes several types of neotropical and forest and riverine ecosystems. These forests provide important local and global ecosystem services, such as a diversity of locally used and globally marketed products, water input for hydro-electricity production and carbon sequestration. In some parts of the watershed, agricultural lands function as corridors connecting forested areas. Yet the area is poised near a threshold of significant and probably irreversible land degradation (García-Barrios t al., 2009; Sanfiorenzo-Barnhard et al., 2010; Validivieso-Pérez et al., 2008).

Human colonization started in 1950. Local people struggled to acquire land from the government. Today, the area has 7000 inhabitants who rely on diversified livelihood strategies (maize, cattle, coffee, cyclic migration and poverty subsidies). Due to Mexico's forestry, agricultural, rural and migratory policies in the era of globalized markets, half of the watershed has been deforested through regional commodity booms: first lumber extraction, then intensive maize production on steep slopes and currently extensive cattle grazing. The net deforestation rate decreased after the reserve was created in 1994, but the marginal increase in secondary succession has had limited impact on biodiversity conservation. Rangelands still harbor a wide variety of herbaceous and woody species, but open and over-grazed grasslands are becoming more dominant (García-Barrios t al., 2009; Sanfiorenzo-Barnhard et al., 2010; Validivieso-Pérez et al., 2008).

Many farmers still perceive more limitations than opportunities from having their land in a biosphere reserve. Consistent government policy for the buffer zone is lacking, and conflicting trends are being promoted by uncoordinated government agencies (García-Barrios t al., 2009). Collaboration projects have recently developed between visionary farmers, conservation officers, NGOs and research institutes, mainly focused around community-based fire control, small scale reforestation, introduction of fodder trees into pastures and agroforestry palm and coffee (Speelman et al., submitted for publication).

3.1.6. Koubri, Burkina Faso

The Koubri district is in the Central Plateau, 25 km south of Ouagadougou, and has a semi-arid tropical climate. Population density is high. The Central Plateau originally was an open woody savanna ecosystem, and is now highly transformed by agriculture. 88% of the population is engaged in smallholder swidden agriculture, and food security is an issue. The main crops are sorghum, millet, cowpea and maize (Hien, 1998), and irrigated rice and vegetables to a lesser extent. A mosaic of different land uses and gradients of intensification now characterizes the landscape: irrigated fields in the lowland area; low-input rainfed and short fallow farming in high population density areas; longer fallows, intermittently used as rangelands, in areas with poorest soils; and the savanna reserve, used for extraction of non-timber products, such as shea for global cosmetic markets.

Since the early 1980s, population and market growth, along with changing rainfall patterns and declining cereal yields, have exerted strong pressure on available land and led to severe land degradation (Reij et al., 2005) and decline in food security (Hien, 1998; Reintjes, 1986). Cropping methods and cultivars are more homogeneous, and many traditional crop varieties are replaced by modern ones. Loss of biodiversity has reduced wood and non-timber forest products. Short fallows dominated by shrubs are expanding, but with reduced plant and animal diversity. Erosion of indigenous knowledge constitutes a further threat to agrobiodiversity (Balma et al., 2003). To preserve the open savanna, the Government set aside one-third of Koubri as a reserve, but enforcement of existing legislation on biodiversity and forest conservation is lacking.

The main concern lies in increasing soil quality for agricultural intensification (Hien, 1998; Reij et al., 2005; Batterbury, 1994; Ouedraogo and Millogo, 2007) and in agroforestry for firewood, construction and non-timber forest products (Ayuk, 1997). Awareness for these issues is being generated by NGOs who are also supporting farmers with training.

3.1.7. Hoeksche Waard, The Netherlands

The Hoeksche Waard is an island near Rotterdam, which has been gradually reclaimed from the sea since the 15th century, so most terrestrial biodiversity has arrived in the last 500 years. There is widespread interest in agrobiodiversity and associated ecosystem services such as biological pest control and soil biodiversity for agriculture, water quality, landscape aesthetics and recreation/tourism (Steingröver et al., 2010; Rutgers et al., 2012).

Since 1950, the area has undergone major socioeconomic transformations, with land reallocation and land use change toward specialization and intensification of agriculture. Since 1990, various environmental regulations, such as the ban of certain pesticides and restricted fertilizer use, have been imposed. Biodiversity came on the political agenda when farmers joined with local NGOs who work to protect the cultural heritage functions of the landscape against the urban sprawl of nearby cities. In 2005, the Hoeksche Waard received the legal status of a 'National Landscape' to conserve its unique characteristics (Steingröver et al., 2010).

At present, options for multifunctional agriculture are being explored, including biodiversity-based practices that are compatible with commercial farming. Implementation of field margins on farmland is steadily increasing, facilitated by agri-environmental subsidies. Consultation workshops, economic impact assessments and collaborations for biodiversity restoration have involved different stakeholders such as farmers, extension workers, researchers, water management agencies, nature conservation NGOs, and local, regional and national government bodies (Steingröver et al., 2010). Achievements include the establishment of biodiverse field margins along arable fields, re-establishment of natural vegetation around creeks and restoration of high biodiversity nature areas. A 'green-blue network' along dikes and creeks has been designed to improve the value of biodiversity and water quality (Sloots and van der Vlies, 2007).

