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LINKING DEFORESTATION SCENARIOS TO POLLINATION SERVICES AND ECONOMIC RETURNS IN COFFEE AGROFORESTRY SYSTEMS

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Abstract. The ecological and economic consequences of rain forest conversion and fragmentation for biodiversity, ecosystem functioning, and ecosystem services like protection of soils, water retention, pollination, or biocontrol are poorly understood. In human-dominated tropical landscapes, forest remnants may provide ecosystem services and act as a source for beneficial organisms immigrating into adjacent annual and perennial agro-ecosystems. In this study, we use empirical data on the negative effects of increasing forest distance on both pollinator diversity and fruit set of coffee to estimate future changes in pollination services for different land use scenarios in Sulawesi, Indonesia. Spatially explicit land use simulations demonstrate that depending on the magnitude and location of ongoing forest conversion, pollination services are expected to decline continuously and thus directly reduce coffee yields by up to 18%, and net revenues per hectare up to 14% within the next two decades (compared to average yields of the year 2001). Currently, forests in the study area annually provide pollination services worth 46 Euros per hectare. However, our simulations also revealed a potential win-win constellation, in which ecological and economic values can be preserved, if patches of forests (or other natural vegetation) are maintained in the agricultural landscape, which could be a viable near future option for local farmers and regional land use planners.

Key words: bee diversity; Coffea arabica L.; *crop yield; ecosystem service; forest margin areas; land use and land cover change (LUCC) model; net revenues; policy scenario; rain forest; spatial modeling.*

Introduction

Forest conversion, agricultural expansion, and infrastructure extension have transformed landscapes throughout the world, resulting in biodiversity loss and threatened ecosystem services (Chapin et al. 2000, Achard et al. 2002, Balmford et al. 2002, Geist and Lambin 2002, Millennium Ecosystem Assessment 2005). During recent years the concept of ecosystems services is increasingly used to describe different categories of benefits for human society attainable from natural and human-influenced ecosystems (Constanza et al. 1997, Daily et al. 1997). Land use changes may affect important ecosystem services, but effects on societies' benefits are poorly understood. While goods like crop yields are tangible and can easily be measured, an economic quantification of ecosystem services like air quality, carbon storage, water retention, biological control, and pollination is difficult. However, ecosystem services have been recently estimated to be worth several trillion Euros (Constanza et al. 1997), and already the direct benefits from tropical forests can exceed those obtained from converted habitats (Balmford et al. 2002).

Globally, important crops like coffee, as well as many other cultivars (Free 1993), benefit from pollination services of nearby forests or other natural habitats, which provide forage and nesting space for pollinators (Kremen et al. 2002, 2004, Roubik 2002*b*, Klein et al. 2003*a*, De Marco and Coelho 2004, Ricketts 2004). Pollination represents a basic ecosystem service with an estimated economic benefit between 90 billion and 160 billion Euro at the global scale (Constanza et al. [1997] and Kearns et al. [1998], respectively). Thus, it is of great interest to understand how future land use changes might affect ecologically and economically important functions provided by natural forests.

Policy scenarios are a valuable tool to evaluate the consequences of socioeconomic and environmental drivers on land use and land use change at different spatial scales (Alcamo et al. 1998, Lambin et al. 2001, Alves 2002, van Jaarsveld et al. 2005). While spatially explicit simulation models have been employed to quantify policy scenarios in terms of land cover/land use change (e.g., Irwin and Geoghegan 2001, Verburg et al. 2004), expanding such scenarios to assess the impacts on biodiversity and ecosystem services has been rarely realized, partly due to the limited availability of empirical data that quantify the relationship between land use patterns and ecosystem services.

Here, we use recent results on the effects of forest distance on the fruit set of coffee, to evaluate future risks

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to coffee yields and farmer's revenues under different land use scenarios. Pollinator availability improved fruit set and crop yield of highland coffee (*Coffea arabica* L.) between 15% and 50% (Roubik 2002*a*). With increasing forest distance pollinator diversity and fruit set of coffee is significantly reduced (Klein et al. 2003*a*, *b*, De Marco and Coelho 2004, Ricketts et al. 2004). Here, we used the results of Klein et al. (2003*a*, *b*) and a novel spatially explicit land use model to analyze effects of different scenarios of future land use and land cover change on pollination services and related yields of small-scale coffee agroforestry systems in Sulawesi, Indonesia. Additionally, we estimated the economic value of the pollination services of present forests and evaluated the potential future reduction of the net revenues of coffee farmers.

Methods

Study region

The study was carried out in Central Sulawesi, Indonesia, at the northeastern border of the Lore Lindu National Park (LLNP) at an elevation between 500 m and 1600 m. The study region belongs to the broad valley of the Palolo river, which forms the central part, while the northern and southern parts are shaped by moderate to steep slopes. The climate is tropical humid with 2000 mm rainfall per year and an annual mean temperature of 23°C. As shown in Fig. 1, the southern part of the research area is situated within the LLNP. The protected forest close to the border is already partly converted into agricultural land and small coffee and cocoa plantations, which are owned by farmers living in villages adjacent to the LLNP. Presently, coffee (almost exclusively *Coffea arabica*) is grown mostly between 600 and 800 m above sea level, and is frequently intercropped with cacao (*Theobroma cacao L.*). Agricultural crops, dominated by paddy rice are preferably grown in the valley, i.e., the lower, plain areas, but maize, upland rice, and coffee are also grown on adjacent slopes.

