Landscape dynamics and ecosystem service benefits in the biodiversity hotspot of north-eastern Madagascar

Generating knowledge for navigating conservation–development trade-offs

Inauguraldissertation
der Philosophisch-naturwissenschaftlichen Fakultät
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Vorgelegt von

Julie Gwendolin Zähringer

von Glarus Nord GL

Leiter der Arbeit:
Prof. Dr. H. Hurni
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Geographisches Institut
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Der Dekan

Bern, ………………………… Prof. Dr. Gilberto Colangelo

Summary

Around the globe, tropical forests are vanishing and important ecosystem services (ES) are being lost. In many places the drivers of deforestation have shifted away from smallholders expanding land through shifting cultivation, towards large-scale agricultural investments. The biodiversity hotspot of north-eastern Madagascar seems to be an exception to this trend. Therefore, international conservation and development actors have been trying to change local people's land use activities away from shifting cultivation towards more intensive irrigated rice production. However, to date, this strategy has shown little success, due to the complex reality of these land use activities. Shifting cultivation is characterized by very high spatio-temporal characteristics and therefore hardly occurs on any maps. To improve our understanding on the different land use activities and the benefits they provide to land users, we need approaches which allow us to draw inferences from remotely sensed land cover to land use, and link this with ES benefits. The objective of this thesis is therefore to establish a spatially explicit knowledge base on the current state of land use and the benefits local stakeholders obtain from ES in north-eastern Madagascar, as well as on the dynamics of deforestation and land use since 1995.

Our results show that while the area of hill rice fields in shifting cultivation remained almost stable between 1995 and 2011, irrigated paddy rice production increased slightly (in terms of surface area). Although shifting cultivation was mainly rotational (i.e. hill rice fields were established in fallows), the slashing and burning of forests to acquire new land for shifting cultivation increased to a greater degree during the 2005-2011 interval than during 1995-2005. This indicates that an increase in irrigated rice production does not automatically lead to less shifting cultivation and, in turn, reduced deforestation. Using a landscape mosaic approach, we were able to delineate shifting cultivation and permanent land use systems in north-eastern Madagascar. Currently, the study region is dominated by mixed rice production systems, with more rice produced through irrigated than shifting cultivation. Also, the main observed change trajectory points towards landscape intensification, away from shifting cultivation towards more irrigated rice production. At the same time, shifting cultivation is still present to some extent in more than 80% of the study region (in terms of area) and more than 80% of the interviewed households still use shifting cultivation to meet at least part of their subsistence rice needs. This confirms that despite government sanctions and intense efforts of conservation actors, shifting cultivation is far from being eradicated from the landscapes of north-eastern Madagascar. Different land uses provide specific bundles of ES to local land users, depending on the wider landscape context. Also the composition of different household types in terms of the ES benefits they obtain differs between landscape types.

Combining the analysis of satellite imagery with socioecological data to analyse coupled human–environment systems, we embed our findings in land system (or land change) science. Land system science applies a sustainability perspective to investigate the dynamics of complex human–environment systems. With our results we hope to contribute to the knowledge base required for navigating the trade-offs between forest conservation and development in this biodiversity hotspot of global importance.

Résumé

Les forêts tropicales de ce monde ont tendance à disparaitre, entrainant ainsi la perte des plus importants services écosystémiques. Dans différentes localités, les principaux responsables de la déforestation sont passés de petits exploitants pratiquant le système de culture sur brûlis aux grands exploitants agricoles. Le « hotspot » de biodiversité du nord-est de Madagascar fait exception à cette tendance. De ce fait, les acteurs internationaux de conservation et de développement tentent d'orienter les populations locales habituées à la culture sur brûlis vers un système de culture irriguée. Due à la complexité de l'utilisation des terres par la population locale, cette stratégie est, jusqu'à ce jour, peu efficace. Le système de culture sur brûlis se caractérise par une dynamique spatio-temporelle très élevée, ce qui explique la difficulté de suivi par télédétection. Pour mieux comprendre les différentes formes d'utilisation des terres et leurs avantages, certaines approches reliant la télédétection de l'occupation du sol à l'utilisation des terres et aux services écosystémiques rendus sont fondamentales. L'objectif de cette thèse est ainsi d'établir une base de données spatiale sur l'utilisation actuelle des terres et les bénéfices liés aux services écosystémiques obtenus par la population locale au nord-est de Madagascar ainsi que sur la dynamique de la déforestation et l'utilisation de terres agricoles depuis 1995.