3.1.8. Sacramento Valley, California, USA

Yolo County, in the Sacramento Valley, is within the biodiversity hotspot of the California Floristic Province (Myers et al., 2000).

Oak-dominated woodlands, savannas, and wetlands were the main vegetation types before European settlement 150 years ago. Today, intensive row crops and livestock, geared to national markets, are the main agricultural systems, with only a small fraction consumed locally. Year-round agriculture has greatly reduced biodiversity in irrigated lowland crop fields and in grazed upland grasslands (Barbour et al., 1993).

The region's trajectory has been toward greater intensification, less diversity of crop species, larger farm sizes and fairly stable markets for commodities (Jackson et al., 2011). Dam building and groundwater extraction now makes irrigation possible in the entire lowland area, and has reduced erosion and flooding (Vaught, 2007). Riparian corridors now have low species richness (plants, nematodes, and microbial communities) and low scores for soil quality and riparian health (Culman et al., 2010; Young-Mathews et al., 2010). In addition, they move crop pesticides to the San Francisco Bay delta (Moore et al., 2008; Smalling et al., 2007). Restoration activities have increased in the past 10 years, including planting of native, drought-adapted trees, shrubs and grasses for hedgerows, riparian and canal buffer strips and for upland grassland restoration (Lulow et al., 2007; Smallwood et al., 1998).

State legislation in 2006 requires planning for climate change. Mitigation and adaptation measures for agriculture are underway (Jackson et al., 2011; Lee et al., 2009). Stronger implementation of legislation to reduce non-point source pollution is also occurring. There are collaborations between NGOs, farmers and researchers for restoration (Brodt et al., 2009; Seavy et al., 2009) and for transition to organic production (Smukler et al., 2010). Local initiatives to increase processing facilities and diversify markets are aimed at supporting long-term agricultural production in the area.

3.2. Classification of landscapes using five capital assets

In the PCA ordination of capital assets, sites dominated by high-input intensive agriculture (Hoeksche Waard, NL and Sacramento, US) were distant from the other six sites (Fig. 2). The four tropical forest/agroforest sites were more similar than were the Koubri, BF or Sierra Madre, MX sites. The ordination revealed a gradient in land use and management along axis 1 of the PCA bi-plot, which explained 56% of the variation. The loading scores on the left side of axis 1 (i.e., termed negative loading scores) included higher financial assets, credit for investment (*Credit*) and savings in liquid assets (*Savings*); the physical assets, irrigation availability (*Irrig*) and farm ownership of a car or truck (*Truck*); and natural capital in the form of harvested portion of the net primary productivity (*HarvNPP*). On the right side of axis 1, the most positive loading scores were for higher natural capital, including use of endemic plants for food and medicine (*PlantUse*), use of both traditional and improved varieties of crops and domesticated animals (*Germplasm*), land in parks/preservation areas (*Parks*), as well as for high human capital as indicated by strong farmer knowledge of flora and fauna (*Know*) and family structure of farms (*Family*).

The Western Ghats, IN site had the highest loading score on axis 1, with the other three tropical forest sites nearby (Fig. 2). This cluster of four sites was associated with indicators with high loading scores on axis 1 and a high biodiversity index of various taxonomic groups (*BDIndex*) (Table 2). For the landscapes in this cluster, wildland biodiversity conservation co-occurs with utilization of agrobiodiversity for human needs. These indicators of natural capital co-located with four indicators of high human capital, two of which have very high loading scores on axis 1 (*Know* and *Family*), but also younger age of the farmer as an indicator of his/her willingness to innovate/invest in new interventions (*Age*), and a variable used as an indicator of knowledge transfer, i.e., a high proportion of the population as farmers (*FarmPop*). Formal education (*Educ*), however, was low in this cluster. The linkage between these indicators of human and natural capital implies that local knowledge and its exchange within households and communities was highly interconnected with biodiversity use and conservation.

At the lower end of the axis 1 of the PCA biplot, high levels of physical capital was closely associated with the Hoeksche Waard, NL and Sacramento, US sites, which also had the highest harvested proportion of net primary productivity (*HarvNPP*) (Fig. 2). Several indicators of high physical capital at these sites were: mechanization and tillage (*Tillag*); irrigation availability (*Irrig*); farmer ownership of a car or truck (*Truck*); internal access to markets by a road network (*Roads*); infrastructure of external markets (*Transport*); and availability of postharvest storage (*Storage*). High external inputs, such as fertilizers and pesticides as a high percentage of inputs, and used by a high percentage of farmers (*ExtInp1* and *ExtInp2*), were not restricted to these sites, which explains their loading scores slightly outside the main cluster. Several indicators for financial capital were closely aligned with high physical capital assets at these two sites: savings as liquid assets (*Savings*), formal financial institutions (*Finance*), use of credit for investment (*Credit*), and use of microcredit by impoverished farmers (*Microcredit*), who actually are rare in the NL and US sites. These indicators reflect the stability as well as dependence on financial capital of high-input agriculture in these sites, which also undoubtedly contributes to the high food security (*FoodSec*) and health (*Health*) scores. Other indicators of financial capital, however, were more variable amongst the eight sites: government subsidies to farmers (*Subsidies*), remittance of money from outside the region (*MoneyImp*), and degree of market integration of farmers and products (*Market1* and *Market2*).