Pollination services at risk

The scenarios presented in this study are based on the results of field experiments carried out by Klein et al. (2003*a*, *b*, *c*) in the same region. The studied systems are typical small-scale coffee agroforestry systems with a variety of shade trees. Highland coffee, *Coffea arabica,* is potentially wind pollinated but recent studies show that fruit set is significantly enhanced by insect pollination (Roubik 2002*a*, Klein et al. 2003*a*). In a regional context the diversity of pollinators in coffee agroforestry systems was determined by the distance to the natural forest margin and additionally by local management practices (Klein et al. (2003*b*, *c*). Most interestingly, both the species richness of coffee pollinators and the fruit set of highland coffee declined with increasing forest distance (Klein et al. 2003*c*). Thus, coffee pollination services are at risk due to ongoing forest conversion in the study region.

We used these empirical results to analyze the potential effects of future land use change on the spatial distribution of pollination services. The effect of forest distance on the fruit set of coffee can be expressed as

$$F = a + b \times \sqrt{D} \quad (1)$$

where F is the percentage fruit set of coffee, a and b are highly significant fitted constants ($a = 85.22$ and $b = -0.64$; $P < 0.005$; $R^2 = 0.34$) , and D is the distance of the coffee plantation to the forest in meters (based on data from Klein et al. 2003*c*).

The range of Eq. 1 is limited by the maximum fruit set of 85.2% at the forest edge (20 bee species), and the minimum fruit set of 60.4% in 1500 m distance (three bee species) that is similar to fruit set of treatments with only wind pollination (Klein et al. 2003*a*). Thus, we do not expect further reductions of fruit set at larger distances and consequently limited the potential yield reductions in the scenarios to the above-mentioned range. Therefore, in the gridded spatial data sets, in which every 250-m pixel was evaluated using a geographic information system, distances larger than 1500 m were set to 1500 m (for the calculations of coffee yields). Coffee yields were assumed to be proportional to the fruit set of coffee and were expressed as a fraction of the yields harvested in 2001. This assumption is also supported by the positive correlation between fruit weight and fruit set (Roubik 2002*b*; A. M. Klein, *unpublished data*). Furthermore, the frequency of coffee-flower visiting bees could be directly related to the coffee yield per ha measured as number and weight of harvested bags filled with fresh coffee berries (D. Veddeler, *unpublished data*). There was no effect of forest distance on rates of coffee bean infestations by the coffee berry borer *Hypothemus hampei* (A. M. Klein, *unpublished data*).

Land use change model and policy scenarios

The simulation experiments were carried out with the new SImulation of Terrestrial Environments model (SITE model), recently developed at the University of Kassel. In this paper, land use change is simulated in a spatially explicit fashion on a 250-m grid in yearly time steps. The core of the model consists of a "generalized cellular automata" approach. In the land use model, the allocation of land use is based on biophysical suitability (climate, soils, topography), allocation factors (e.g., distance to the next river, land use on adjacent cells, preferred walking distance to field), demography (population growth rate, migration), and the land use strategies of farmers (e.g., moderate or high intensity agriculture, forest use) and other restrictions like the protection of the LLNP area. A detailed description of the SITE model is given in M. Mimler and J. A. Priess (*unpublished manuscript*). Simulation experiments were calculated for the period 2002–2021, and were based on