Nos résultats montrent que la superficie en termes de riziculture sur brulis est restée plus ou moins constante entre 1995 et 2011 tandis que celle de riziculture irriguée a légèrement cru. Néanmoins, le système de culture sur brulis avait un caractère rotationnel (les nouveaux champs dans les jachères), la coupe et le mis à feu des forêts pour l'obtention de nouveaux terrains de culture a augmenté entre 2005 à 2011 comparé à la période entre 1995 à 2005. Ceci implique que l'augmentation de la superficie en termes de riziculture irriguée n'entraine pas nécessairement une diminution de celle des cultures sur brûlis ; et par conséquent, une réduction de la déforestation. En utilisant une approche de mosaïques de paysage, nous avons réussi à délimiter les parcelles de culture sur brûlis et des systèmes d'utilisation permanente des terres au nord-est de Madagascar. Actuellement, la région d'études est fortement dominée par un système mixte de production rizicole, une domination de la production provenant de la riziculture irriguée sur la culture sur brûlis. De plus, le principal changement observé tend vers une intensification au niveau du paysage, autrement dit, moins de culture sur brûlis pour plus de riziculture irriguée. Tout de même, la culture sur brûlis est toujours dominante à plus de 80% de la superficie de la région d'études et assure une partie conséquente de la subsistance de plus de 80% des ménages enquêtés. Ceci confirme que malgré les sanctions gouvernementales et les efforts fournis par les acteurs de la conservation, la culture sur brûlis est loin d'être éradiqué du paysage du nord-est de Madagascar. En fonction de ce paysage, différentes utilisations des terres offrent différents lots de services écosystémiques aux exploitants locaux. Aussi les caractéristiques des différents types de ménages en fonction des bénéfices des services écosystémiques obtenus diffèrent par types de paysages.

En combinant l'analyse des images satellitaires avec les données socio-écologiques en vue d'analyser les systèmes homme-environnement, nos résultats contribuent à la communauté scientifique de «land system science». Cette dernière applique une perspective durable dans l'investigation des dynamiques du complexe homme-environnement. Avec nos résultats, nous espérons contribuer à la connaissance de base nécessaire pour étudier les conflits entre la conservation des forêts et le développement dans ce point chaud de la biodiversité d'importance globale.

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Part I: Background and overview

Introduction

Human needs for food, fibre, and other services from natural and cultivated ecosystems are driving worldwide land cover and land use changes (Foley et al. 2005). As a consequence, land cover and land use changes have tremendous impacts on the planet's climate system, water and nutrient cycles, and human societies (MEA 2005). Tropical deforestation is arguably the most important global land cover change leading to huge losses of biodiversity and carbon stocks (Dirzo and Raven 2003; Laurance 1999; Pimm and Raven 2000). In the tropics, forest was the most important source of agricultural land expansion towards the end of the 20th century (Gibbs et al. 2010). Local smallholders and their subsistence food production systems, often based on shifting cultivation, have long been held accountable for tropical deforestation (Allen and Barnes 1985; Myers 1980). More recently, indirect factors such as economic incentives (Geist and Lambin 2002) and globalized demands for commercial crop cultivation have been identified as increasingly important factors of tropical deforestation (DeFries et al. 2010; Lambin and Meyfroidt 2011; Rudel et al. 2009). This global trend of land use intensification has led to the demise of shifting cultivation in many places, mostly in South East Asia and East Africa (van Vliet et al. 2012).