Axis 2 of the PCA biplot only explained 15% of the variation, and generally represented a gradient in agricultural stability and intensification (Fig. 2). The most negative loading scores were higher water quality (*CleanH2O*), involvement of both genders in farming (*Gender*), higher soil fertility (*Soil*), and low migration from rural to urban (*Migr*). The most positive loading scores were high percentage of farmers using external inputs (*ExtInp*), participation of landowners in site projects (*%Particip*), external inputs as percentage of inputs (*ExtInp2*), remittance of funds from outside the region (*MoneyImp*), and percentage of products sold in markets (*Market2*).

At the positive end of axis 2, the Sierra Madre, MX and Koubri, BF sites had long-term farmer connection to the land (*LandConn*) and the highest engagement in site projects (*%Particip*) (Fig. 2). For these sites, however, soil fertility (*Soil*) and water quality (*CleanH2O*) are low, and along with social factors that have caused workers to leave (see above) and import money (*MoneyImp*), have created farming instability. At the negative end of axis 2, three of the tropical forest/agroforest sites (Jambi, ID; Zona da Mata, BR; and Pacajá, BR) formed a cluster that was associated with more equal dominance of men and women in farming (*Gender*), and higher soil and water quality (*Soil* and *CleanH2O*, respectively).

Hierarchical clustering generated three clusters: (1) Hoeksche Waard, NL and Sacramento, US; (2) Jambi, ID; Pacajá, BR; Zona da Mata, BR; and W. Ghats, IN; and (3) Koubri, BF and Sierra Madre, MX (Fig. 3). The clusters are generally consistent with the ordinations, allowing the designation of a set of socio-ecological domains, which can be summarized as follows. The 'Temperate High-Input Commodity Agriculture' domain has highly productive farmlands that rely on high inputs of fossil fuels, agrochemicals, and has little or no intact or wildland ecosystems (Hoeksche Waard, NL and Sacramento, US). Loss of soil and water quality due to high agrochemical inputs, heavy machinery and lack of irrigation and drainage stability are threats to long-term productivity. Major investments are required to increase the

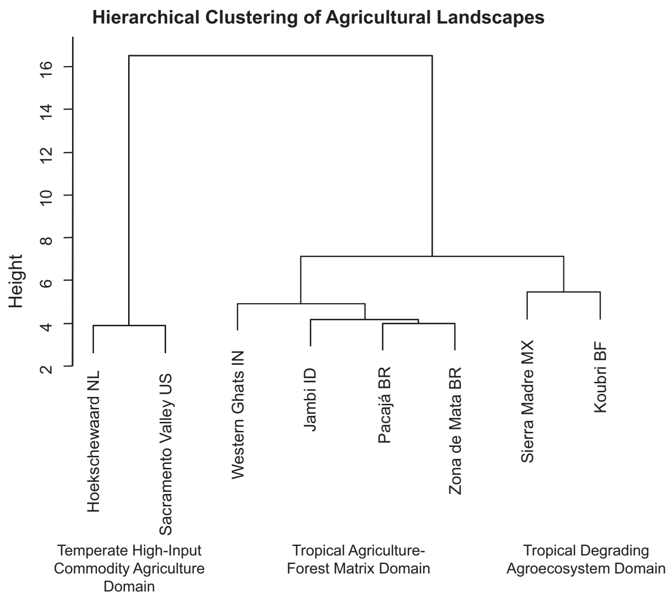

Fig. 3. Classification of the eight agricultural landscapes based on the 40 indicator values for capital assets. The same data were used in the ordinations in Fig. 2. Height refers to the distance measure among sites (Ward's method).

multifunctionality of these landscapes, such as for the ecosystem services from restoration of semi-natural habitats or maintenance of cultural heritage, and the stability of livelihoods for small- to mid-size farmers and migrant farmworkers. The 'Tropical Agriculture-Forest Matrix' domain is a matrix of natural forests, forests managed for traditional products and agricultural fields. This domain experiences threats from deforestation and plantations or has already undergone such changes in parts of the landscape (Jambi, ID; Pacajá, BR; Zona da Mata, BR; and W. Ghats, IN). The 'Tropical Degrading Agroecosystem' domain has had significant forest conversion, and degradation of soil quality in farmlands is associated with high rural outmigration, food insecurity, and susceptibility to extreme weather events (e.g. drought or flooding) (Koubri, BF and Sierra Madre, MX).

3.3. Biodiversity-based interventions for ecological intensification of agriculture

We identified 22 types of biodiversity-based interventions for ecological intensification across the sites (Table 3). The 9 types of field-scale interventions refer to changes in management that could be adopted by an individual farmer. The 13 types of landscape-scale interventions typically require multi-scale and/or multi-stakeholder processes for implementation (examples of such interventions follow in Table 4).