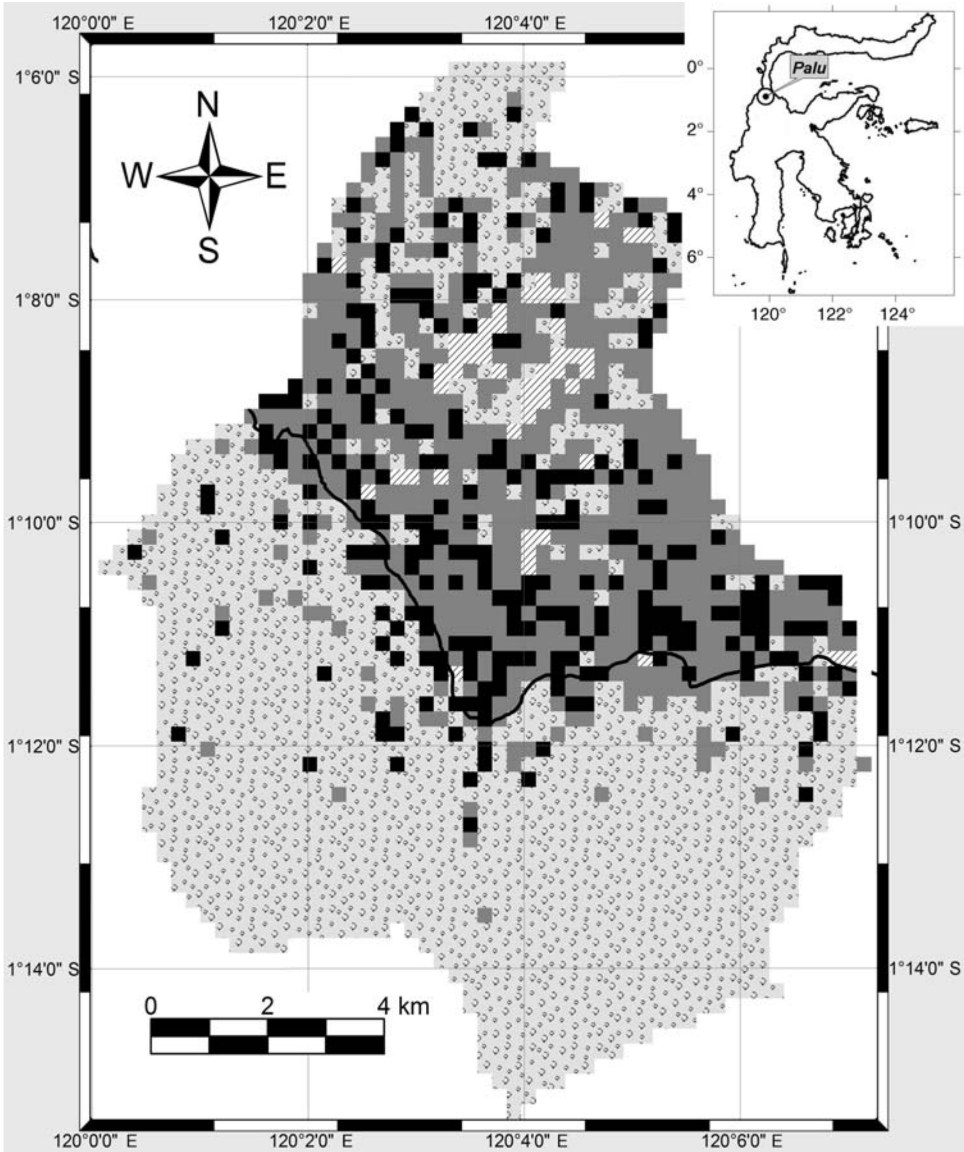

FIG. 1. Gridded land-use/land-cover map of the research area south of the city of Palu in Sulawesi (black circled dot in the inset map). The light gray with tree symbols shows primary and secondary forest; medium gray, agriculture; black, coffee plantations; hatched area, hamlets and villages; black line, road and Lore Lindu National Park boundary. Note that the entire area south of the border line belongs to the Lore Lindu National Park (LLNP).

the land cover/land use distribution of 2001. The land cover in the year 2001 was derived from a LANDSAT ETM+ scene (path 114/row 61) of 24 August 2001 classified by Haertel et al. (2002, as cited in Maertens 2003).

Four different scenarios of land use change were generated, based on assumptions about demographic trends, local and regional policies, socioeconomic development, and land use strategies of local smallholders (Table 1). Human population growth was calculated according to the United Nations database (Indonesia: high scenario [United Nations 2004]). The differences between the low and high United Nations scenarios were not very pronounced in terms of land use change within the next two decades (data not shown here), because regional demographic trends are dominated by immigration to the comparatively less densely populated rural areas of Sulawesi ($<$20 inhabitants/km^2). Per capita demand for agricultural land was estimated from 1980–2000 village statistics and compared against the LANDSAT ETM+ scene of 24 August 2001 (Haertel et al. [2002], as cited in Maertens [2003]). The calculated value of 0.23 ha per capita was consistent with FAO (2004) estimates for Indonesia (0.21 ha per capita) for the same year.

TABLE 1. Land use strategies and driving forces of land use change: historical/present situation and four policy scenarios.

Parameters	Present situation (1980–2001)	Business as usual (BaU)	Agricultural progress (AgPro)
Policy			
Rural immigration†	continued	continued	continued
Economic stimulation‡	low	low	**high**
Protection of LLNP§	imperfect protection	protection (50%)	protection (50%)
Agricultural activities			
Subsistence crops	self sufficiency	self sufficiency	self sufficiency **production for market**
Cash crops‖	moderate intensity	moderate intensity	**increased intensity**
Forest use (logging)	for subsistence mainly	for subsistence	for subsistence

Note: The most important drivers of each scenario are shown in boldface.

† Migration was/is either controlled via the official transmigration program, which affects only a small fraction of migrants in Central Sulawesi, or in the case of spontaneous migration at the village level, via access to land and other resources, which is negotiated between representatives of the villagers and the newcomers.

‡ Improved market access via improved infrastructure and increased access to credits (see Maertens 2003:116–119).

§ In the scenarios presented here, the protection of Lore Lindu National Park (LLNP) forest grid cells was simulated as a 50% reduction in suitability for agricultural crops.

‖ The spatial extent of coffee plantations was kept stable in all land use change scenarios, in order to enable the comparison to the present situation.

We developed the following four scenarios:

1) In the "business as usual" (BaU) scenario, the present demographic trend (1970–2001) of a high, but decreasing, population growth rate and considerable rural immigration is continued, as well as local policies to protect the LLNP with moderate efficiency. LLNP protection is simulated by reducing the suitability for agricultural and residential use of protected grid cells by 50%. Local farmers are assumed to continue cultivating their fields with the same labor intensity and frequency of field visits as before.

2) The "agricultural progress" (AgPro) scenario is based on economic measures suggested by (Maertens et al. 2003), the same demographic assumptions and the continued protection of the National Park. In contrast to the other scenarios, agricultural land use practices of farmers are supposed to be more labor intensive, resulting in a preferred smaller walking distances to the fields due to (1) more frequent field visits and (2) a higher investment of labor per unit agricultural area (weighing factor: 10). This process of agricultural intensification has been taken into account by simulating a slightly reduced amount of agricultural area cultivated per capita (initial value, 0.23 ha; −1% per capita per year).

3) The "high migration" (HiMig) scenario differs from the previous ones in the increased immigration rate (1.5-fold), caused by economic problems and high population pressure elsewhere in the archipelago. All other assumptions are the same as in the BaU scenario.

4) The "forest encroachment" (ForEnc) scenario was developed for the evaluation of the consequences of rapid deforestation. ForEnc was inspired by recently increased forest conversion activities in the nearby Dongi-Dongi area, an illegal forest invasion during which more than 2200 ha of protected forest were lost within only three to four years (Erik 2002, Erasmi et al. 2004). In this scenario, we assume the complete failure of regional protection policies, resulting in increased logging and forest conversion activities in protected and non-protected forests. Due to the unsustainable forest use (e.g., conversion of forest on steep land unsuitable for agriculture), the per capita land demand in the ForEnc scenario is slightly increasing (+1.5% per capita per year), which is equivalent to approximately 250 m^2 of additional demand for land per household per year (Table 1).