An exception to this trend appears to be Madagascar, which has been labelled a global biodiversity hotspot due to its high number of endemic plant and animal species (Myers et al. 2000). As in other shifting-cultivation hotspots around the globe (Ickowitz 2006; Mertz et al. 2009), shifting cultivation in Madagascar has since colonial times been considered irrational and unsustainable, leading to the destruction of biodiversity-rich forests (e.g. Humbert 1927; in Kull 2000). However, shifting cultivation is far more than a simple agricultural technology and provides numerous adaptive advantages in a context as exposed to environmental, economic, and political constraints as the eastern escarpment of Madagascar (Kull 2004). With the aim of finding sustainable solutions to the pressing issues of biodiversity loss, food insecurity, and extreme poverty, in the late 1980s researchers of the Institute of Geography, University of Bern, established a research site on the eastern escarpment of Madagascar, in Beforona municipality. Using participatory approaches, they studied the biophysical, social, and economic interrelations of the diverse local land use systems, and proposed potential sustainable pathways towards more sustainable development. The present thesis, begun almost a decade after the project above closed, continues in this line of research but expands its spatial focus to encompass a larger part of the north-eastern escarpment including the protected areas of Makira and Masoala. Although most scholars and practitioners writing about the tropical forests of Madagascar mention shifting cultivation as the looming threat posed to their long-term existence, there is surprisingly little evidence on shifting cultivation in terms of its past development, current state, and future projections.

The main goal of this thesis is therefore to establish a spatially explicit knowledge base on the current state of land use and the benefits local stakeholders obtain from ecosystem services (ES), as well as on the dynamics of deforestation and land use since 1995. Applying a mixed methods approach combining remote sensing data with socioecological information to analyse coupled human–environment systems, this thesis is embedded in land system (or land change) science. This science community aims at investigating causes and consequences of land cover and land use change using a socioecological systems perspective (Reenberg 2009; Turner II, Lambin, and Reenberg 2007; Verburg et al. 2015). The ES concept (MEA 2005) can thereby be used to frame the links between land use and human well-being.

In the remainder of Part I, I will present an overview of the papers constituting the core of this thesis and introduce the study context of forested landscapes, with a special focus on north-eastern Madagascar. I will then introduce the research approach and methods, followed by key insights and an overall synthesis. Part II consists of the six peer-reviewed publications spanning the field from the conceptual foundations to methodological insights and evidence from in-depth studies at different levels.

Overview of research papers

The present thesis consists of six individual peer-reviewed papers (five published, one submitted). *Paper I* provides an overview of the ES concept in terms of its strengths, weaknesses, opportunities, and threats as perceived by a group of young ES researchers. *Papers II to IV* constitute the core of the thesis focusing on the regional level of north-eastern Madagascar. *Paper II* builds the basis for further analysis and provides insights on deforestation dynamics considering forest and four agricultural land cover categories. *Paper III* uses a landscape mosaic approach to generalize from land cover to land use in order to understand landscape change trajectories of intensification and extensification. *Paper IV* concludes the regional-level analysis linking the observed landscape types with spatially explicit perceptions of ES benefits. *Paper V* takes an in-depth look at a case study located to the south of our study region, to explore deforestation and forest fragmentation from a sustainable livelihood perspective. In *Paper VI* we contrast our findings with peoples' perceptions of ES in a different biodiversity hotspot in the humid Guinean forest zone of West Africa.

Table 1. Overview of peer-reviewed papers building the core of the thesis

No.	Title	Authors	Peer-reviewed journal	Current state
	The ES concept as a conceptual foundation			
I	Strengths, Weaknesses, Opportunities and Threats: A SWOT analysis of the ecosystem services framework.	Bull, J. W., Jobstvogt, N., Böhnke-Henrichs, A., Mascarenhas, A., Sitas, N., Baulcomb, C., Lambini, C.K., Rawlins, M., **Zähringer, J.**,… Koss, R.	**Ecosystem Services**, 17, 99–111.	Published (2016)
	Land system science for generalizing from land cover to land use to landscape change			
II	Revealing Regional Deforestation Dynamics in North-Eastern Madagascar—Insights from Multi-Temporal Land Cover Change Analysis.	**Zaehringer, J.G.**, Eckert, S., & Messerli, P.	**Land**, *4*(2), 454–474.	Published (2015)
III	Beyond deforestation monitoring in conservation hotspots: Analysing landscape mosaic dynamics in north-eastern Madagascar.	**Zaehringer, J.G.**, Hett, C., Ramamonjisoa, B., & Messerli, P.	**Applied Geography**, 68, 9–19.	Published (2016)
	Linking land use to ES beneficiaries			
IV	Navigating conservation–development trade-offs in biodiversity hotspots: landscape types, ecosystem services, and livelihoods in north-eastern Madagascar.	**Zaehringer, J.G.**, Schwilch, G., Andriamihaja, O.R., Ramamonjisoa, B., & Messerli, P.	**Ecosystem Services**	Submitted