Managing soil biota to improve soil fertility was the only field-scale intervention shared among all landscapes, possibly influenced by the strong awareness of soil science by researchers within the group, and reflects the types of biases that occur in studies based on expert knowledge (Geneletti, 2005). At the field-scale, types of management interventions for the Jambi, ID; Koubri, BR; Pacajá, BR; Sierra Madre, MX; W. Ghats, IN and Zona da Mata, BR landscapes included more productive genotypes of crops, trees and pastures; domestication of native fruit trees and native fodders (herbs and trees); capacity building for soil fertility/crop management; and exploring options for adaptation to climate change (Table 3). Increased firewood production systems were unique to Koubri, BF and Sierra Madre, MX. Overall, this set of interventions was largely focused on food security and poverty alleviation. In contrast, key field-scale interventions suggested for the Hoeksche Waard, NL and Sacramento, US sites were for environmental quality and conservation of wildlife (Table 3). An example was restoration of field margins to increase the biodiversity of plants and beneficial insects. New biocontrol agents for pests and diseases were only mentioned for the California landscape. The types of field-scale interventions thus tended to be similar within domains. Nearly every type of intervention was considered a priority for the sites in the 'Tropical Degrading Agroecosystem' domain (6.5 interventions on average), whereas this decreased to 3.75 for the 'Tropical Agriculture-Forest Matrix' domain, and only 2 for the 'Temperate High-Input Commodity Agriculture' domain.

Three landscape-scale interventions were held in common across all sites: support for a mosaic of agro- and natural ecosystems for a diverse set of ecosystem services; channeling benefits of ecosystem services to their providers; and scoping and consensus building among multiple stakeholders for the value of biodiversity (Table 3). In nearly all of the landscapes, interventions for water issues (e.g. quality, supply or flooding) were considered high priority issues, as were interventions for the configuration of the ecosystem mosaic for ecological connectivity for biota. Diversification of cropping systems and development of new markets was considered highly important in half of the landscapes at this scale. Increase in the genotypic variation of existing commodities was a priority in two tropical forest sites, and increasing cash commodities within natural ecosystems were also priorities there and in the African site. Land management to reduce poverty was considered important, except for Pacajá, BR and W. Ghats, IN and the most intensively managed landscapes. Aesthetic value was considered of high importance in the temperate, high-input landscapes, but also in the Sierra Madre, MX biosphere reserve. Only in the Netherlands' landscape was high priority placed on biodiversity-based interventions to increase income from tourism and recreation. Thus certain types of landscape-scale interventions, mainly those related to the value and benefit-sharing of multiple ecosystem services, were considered priorities across all landscapes, but there was otherwise considerable variation among landscapes due to biophysical and social-ecological factors. The number of identified landscape-scale interventions generally followed the order (high to low) of 'Tropical Agriculture-Forest Matrix' > 'Tropical Degrading Agroecosystem' > 'Temperate High-Input Commodity Agriculture' domains.

Researchers provided examples of specific actions pertaining to the biodiversity-based interventions at each site, and these were organized by the capital assets and their components deemed most important for its implementation (Table 4). Use of native plants was mentioned for many of the landscapes, either for food, intercrops or timber harvest (Jambi, ID; Koubri, BF; Sierra Madre, MX; and Zona da Mata, BR), or for the creation of semi-natural habitats along farm margins to increase regulating services and environmental quality (Hoeksche Waard, NL and Sacramento, US). Native plants were consistently seen as a viable way to utilize natural capital, but the species and circumstances were different, and so was the purpose. In general, most of the different components of natural capital were considered available for ecological intensification at all sites, and the bigger issue was implementation pathways.

The specific actions thought to increase implementation of biodiversity-based management consistently involved greater networking and consensus-building among actors at the landscape scale (Table 4). But the approaches were different. The priority was on spatial planning at some sites (Hoeksche Waard, NL and Jambi, ID), while at other sites, it was on government or other outside support (Koubri, BF and W. Ghats, IN), capacity building (Sacramento, US and Zona da Mata, BR) or multi-stakeholder design and cooperation (Sierra Madre, MX and Hoeksche Waard,

Table 3
List of key field- and landscape-scale interventions that are based on biodiversity management. An X indicates that the researcher(s) from a particular site regarded the intervention as high priority based on their participatory research with local stakeholders, with active interest occurring in that landscape.

Biodiversity-based interventions	Tropical agriculture-forest matrix domain				Tropical degrading agroecosystem domain		Temperate high-input commodity agriculture domain	
	Western Ghats, India	Jambi transect, Sumatra, Indonesia	Pacajá, Pará, E. Amazon, Brazil	Zona da Mata, Minas Gerais, Brazil	Sierra Madre, Chiapas, Mexico	Koubri, Central Plateau, Burkina Faso	Hoeksche Waard, The Netherlands	Sacramento Valley, USA
Field-scale interventions								
Domestication of native fruit trees	X	X	X			X		
More productive tree clones/genotypes		X			X	X		
More options for increased firewood production					X	X		
In situ conservation of genetic resources for crops/livestock	X					X		
More plant diversity options to produce high yields	X	X	X	X	X	X		
Manage soil biota to improve fertility for crops	X	X	X	X	X	X	X	X
Find new biocontrol agents for pests and diseases								X
Restoration of biodiversity on field margins					X		X	X
Explore biodiversity options for adaptation to climate change				X	X	X		X
Landscape-scale interventions								
Diversification of cropping systems and new markets	X		X	X				X
Increase commodity genotypic variation across landscape	X	X						
Increase cash commodities within natural ecosystems	X	X				X		
Support for a mosaic of agro- and natural ecosystems for diverse set of ecosystem services	X	X	X	X	X	X	X	X
Ecological connectivity for threatened flora and fauna	X		X	X	X		X	X
Awareness of agroforests in vulnerable slope positions		X		X	X			
Land management to reduce poverty	X	X	X	X	X	X		
Channel benefits of ecosystem services to providers	X	X	X	X	X	X	X	X
Increase aesthetic value of ecosystem mosaic					X		X	X
Income generation from tourism and recreation related to biodiversity conservation/restoration							X	
Restoration of natural vegetation/afforestation for water flow regulation		X		X	X		X	X
Cope with water supply/flooding as related to climate change				X	X	X	X	X
Scoping and consensus among multiple types of stakeholders for value of biodiversity	X	X	X	X	X	X	X	X

Table 4
High priority local actions for each landscape deemed important by local researchers to support the recommended field- and landscape-scale interventions in Table 3. Researchers from each site gave examples of the different kinds of capital assets for biodiversity-based ecological intensification.