Economic evaluation of pollination services

The economic contribution of forests to the production of coffee beans was calculated as average yield increase per hectare of forest. Only the forests within the 1500 m forage distance of bees were used for the valuation of pollination services.

Additionally, the net revenues of coffee farmers were estimated for the four policy scenarios, based on prices, fixed and variable costs of 2001 (see Table 2). According to the National Statistics Bureau of Indonesia (data *available online*),[5] average coffee yields in Central Sulawesi were 468 kg/ha both in 2001 and 2002, which is close to coffee yields reported in our household survey in 2000/2001 (581 kg/ha; see Zeller et al. [2002] for a description of the survey methodology), and about half of the average value of 891 kg/ha reported for the same period for entire Indonesia (data *available online*).[6] We calculated the mean producer price of 1998–2003 for highland coffee paid to coffee farmers in Indonesia, which was 1.19 €/kg green beans (International Coffee Organization 2004).

RESULTS

Land use change scenarios

The process of forest conversion within and outside the LLNP continued in all scenarios. Continued popu-

[5] 〈http://www.bps.go.id/index.shtml〉

[6] 〈http://apps.fao.org〉〉

TABLE 1. Extended.

High migration (HiMig)	Forest encroachment (ForEnc)
doubled low protection (50%)	**doubled; no control** low **no protection**
self sufficiency	self sufficiency
moderate intensity for subsistence	moderate intensity **commercial**

lation growth resulted in the increase of residential and agricultural areas, while forest areas decreased respectively (Table 3). Due to differences in scenario assumptions concerning immigration and land use strategies, forest conversion ranged between 4% and 44%, which is equivalent to deforestation rates between 0.18% per year and 2.20% per year. Additionally, large differences were observed in the simulated distribution of land-use/land-cover types. The AgPro scenario was the only one, in which the present distribution of patches of primary and secondary forests within the agriculturally dominated landscape—mainly the broad valley bottom—was maintained (primary and secondary forests were assumed to be comparable in their capacity to support pollinators). In the BaU, HiMig, and ForEnc scenarios, the lowland forests completely disappeared and the northern boundary of the LLNP forests was shifted southward. In the ForEnc scenario (see Fig. 2a for the land-use/land-cover change sequence), in which increased logging activities were simulated, forest conversion both on the northern and southern slopes of the central valley were strongest, followed by the HiMig scenario. In the BaU and AgPro scenarios, the southern forests remained almost untouched, while in the BaU scenario a clear decrease occurred in the forest areas in the northern part of the Palolo valley (Figs. 2b and 3).

Pollination

The spatial analysis revealed the lowest average distance of 157 m between forest areas and coffee plantations in the year 2001. All plantations were located within the 1500-m bee forage zone (maximum distance $\leq$1000 m), and profited from pollination services. After 20 simulated years, distances between forests and coffee sites increased in all land-use/land-cover change scenarios in the order AgPro, BaU, HiMig, ForEnc. In consequence, fruit set of coffee, (initially 80% in 2001) decreased in all scenarios (Fig. 4). The decrease in pollination services presented a dichotomy between the AgPro and BaU scenarios on one hand, and the HiMig and ForEnc scenarios on the other hand. In the latter, decrease in pollination was strongest in the first few years, during which the forest patches remaining in the valley, close to many of the coffee plantations, were converted (see Fig. 2a, land use after five years). Further forest conversion mostly on the northern and southern slopes, where less coffee plantations were located, had a less pronounced effect on the fruit set of coffee (Fig. 4). After 20 years, increased pollination limitation resulted in a mean fruit set of only 67% in the HiMig and of 66% in the ForEnc scenarios. In the other two scenarios, the forest plots in the valley were either preserved (AgPro), resulting in minor reductions (mean fruit set of 79%), or disappeared more gradually (BaU) causing increasing reductions of coffee yields over the entire simulation period of 20 years and a final mean reduction to 70% fruit set. Note that we assumed the same pollinator diversity for all forest patches, irrespective of patch size, because the relation between patch size and pollinator diversity is unknown for tropical forest fragments.

Economic evaluation of pollination services

Based on the mean producer price of 1.19 €/kg green coffee beans, the total value of the 2001 coffee harvest within the study area (1656 ha coffee plantations) was 1.1

TABLE 2. Average net revenues of coffee farmers in 2001.

Factors	Unit	Unit cost (IDR)	Quantity	IDR/ha
Costs				
Annualized establishment costs†				54 915
Cleaning	labor days	10 000	4.0	40 000
Pesticides				5900
Harvest coffee	labor days	10 000	6.0	60 000
Transport				18 000
Processing				751 809
Total costs				930 625
Revenues				
Coffee yield (green beans)	kg/ha	10 515	478.5	5 031 340
Net revenues, IDR 2001‡				4 100 715
Net revenues, Euro 2001	IDR → Euro			€ 464.09
			8835.981	

Note: All values except the last line are given in Indonesian Rupiahs (IDR).

† Total establishment costs are IDR 570 000 calculated for a productive period of 15 years.

‡ ICO producer price (mean of 1998–2003). Note that local farmers in 2001 reported receiving only IDR 4800 (= € 0.54) per kg which is close to the all time low reported by ICO.

TABLE 3. Land use and land cover in 2001 and 2021.