V	Understanding deforestation and forest fragmentation from a livelihood perspective.	Urech, Z. L., **Zaehringer, J.G.**, Rickenbach, O., Sorg, J.-P., & Felber, H. R.	**Madagascar Conservation & Development**, *10*(2), 67–76.	Published (2015)
	Exploring ES trade-offs in a different forested landscapes context			
VI	People, protected areas and ecosystem services: a qualitative and quantitative analysis of local people's perception and preferences in Côte d'Ivoire.	Amin, A., **Zaehringer, J.G.**, Schwilch, G., & Koné, I.	**Natural Resources Forum**, *39*(2), 97–109.	Published (2015)

Study context

Tropical forest landscapes have been modified by humans for tens of thousands of years with increasing intensity (Malhi et al. 2014; Wright 2005). Despite decades of international conservation efforts, they are still shrinking today (Hansen et al. 2008; Hansen et al. 2013). In many countries the concern has now shifted to large-scale forest clearance linked to engagement in international agricultural markets and the growth of urban populations (DeFries et al. 2010; Lambin and Meyfroidt 2011; van Vliet et al. 2012). Madagascar seems to be an important exception to this trend, with the retraction of its humid forest frontier still due to smallholders' expansion of agricultural land to produce subsistence rice through shifting cultivation (van Vliet et al. 2012). In the next section I will introduce the context of deforestation and conservation in Madagascar.

Deforestation crisis and the conservation boom in Madagascar

Due to its exceptional degree of endemism, coinciding with rapidly advancing forest loss, Madagascar has been labelled one of the world's prime biodiversity hotspots (Ganzhorn et al. 2001; Myers et al. 2000). After extensive exploitation of its natural resources for profit through the colonial powers in the first half of the 19th century (Jarosz 1993), since the 1980s Madagascar's forests and the local smallholder farmers using them have become the focus of the global conservation community. In 2003, during the World Parks Congress in Durban, South Africa, President Ravalomanana pledged to triple the area under conservation within 5 years (Kull 2014). Already long before, state actors have sought to put a halt to shifting cultivation (Kull 2004), which has been the main direct cause for the clear-cutting of forests along the eastern coast since the country's independence. However, forest degradation through selective logging of high-value timber species is also an important concern for the long-term integrity of the tropical forest ecosystems (Barrett et al. 2010; Randriamalala and Liu 2010; Schuurman and Lowry 2009). Remaining forest massifs along the eastern escarpment are becoming more and more fragmented affecting the provision of ecosystem goods and services at the local (e.g. non-timber forest products) (Urech et al. 2011) as well as the global (e.g. carbon sequestration) level (Ferguson 2009; Brimont et al. 2015).

The often reported claim that Madagascar has lost 90% of its forest cover to date (e.g. Nayar 2009; Hannah et al. 2008; Johnson et al. 2011; Myers et al. 2000) is based on the assumption that the island was once entirely covered in forest. However, there has been evidence to reject this hypothesis for a long time (Kull 2000). Records of sub-fossil fauna, pollen, and charcoal deposits have shown that the island featured different types of ecosystems long before humans populated it (e.g. Burney 1997; Dewar 1984; Dewar and Burney 1994; Matsumotot and Burney 1994). Nevertheless, until now it is still difficult to obtain reliable estimates of changing deforestation rates over time. Differences in methods used to assess forest loss – and wrongly cited references – make comparisons over time a challenging task (McConnell and Kull 2014). Furthermore, due to the strong global empathy with Madagascar's fauna and flora, national-scale land cover change analysis has so for focused on the binary analysis from forest to non-forest (Grinand et al. 2013; Harper et al. 2007; MEFT Ministère de l'Environnement, des Forêts et du Tourisme, USAID, and CI Conservation International 2009; ONE Office National pour l'Environnement et al. 2013). This restricts our understanding of the land change processes at work and explains the lack of studies investigating shifting cultivation dynamics in a spatially explicit way. The scarce scientific knowledge on the current extent and trajectories of shifting cultivation along the north-eastern escarpment is almost exclusively based on case studies clustered between the capital, Antananarivo, and the port of Toamasina on the eastern coast (Klanderud et al. 2010; Messerli 2004; Styger et al. 2007). This presents a considerable lack of evidence given the large amount of attention shifting cultivation has received from conservation and development stakeholders (Conservation International 2011; Freudenberger 2010; Holmes et al. 2008; World Bank 2013; WWF 2007).