	Human capital	Social capital	Financial capital	Natural capital	Physical capital
Tropical agriculture-forest matrix domain					
Western Ghats, India					
Field-scale actions	Reinforce traditional knowledge with participatory resource management and tenure on land and resource use	Strengthen local community institutions for eco-friendly agriculture and a common set of shared benefits	Purchase necessary inputs and tools to obtain premium prices for organic agriculture and forest products	Manage biodiversity in several unique agroforestry systems for productivity and sustainable resource use	Establish decentralised seed banks and nurseries for local forest and crop taxa
Landscape-scale actions	Involve community more effectively in conservation and co-management of different forest and agroforest types	Support the local village to protect biodiversity-rich forests and their food and soil resources	Develop ability for local community to find markets for agricultural and forest products at premium prices	Solve problems such as spread of specific weeds, human and animal conflict, and greater crop diversification	Process agricultural and forest products in a decentralised way that increases participation in markets
Jambi Transect, Sumatra, Indonesia					
Field-scale actions	Support awareness for rich biodiversity of agroforests and the risk of loss of both food and cash crops (e.g. rubber)	Develop local standards for access and benefit sharing for sustainable agroforest intensification	Establish ecocertification to obtain premium prices for rubber	Escalate domestication of valuable local trees, and requirements for pollination and dispersal	Relatively less important than other forms of capital
Landscape-scale actions	Cope with costs and benefits of intensification options (e.g. oil palm and fastwood for pulp and paper)	Make spatial plans at village and district level to keep existing rubber agroforests in the watershed protection zone	Develop market channels for ecocertified rubber and landscape level translation of national REDD incentives	Value agroforests for riparian zone and slope stabilization, and as connectivity between protected areas	Promote multi-scale spatial planning for new roads to be built outside of sensitive areas
Pacajá, Pará, E. Amazon, Brazil					
Field-scale actions	Educate farmers on existing data on biodiversity and ecosystem services for their farms and livelihoods	Increase capacity building for improved soil management, based on soil biology research	Foster access to credit, justified from income from ecocertification for specific types of farm products	Improve soil fertility management, with different needs for pasture, crop and agroforestry rotations, fallows and intercrops	Relatively less important than other forms of capital
Landscape-scale actions	Develop awareness for the costs and benefits of specific types of high input vs. ecological intensification options	Improve networking so that communities understand the value of the existing forest	Find more market channels and support development of new forest and agroforest products	Determine how the connectivity between the remaining corridors of protected forests can be enhanced	Improve roads for market access
Zona da Mata, Minas Gerais, Brazil					
Field-scale actions	Learn from the experience of other farmers on how to manage the trees in various types of agroecosystems	Create local standards for access and benefit of agroforests, and for soil, water and food quality	Develop agroforest ecocertification based on a set of attributes related to ecological and community benefits	Increase use of valuable local trees, as intercrops with coffee, and in pastures, and to protect springs	Access tools for seeding and management of agroforestry systems, and fences to protect springs
Landscape-scale actions	Build up awareness of costs and benefits of monocultural options (e.g. coffee, pasture, eucalyptus, cane) vs. agroforestry systems	Increase knowledge and capacity building of local government councils with villages and agroecological network of consumers and producers	Support for the construction of the agroecological/solidarity network, such as school food program	Demonstrate role of biodiversity connectivity of riparian zone, forest fragments and agroforestry systems	Generate infrastructure to connect consumers and producers, enlarging the market for local products
Tropical degrading agroecosystem domain					
Sierra Madre, Chiapas, Mexico					
Field-scale actions	Gain appreciation of the current and potential value of conserving and using multi-purpose trees for cattle production	Facilitate the recently formed local silvopastoral organization through multi-stakeholder support	Reorient part of the poverty subsidies into investment for silvopastoral improvement; develop organic cattle market	Domesticate and improve management of local multi-purpose trees for valuable and sustainable cattle production	Relatively less important than other forms of capital

Table 4 (*Continued*)