Start year and scenario	Residential area (ha)	Agricultural area (ha)	Forest area (ha)	Mean deforestation rate 2002–2021 (% per year)
Start year 2001	294	3506	7975	0.60†
Scenarios 2021				
BaU	438	4525	6813	0.73
AgPro	438	3650	7688	0.18
HiMig	538	5256	5981	1.25
ForEnc	538	6775	4463	2.20

Note: The spatial extent of coffee plantations was kept stable in all scenarios (1656 ha).
† The rate was reported by Erasmi et al. (2004) for the entire Lore Lindu region (~7500 km^2) and is over the period 1972–2001.

million Euros. Primary and secondary forests in the 1500-m forest zone surrounding the coffee plantations, summed up to 5659 ha. Thus in the year 2001, the pollination service ensured by neighboring forests translated into an economic benefit of 258 000 € for the coffee farmers, which is equivalent to 46 €/ha "pollination" forest.

To assess the potential economic value lost due to future reductions in pollination services, we calculated crop yields per hectare coffee plantation, based on the four different land use scenarios. The dichotomy observed for the fruit set, between the AgPro scenario on one hand, and the BaU, HiMig, and ForEnc scenarios on the other hand, was replicated in the calculations of the net revenues for coffee production over the next two decades. All net revenues decreased during the simulations and revealed cumulative reductions between 8 and 101 €/ha coffee after 20 years (changes over time are identical to the pattern in Fig. 4).

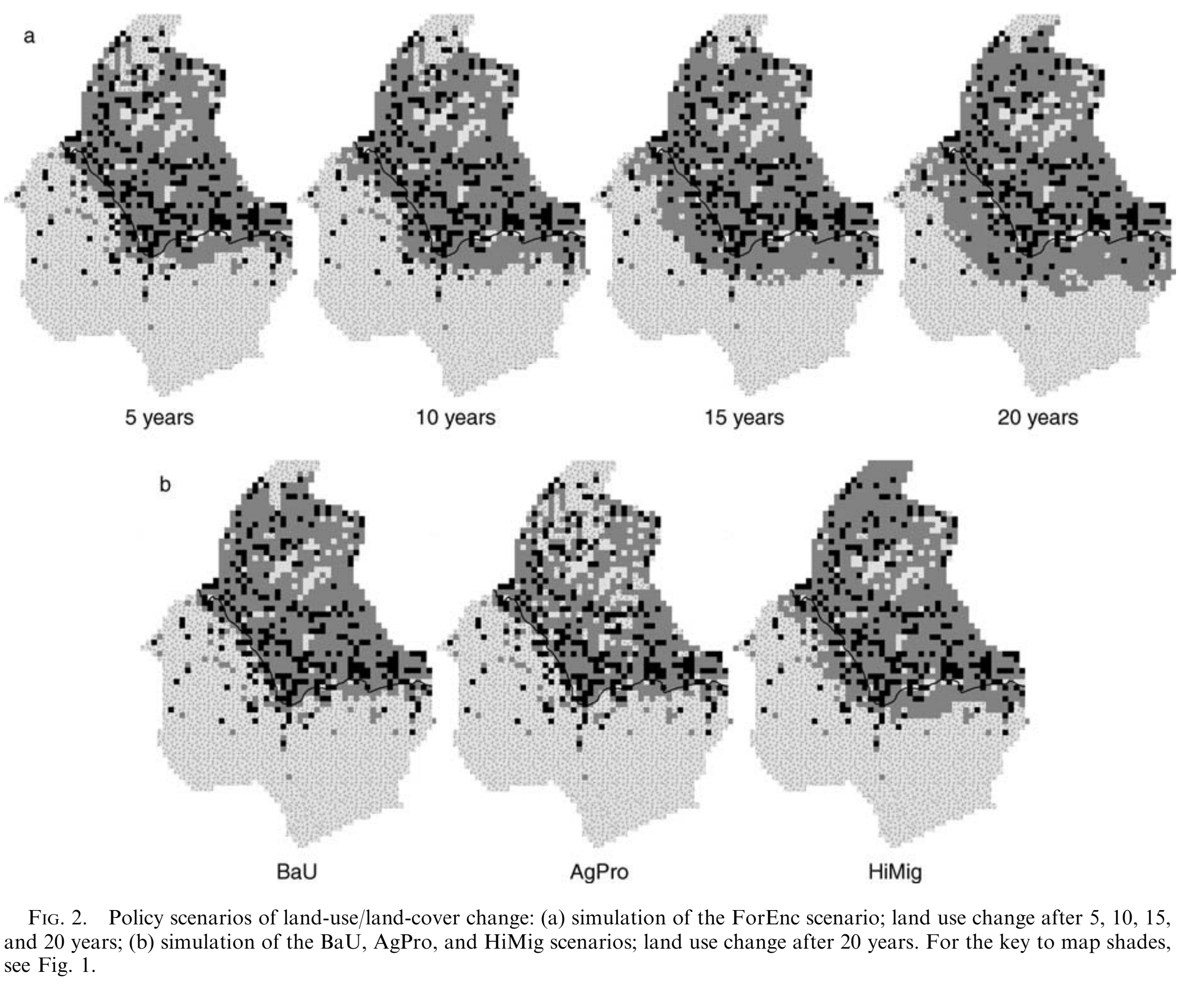

FIG. 2. Policy scenarios of land-use/land-cover change: (a) simulation of the ForEnc scenario; land use change after 5, 10, 15, and 20 years; (b) simulation of the BaU, AgPro, and HiMig scenarios; land use change after 20 years. For the key to map shades, see Fig. 1.