Other than in many tropical forest countries around the world, the narrative dominating the deforestation discourse in Madagascar is still one of rural households, caught in poverty and traditional beliefs, slashing and burning forests to plant subsistence rice to assure their survival (e.g. Sussman, Green, and Sussman 1994; Styger et al. 2007; Hume 2006). Conservation and development strategies are therefore mainly concentrated on the intensification of land use away from shifting cultivation towards permanent irrigated rice production (Freudenberger 2010). However, there is little evidence on the success of this approach, and the focus on single components of the agricultural production system has been questioned (Brimont et al. 2015; Messerli 2004; Pollini 2009; Freudenberger 2010). Instead of showing a win-win outcome for conservation and development, several studies have documented a lack of benefits or even negative impacts from protected areas in eastern Madagascar to land users living in their vicinity (Ferraro 2002; Keller 2008; Keller 2015; Marcus 2001; Ormsby and Kaplin 2005; Poudyal et al. 2016). This suggests that in the present situation, with stakeholders exhibiting diverging claims on land use, trade-offs between different ES are inevitable. The way forward would therefore comprise acknowledging these trade-offs and enabling stakeholders to engage in a deliberation to find a balance between their demands.

The study region: north-eastern Madagascar

We selected our study region in north-eastern Madagascar (Figure 1) because it is home to some of the last remaining humid primary forests containing the extraordinary biodiversity for which Madagascar is known (Ganzhorn et al. 2001; Myers et al. 2000). It features a number of protected areas which have the aim of halting deforestation and forest resource exploitation. We chose the administrative region of Analanjirofo for the analysis, as this is the level at which decision-making for regional development takes place. However, the northernmost tip of the Analanjirofo region is not included as the available satellite imagery did not extend this far. Instead, we included the Masoala peninsula, part of which belongs to the Sava administrative region, as it represents a biodiversity hotspot of great interest to many conservation actors.