	Human capital	Social capital	Financial capital	Natural capital	Physical capital
Landscape-scale actions	Deal with ecological and social challenges and opportunities of constructing an agrobiodiverse landscape in a MAB[a] buffer zone	Increase the capacity of all stakeholders to address landscape management issues through non-opportunistic cooperation	Create integrated marketing processes and other support systems for ecocertified livestock products	Increase connectivity of the core and buffer zones, riparian corridors, and at the same time, stabilize soil erosion on steep slopes	Develop new infrastructure, e.g. cattle fencing, and methods for tree planting at various distances from the MAB[a] core areas
Koubri Plateau, Burkina Faso					
Field-scale actions	Convey knowledge and options for alternative savanna and crop management to more farmers	Adopt local rules for better governance of savanna lands as awareness already exists (e.g. shea harvest)	Support ecocertification for fair-trade and organic shea, organic; protect shea by temporarily reducing income	Domesticate more savanna tree species and genotypes; establish nurseries, and grafting and compost procedures	Make equipment available for composting and applying organic matter to soil
Landscape-scale actions	Develop awareness of decision makers for problems, solutions, and need for knowledge on savanna use	Support by local governing bodies for resilience to climate change rather than just short-term responses	Generate subsidies to make risky conversions and try out new types of agrobiodiversity	Bring in new crops from outside landscape, and tree species for medicinal use and stability of water resources	Build canals, other types of water transport systems or boreholes
Temperate high-input commodity agriculture domain					
Hoeksche Waard, The Netherlands					
Field-scale actions	Develop awareness and knowledge among farmers on the benefits and use of biodiversity in and around their fields	Share knowledge and experiences among farmers and stimulate consensus-building among different types of land managers	Expand financial incentives to implement field margins, crop diversification, and reduced tillage	Value and stimulate the diversity of crops, wild plants and soil biodiversity for providing ecosystem services	Adjust and design machinery for controlled traffic, and farming operations for reduced-tillage agriculture
Landscape-scale actions	Develop awareness and knowledge among relevant stakeholders on the synergies between farm- and landscape-level biodiversity	Develop spatial plans and support for biodiversity and ecosystem services restoration by connecting relevant stakeholders	Maintain and develop financial incentives for biodiversity-friendly management, scientific development and monitoring	Value non-productive landscape elements providing ecosystem services and improve connectivity functions within the landscape	Improve management of roadsides, creeks and ditches for their contribution to biodiversity connections within the landscape
Sacramento Valley, Yolo County, California, USA					
Field-scale actions	Develop planning and communication tools for farmers to diversify and to use new management practices	Create opportunities for exchange of experiences to decrease fertilizer and pesticide inputs in row and orchard crops	Provide farmers with the means to rent/buy/adapt farm equipment for new crops and field margin management	Utilize native, drought-adapted perennial species for riparian corridors, hedgerows, and marginal lands	Use fencing and channel berms to create better habitat for wild species and reduce runoff into waterways
Landscape-scale actions	Increase information from local knowledge and research to plan for drought, climate change, and increased flooding	Gain support for multistakeholder exchange of ideas to diversify land use in specific regions of the landscape	Generate grants and payments to try out new commodities and inputs for vulnerable soils and regions, and to continue to adapt	Take inventory of biodiversity and natural resources on private land, and develop site-specific restoration methods	Develop equipment repositories and postharvest facilities to improve capacity for crop diversification

[a] MAB = UNESCO Man and the Biosphere Reserve.

NL). Across the landscapes, the results suggest that individual knowledge of the social-ecological system (human capital) goes hand-in-hand with leadership and the maintenance of a dynamic set of social norms and institutions (social capital) that support ecological intensification (Ostrom, 2009). Awareness and knowledge for new implementation of ecological intensification was a key issue at all sites, even in the landscape with high utilization of traditional knowledge (W. Ghats, IN).

For the two sites in the 'Temperate High-Input Commodity Agriculture' domain, financial capital for field-scale actions was considered most important for equipment and incentives to implement field margin restoration and new farming practices for ecological intensification. But for the other six sites, in contrast, financial capital was considered most necessary for developing market value chains through eco-labeling and eco-certification to increase the use of agrobiodiversity, and support agroecological approaches rather than high-input intensification.

4. Discussion

In the scientific literature, there are surprisingly little observational and experimental data describing the social-ecological aspects of coupled human and natural systems across biomes. In this study, use of an expert judgment approach suggests that biodiversity use and conservation is closely aligned with aspects of human capital related to local knowledge and its exchange. Food security, however, was highest where agricultural intensification relied on agrochemical inputs, and was supported by strong financial and physical capital assets. These results suggest that resolving the current debate on biodiversity conservation vs. food security requires much greater attention to livelihoods, cultural integrity and other aspects of human well-being (Barrett et al., 2011; Phalan et al., 2011a,b; Tscharntke et al., 2012). Other literature has shown that the potential for new interventions to provide ecosystem services depends on the initial conditions in a landscape, and apparent 'win–win' solutions often have not delivered on their promises due to social-ecological complexity (Barrett et al., 2011). Our landscape descriptions emphasize that such complexity has strong cultural and historical roots, which can be more important than cautionary environmental science in determining decisions for land management. Despite the unique complexity in each landscape, this study was able to distinguish social-ecological domains based on rural livelihood resources associated with capital assets. Many other domains undoubtedly exist globally, and a more comprehensive monitoring system could better identify assets across biomes (Sachs et al., 2010). Nevertheless, this initial approach suggests that different domains will benefit from different types of biodiversity-based interventions that necessitate different sets of capital assets.