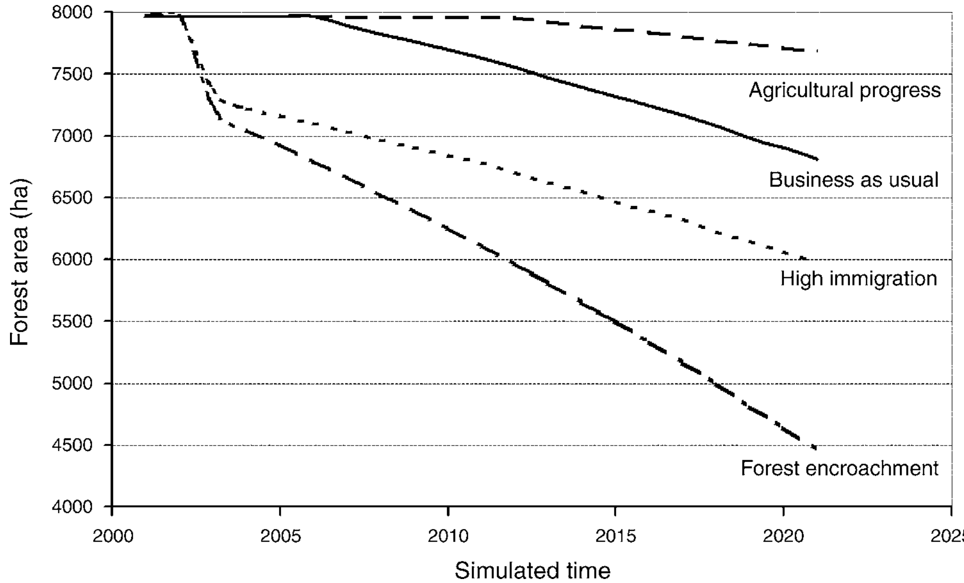

FIG. 3. Change in forest cover simulated in four policy scenarios for the period 2001–2021.

Cumulative losses of net revenues over 20 years ranged between 0.3% in the AgPro scenario and 13.8% in the ForEnc scenario (Table 4).

DISCUSSION

The quantification and valuation of ecosystem services is poorly understood (Kremen 2005, Steffan-Dewenter et al. 2005), and to date only a few estimates for the many services provided by natural systems have been published (Constanza et al. 1997, Balmford et al. 2002). Over the last decade pollination services, which are vital for many agricultural production systems, have received increasing attention, covering biological, economic, and land use aspects (Roubik 2002*a*, Klein et al. 2003*b*, *c*, Kremen et al. 2004, Ricketts et al. 2004). However, we know of only a few other studies, applying a combination of field research and spatially explicit model simulations, to assess the potential ecological and economic impacts of land use change on ecosystem services (Guo et al. 2000, van Jaarsveld et al. 2005). In this study, we use different

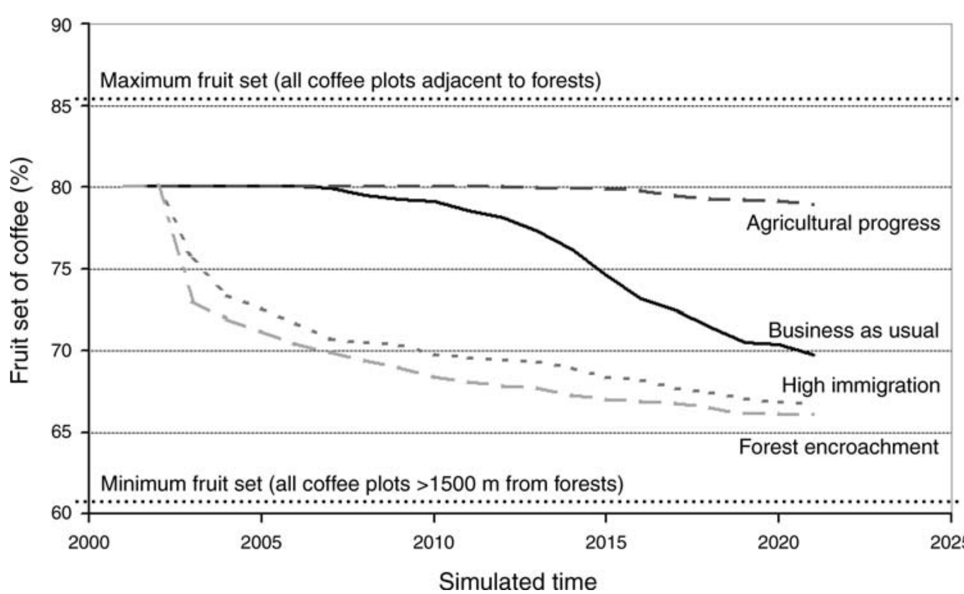

FIG. 4. The fruit set of coffee, as affected by land-use/land-cover change, simulated in four policy scenarios for the period 2001–2021. The calculations are based on Eq. 1, which is derived from fieldwork of Klein et al. (2003*a*) in the same region. The authors reported 85.2% as the maximum fruit set at the forest border, while the minimum fruit set was 60.4% (distance to nearest forest $\geq$1500 m). The coffee-growing area was kept constant throughout the simulation experiments.

TABLE 4. Cumulative losses of net revenues of all coffee farmers, simulated in four policy scenarios.

Cumulative losses	BaU	AgPro	HiMig	ForEnc
Euro (€)	850 310	60 757	2 360 139	2 660 008
Percentage	4.5	0.3	12.5	13.8

Note: Cumulative losses of net revenues were calculated as differences between revenues with continued high pollination rates, as observed in 2001 (€ 18 836 000; 1656 ha for the period 2002–2021), and reduced coffee yields simulated in four policy scenarios.

patterns and spatial coverages resulting from land use change simulations to calculate changes of pollination services provided by tropical rainforests and to assess the economic value of both pollination services and the natural habitat providing it.

Policy scenarios and land use and land cover change

The SITE model (M. Mimler and J. A. Priess, *unpublished manuscript*) was developed for regional land use change studies using a rule-based approach. Rule-based models include available expert knowledge and explicitly represent causal relationships (e.g., in our study derived from the household and village surveys, statistics, and satellite imagery). In consequence, such models are well suited for a broad range of scenarios, while empirical or regression models should only be used for scenarios, which are similar to the initial conditions under which the regressions were derived (Priess et al. 2001, Verburg et al 2002). The scenario assumptions employed in this paper are based on socioeconomic developments occurring in Indonesia and other tropical regions, where the expansion of crop production and agroforestry hits the forest frontier. It has been shown by Geist and Lambin (2002) that the underlying proximate causes for the resulting deforestation are manifold, and vary considerably between regions or countries. For this study we generated four scenarios of contrasting policy measures, demographic trends, and farmer's land use practices. It has been shown for our study region that population growth including migration (Maertens 2003) and the availability of land suitable for agriculture (Kreisel et al. 2004) are major factors explaining present and historical land use, and can be considered major drivers of land use change in the near future. The policy scenarios generated for this study are moderate modifications of existing and historical socioeconomic trends and farmer's preferences and land use strategies. We avoided extremely optimistic or pessimistic scenarios (e.g., the "Great Transition" by Raskin et al. [2002] or the "Barbarization" of the Global Scenario Group [*available online*])[7] with respect to economic developments, policy measures or consumption of natural resources. Nevertheless, the resulting extend of land use and land cover change, as well as land use patterns, are highly contrasting and have strong effects on natural and agro-ecosystems, and respective pollination services.

[7] ⟨http://www.gsg.org/⟩⟩

Pollination at risk

Forests, interspersed in an agricultural landscape, continually provide ecologically and economically valuable pollination services. The importance of adjacent or nearby natural vegetation for the pollination of commercially important crops, has repeatedly been reported (Kremen et al. 2002, 2004, Klein et al. 2003*a*, *b*, De Marco and Coelho 2004, Ricketts et al. 2004). The beneficial effect of pollinating insects, which can reach up to 41%-enhanced fruit set in Indonesia (Klein et al. 2003*a*, *c*), may vary between regions and between different crops (Free 1993, Kearns et al. 1998, Roubik 2002*a*, De Marco and Coelho 2004, Kremen et al. 2004, Ricketts et al. 2004). In this study, adjacent forests and forest patches provided near optimal pollination services in the base year 2001, while our simulations indicate that this ecosystem service can be expected to decline in the coming decades due to land use and cover changes. In the ForEnc and the HiMig scenarios the historic rates of forest conversion of 0.6% per year (Erasmi et al. 2004) were exceeded, but on the other hand were slower or comparable to recent nearby forest transformations in Sulawesi and in other forest frontier areas in the tropics (Shriar 2001, Steininger et al. 2001, Geist and Lambin 2002). However, due to the small foraging radius of bees (Gathmann and Tscharntke 2002), not only the extent, but also the location of forest conversion affects pollination services. In Sulawesi, in only 375 m distance from forests, 50% of the beneficial effect of pollination is lost, which means that average fruit set drops from 85% to 73%, (see Eq. 1).

Patch area of remaining forest might also influence species richness and abundance of pollinator communities as larger habitat fragments in many cases show higher species richness and density (Fahrig 2003). However, concrete studies on species–area relationships for pollinators in tropical forest fragments are lacking. Therefore, we could not include effects of patch area in our model suggesting that the potential loss of pollination services might be even larger than estimated in our simulations. However, the minimum area of forest patches in the model was 6.25 ha due to the grid length of 250 m. Considering the nonlinear relationship between habitat area and species richness (Fahrig 2003) we assume that these fragments supported a significant fraction of total pollinator diversity and that the effect of patch area on pollinator availability was less significant than isolation distance. The generality of our simulations is supported by similar effects of nearby natural vegetation on crop yields in several independent studies in different tropical and temperate regions (Kremen et al. 2002, 2004, Klein et al. 2003*a*, *b*, *c*, Ricketts et al. 2004). In consequence, all future land use policies leading to a purely agricultural landscape

TABLE 5. Relationship between coffee yields, pollination services for coffee farmers, and estimated minimum forest cover.

Mean distance between forest and coffee plantations (m)	Coffee yield (%)	Pollination service (%)†	Minimum forest cover (%)‡
150	91	69	8
400	85	48	2

† Pollination service at the forest boundary (0 m distance) is 100%.
‡ Assuming 1-ha forest patches in regular triangular spacing.

without persisting forest patches or other natural habitats, will face a severe reduction in pollination. Alternatively, appropriate local management of agroforestry systems providing continuously available pollen resources and nesting sites could increase diversity of bees in agricultural habitats (Klein et al. 2003*b*), but such appealing strategies of land use management to conserve pollination services are not yet developed. It is a realistic assumption that other ecosystem services might be lost in parallel, and this will result in associated additional negative ecological and economic impacts (Balvanera et al. 2005). There also might be some loss of ecosystem "disservices," e.g., pests, potentially counterbalancing some of the negative impacts.