4.1. Interventions for biodiversity-based agriculture

These results illustrate that ecological intensification is complex and requires commodity-specific, soil-specific and regional planning to cope with ecosystem heterogeneity that might otherwise be overlooked when non-renewable inputs, such as agrochemicals and fossil fuels, are readily available and financially affordable. The specific actions for biodiversity-based interventions differed across the landscapes and require new sets of capital assets. Ecological intensification clearly does not have a 'one-size-fits-all' management framework. It depends on local innovation and participatory research, as well as institutional support from the local beneficiaries of the ecosystem services that it provides (Atwell et al., 2010). Given that biodiversity is locally adapted, biodiversity-based agriculture requires a regional approach that considers local biota, economic conditions, cultures and livelihoods. But this approach can benefit from sharing of global knowledge on social-ecological processes and experiences with successful interventions in other regions.

This set of agricultural landscapes reflects the types of heterogeneity and complexity in dealing with food security, rural development and biodiversity conservation that exist globally. Planning for solutions to these problems is often for short-term fixes rather than long-term provision of multiple ecosystem services. Much of the current global discussion on food security and biodiversity conservation, however, is on limiting the expansion of agricultural area by closing yield gaps for major crops via higher inputs (Burney et al., 2010; Licker et al., 2010), or for more judicious use of non-renewable inputs (Foley et al., 2011). These types of interventions are most relevant to landscapes in the 'Temperate High-Input Commodity Agriculture' domain, and less so for social-ecological domains with reduced potential to benefit from high-input intensification, due to topography, degrading lands, protected areas or poor market access. In the Sierra Madre, MX landscape ('Tropical Degrading Agroecosystem' domain), for example, soils are prone to erosion, and while farmers' use of external inputs is very high, there is still frequent food insecurity. In addition, serious loss of biodiversity in the buffer zone of the MAB reserve has occurred due to intensification of livestock grazing (García-Barrios t al., 2009). Interventions there are now emphasizing human and social capital assets to support agroforestry, biodiversity restoration and production for eco-certified markets (Table 4).

Overall, the number of landscape-scale interventions for biodiversity-based agriculture that were suggested by researchers in this study decreased along the agricultural intensification gradient (Fig. 2; Table 2). This suggests that for complex landscapes composed of many types of ecosystems, such as in the 'Tropical Agriculture-Forest Matrix' domain, land use planning and collective action institutions are now perceived as quite important for ecological intensification and multiple ecosystem services. That perception was less strong among researchers in the 'Temperate High-Input Commodity Agriculture' domain.

4.2. Landscape trajectories for agrobiodiversity and ecosystem services

The landscapes considered in this study have different levels of agricultural production (goods) and biodiversity. Through participatory workshops among the expert group and other local social actors, we produced a consensual ranking of the eight sites to show their importance relative to a theoretical maximum local potential for agricultural production of goods (horizontal axis) and for biodiversity in all ecosystems in the landscape mosaic (vertical axis) (Fig. 4) (van Noordwijk et al., 2006). On the vertical axis, biodiversity is considered to be linked tightly to all types of ecosystem services (MEA, 2005). Individual sites may move either toward higher or lower relative production levels depending on types and level of agricultural inputs, commodities, management technologies, economic and non-economic incentives schemes and rewards (Nelson et al., 2009). Red arrows indicate a pathway to be avoided; production increases at the expense of biodiversity and ecosystem services, or both may suffer, such as in Koubri, BF and Sierra Madre, MX landscapes. Green arrows indicate feasible alternative pathways that increase the bundled set of ecosystem services, and may thus be more socially desirable.

Our hypothesis is that social-ecological domains differ in their potential trajectories for sustainable vs. less socially desirable directions (Fig. 4). In the 'Tropical Agriculture-Forest Matrix' domain, some loss of the high-biodiversity agroforests could support agrobiodiversity-based intensification for local livelihoods. Trade-offs between provisioning agricultural commodities

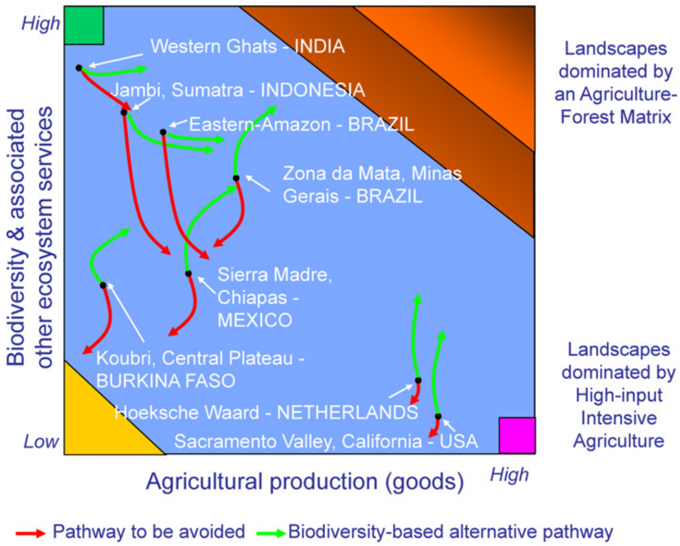

Fig. 4. Hypothetical distribution of sites with respect to their production of agricultural goods vs. biodiversity and associated ecosystem services. The sites were plotted relative to a theoretical maximum local potential (green and purple boxes) for agricultural production of goods (*x*-axis) and for biodiversity in all ecosystems in the landscape mosaic (*y*-axis). Very high biodiversity is not consistent with very high production (orange) and no agriculture would exist at the origin of the bi-plot (yellow). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)
See van Noordwijk et al. (2006).

and biodiversity can be optimized (e.g. reducing shade levels in cacao agroforestry from 80 to 40% led to small decreases in biodiversity while doubling income (Steffan-Dewenter et al., 2007). Instead, rapid deforestation often brings plantation crops (e.g. oil palm, cacao, or coffee) that supply neither local food nor stable income due to global price fluctuations and high risks for disease outbreaks, soil quality loss or climate change (Tscharntke et al., 2011; Cardoso et al., 2012; Donald, 2004). In contrast, the landscapes in the 'Tropical Degrading Agroecosystem' domain can benefit from new crops and biodiversity restoration that improves water and soil quality. Poverty and out-migration are economic disincentives, however, that can result in further loss of both agricultural goods and biodiversity (García-Barrios t al., 2009). In the 'Temperate High-Input Commodity Agriculture' domain, governments often force improvements in regulating and supporting services, despite the aim for production of cheap commodities. The local challenge is to create voluntary economic incentive schemes, including payments for ecosystem services (PES), for the multiple functions of agricultural lands, so that ecological intensification can support farm livelihoods, making farmers less vulnerable to fluctuations of commodity or input markets.

Farmers in the 'Temperate High-Input Commodity Agriculture' domain are often highly subsidized and protected. In the other domains, production is often constrained by ethnic and other social frameworks and relies more strongly on self-sufficiency. For the poorest farmers, increasing evidence shows that 'food sovereignty' can be improved with agroecological methods that support high and stable yields within a matrix of wildlands that conserve wild species (Perfecto and Vandermeer, 2010; Fahrig et al., 2011). Agrobiodiversity also retains cultural services which are often not considered in the food security vs. biodiversity conservation debate.

None of our three social-ecological domains support the notion of land-sparing, i.e., that wild biodiversity can be saved by concentrating intensive agriculture where production conditions are most favorable, in principle leaving more space for wildland biodiversity (Green et al., 2005; Phalan et al., 2011a,b). Pressure to convert wildlands did not diminish with high-input agricultural intensification at any of the sites.

4.3. Collective knowledge and action for ecological intensification

Successful transition to ecological intensification may only be possible when social learning and other institutional frameworks build collective knowledge and promote adaptive management for biodiversity-based agriculture within landscapes (Pontius et al., 2002). Creation of markets for commodities, tourism and external incentive rewards such as PES schemes also generally operate at the landscape or watershed scale (van Noordwijk and Leimona, 2010). Components of an integrated landscape research approach include: (1) understanding the interactions between mosaics of crop production areas and natural habitats within the landscape mosaic (Tscharntke et al., 2005; Swift et al., 2004; Brussaard et al., 2010); (2) building upon local experiences with diversified production systems and evaluation of the effects on farm level economics and livelihood analysis (Cardoso et al., 2001; Méndez et al., 2010; de Souza et al., 2012a,b); (3) analyzing tradeoffs and synergies between biodiversity, sustainable production and ecosystem services at multiple scales including the interactions between croplands and wildlands (Culman et al., 2010; Brown and Schulte, 2011); and (4) examining institutional and behavioral drivers of biodiversity change, including feedback effects of policies and rewards locally and globally (Matthews and Selman, 2006). This type of knowledge needs to have salience and gain credibility among social actors before it can become the basis for negotiation support for policy and institutional changes (Clark et al., 2011).

Local knowledge and innovation is known to be important for implementation of biodiversity-based interventions (Pontius et al., 2002). Extension agents at the eight sites are usually over-committed or absent, and NGOs are increasingly involved in various forms of social bridging that has supported ecological intensification, biodiversity conservation and/or improvement of livelihoods. Maintaining and strengthening collective action inherently depends on factors such as trust, productive conflict that stimulates novel solutions, a culture of openness to new ideas, decision-support tools and supportive policies (Kofinas, 2009). Human rather than social capital assets were more strongly associated with biodiversity use and conservation in the PCA of the eight landscapes (Fig. 2). Locally relevant knowledge and experience for decision support may be necessary before a larger set of social actors become involved in negotiation support (Clark et al., 2011) and biodiversity conservation solutions (Schwartz, 2006). In contrast, top-down regulatory interventions can create conditions that undermine moral and duty-based behavioral social norms and self-governing mechanisms, such as formalized community rules or informal patterns of collective action (Vollan, 2008; Sommerville et al., 2010; Rustagi et al., 2010).

Collective action toward ecological intensification may be greater in domains where resources are scarce and food insecurity is high (Ostrom, 2009). This would suggest that capacity for self-organization may be higher in the 'Tropical Degrading Agroecosystem' domain and lowest in the 'Temperate High-Input Commodity Agriculture' domain. But factors such as the number of farmers, farmers' knowledge about the social-ecological system, trust and reciprocity can increase a domain's capacity for self-organization. Strong leadership can be a catalyst for group decision-making as has occurred in the landscapes in the W. Ghats, IN, Sierra Madre, MX and Zona da Mata, BR. Domains do share similar assets (Figs. 2 and 3), and further field research across the sites may show how exchanges within domains at the global level may generate approaches for collective action at the landscape level.

This exploratory study suggests that more comprehensive multi-landscape research projects may help understand how to support local knowledge, context-specific interventions and policies that stimulate regional innovation and adaptive capacity for ecological intensification at the farm and landscape scales.

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