Economic evaluation

According to Maertens et al. (2003) and van Rheenen et al. (2003) the farmers in the study region typically are involved both in food-crop production, mainly paddy and upland rice, as well as in agroforestry, planting small plots with coffee or cocoa. Income from crop production on average are accounting for 44% of the household income (Schwarze and Zeller 2005). In the year 2001, 80% of the population in the study area (Palolo district) was engaged in coffee production, managing on average 0.5 ha of coffee plantations. Many of the 3440 coffee-growing households operate close to or below the poverty line of 520 Euros per year for a typical household of five persons (van Rheenen et al. 2003). Thus, the income of the majority of the rural population in Palolo would be directly affected by the expected 0.3–13.8% reduction in net revenues from coffee sales. Notably, the lowest losses of ecological and economic values were estimated in the AgPro scenario, in which we simulated policies assumed to reduce forest conversion via controlling migration, intensification, diversification, and improving market access and off farm opportunities. The before mentioned policies are ambiguous with respect to their impact on tropical rainforest conversion; both beneficial and detrimental effects of such policies have been reported from the Tropics (Angelsen and Kaimowitz 1999, Fearnside 1999, Murniati et al. 2001, Geist and Lambin 2002, Maertens et al. 2003) depending on accessibility of land resources.

During recent years, Indonesia established a stable position as the world's fourth most important coffee producer. In some parts of the country, the Indonesian government still encourages the installation of new coffee plantations. Studies from the island of Sumatra revealed even an increase of coffee growing areas (as part of rural development plans) in spite of low producer prices, causing further forest conversion including unintended deforestation of an adjacent National Park (O'Brien and Kinnaird 2003). If we assume a comparable trend in the study area in Sulawesi, future land use dynamics would translate into a constellation similar to the ForEnc scenario presented in this study, or even more severe forest conversion. Moreover, the further conversion of forest leads to a reduction in yields on the already existing coffee plots due to reduced pollination. This might again urge many farmers to clear additional forest or to convert their extensively managed and ecologically sustainable agroforestry systems to annual cropping systems, which might be more profitable in the short term. However, small-scale coffee plantations in Indonesia and elsewhere, usually are located on sloping terrain with inherent high erosion risks, and thus are much less suited for annual cropping than for the currently still dominating coffee and cocoa agroforestry systems.

The estimates for the economic value of the forest, but also the potential financial losses of farmers in Sulawesi, were calculated based on the mean coffee price of 1998–2003, which is at the low end of the range of coffee prices reported by the International Coffee Organization (2004). Our estimate of 46 €/ha strongly contrasts with estimates of 315 €/ha by Ricketts et al. (2004). The discrepancy simply reflects the fact that their estimate is based on a forest area to coffee area ratio of 0.3, while in our study the ratio was 3.4, due to the large forest area of the nearby LLNP. In both studies, the minimum area for providing pollination (and other ecosystem) services is not known, but based on Eq. 1 and a regular triangular spacing of forest patches, we can calculate the number of forest patches per square kilometer, which are needed to provide pollination services for coffee farmers in Sulawesi (Table 5). In the study region, the 1656 ha of coffee plantations are distributed over ~5000 ha of land, translating into a minimum forest cover of 400 ha, considering 70% pollination services as satisfactory. The resulting minimum forest area to coffee area ratio would be 0.25, which is similar to the value reported by Ricketts et al. (2004). The corresponding value of annual pollination services would be 470 €/ha, thus exceeding the estimate of Ricketts et al. (2004) by ~50%.

In the case of increasing coffee prices, the economic value of the forests' pollination services would also increase and might well become more attractive than other forest uses or forest conversion, especially when considering that (1) coffee is only one of many tropical crops depending on pollinators and (2) pollination represents just one out of many services provided by forests (Kremen et al. 2000, Pattanayak and Kramer 2001, Balmford et al. 2002). As an additional effect, potential losses of net revenues would also increase in line with coffee prices, if deforestation continues (given that costs and producer prices follow a similar trend).

Smallholder coffee production is common in Indonesia (van Rheenen 2003, O'Brien and Kinnaird 2003) and other parts of the tropics, especially Central America and Africa (Nair 1993, Soto et al. 2000, Shriar 2001). In consequence, the results of this study are applicable in other coffee growing regions, where coffee is produced under similar conditions. At the global scale, it is unknown how many of the 10.4 million hectares of coffee plantations (FAOSTAT 2004) are managed by smallholders in forest margin areas, and how many of the 25 million people depending on coffee production are small-scale coffee producers. Based on our field and simulation studies in Indonesia, we can safely assume that the average deforestation rate of 1.57% per year for tropical forests (Geist and Lambin 2002), on a global scale causes considerable losses in net revenues of small-scale coffee farmers. However, considering the large number of agricultural crops potentially affected by reduced pollination (Free 1993, Steffan-Dewenter et al. 2005), the total economic losses may be considerably higher.

Improving the livelihood of a growing rural population without destroying the forest ecosystems, which provide the foundation for many of the activities of smallholders, remains one of the most challenging (scientific and societal) tasks. Future changes of land use will not automatically threaten (protected) forests and revenues of rural households. We identified and simulated policy measures and land use strategies, which might aid to identify and explore sustainable options for politicians and farmers in the real world. Our simulations clearly indicate that much of the ecological and economic value can potentially be conserved for future decades, if forest patches are preserved in the agricultural landscape due to changed attitudes of farmers and land use planners. The integration of impact analysis and spatially explicit land use modeling provides a novel tool to quantify the ecological and economical impacts of land use change scenarios, additionally providing the foundation for upscaling ecosystem-service estimates from the regional to larger spatial scales.

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