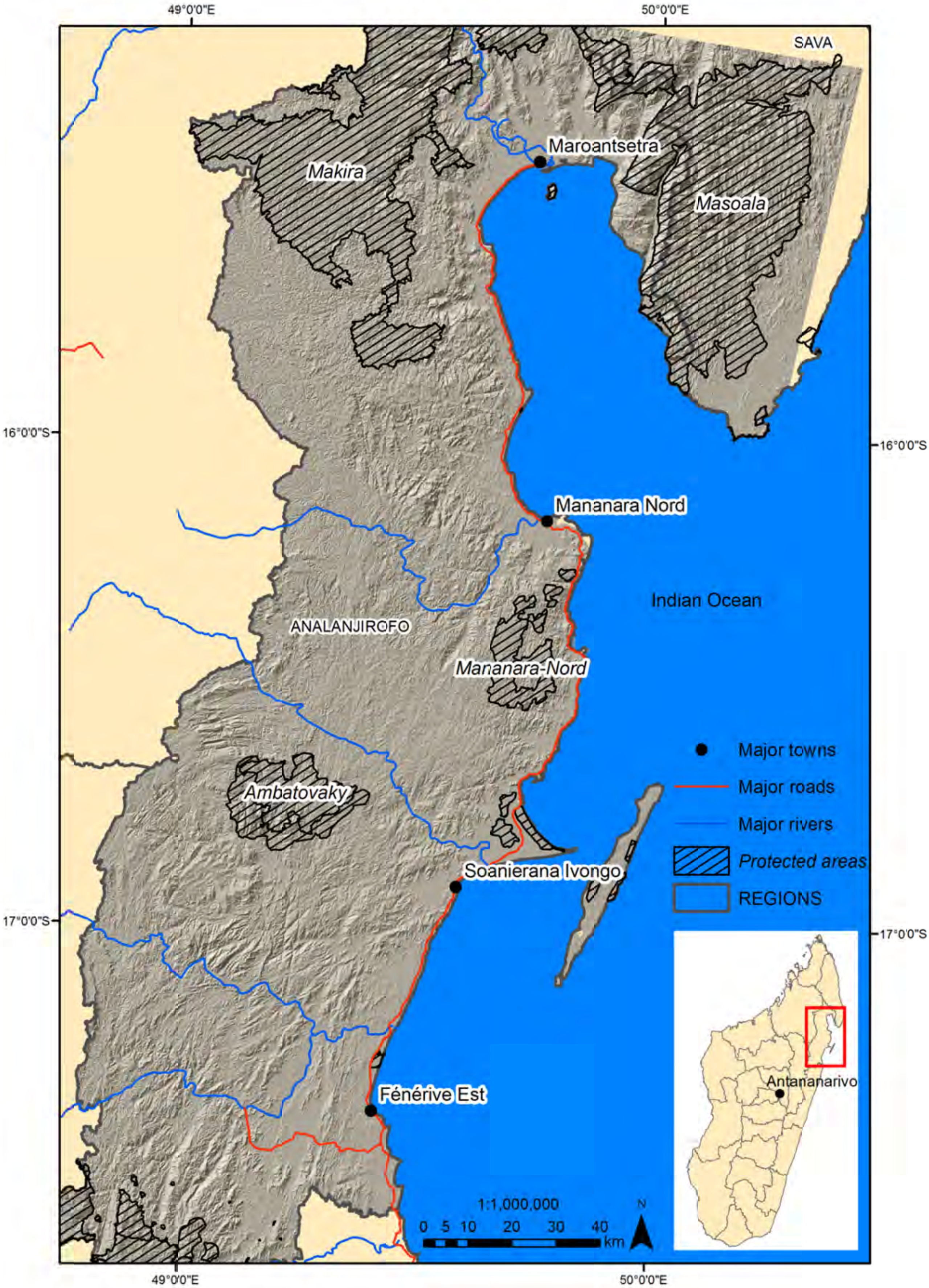

Figure 1. Study region in north-eastern Madagascar with protected areas, major towns, roads, and rivers.

This region receives about 3,600 mm of annual precipitation and has an average annual temperature of 24 °C (Jury 2003). Population in Analanjirofo increased by about 54% from 1995 to 2011 and was estimated at nearly 1 million people in 2011 (INSTAT 2011). Mean annual income from agriculture was about US$ 292 per household and the share of poor people (based on the national poverty line) was estimated at 63.5% in 2013 (INSTAT 2014).

Makira Natural Park, established in 2005, encloses one of the largest continuous rainforests in the country and provides a habitat for more than 18 species of lemurs (Golden et al. 2011). Other large forest conservation sites include Masoala National Park (established in 1997), Ambatovaky Special Reserve (established in 1958), and Mananara Nord National Park (established in 1989). Together these protected areas cover 23% of our study region (IUCN and UNEP 2014). Access to these forests by local land users is restricted, but due to their limited accessibility and limited funding, enforcement is rather weak. Apart from forests, the region is characterized by small plots with diverse land uses. Rice is the main staple crop in Madagascar. Both rain-fed upland and irrigated lowland paddy rice are produced for subsistence by the local land users, ethnically dominated by the Betsimisaraka people. Also important are commercial crops such as clove, vanilla, coffee, and lychee (Locatelli 2000). The volatility in prices for these crops creates uncertainty for local farmers (FAO 2014).

Traditional shifting cultivation is used to produce rain-fed upland rice on moderate to steep slopes. Most commonly land users clear and burn small plots, which they plant with rice (often in combination with maize) for a single year. Subsequently, tuber crops such as cassava or sweet potatoes are often cultivated for another one to two years. Thereafter the fields lie fallow for several years (Messerli 2004). For permanent rice cultivation, land users need access to paddies at the valley bottoms and to irrigation water. Ploughing and weeding the irrigated rice fields is labour intensive, and external inputs such as fertilizers are rare (Locatelli 2000). Clove trees, coffee bushes, and vanilla lianas are often grown in agroforests together with a diverse mix of fruit trees and tuber crops for home consumption. Monocultures of clove trees are also common. Zebu cattle are used for ploughing and in ancestral ceremonies. They mostly graze in irrigated rice paddies after harvest and along footpaths, as relatively few land users have sufficient land for pastures. Small forest fragments, often family owned, are dispersed throughout the region and provide construction materials, wild food, space for burial grounds, and other benefits (Urech et al. 2011).

Agricultural land is managed through a complex system of mixed family- and individual-based rights. Land for rice production through both shifting cultivation is managed at the extended family level with plots allocated to individual households by family elders (Urech et al. 2011). Converting forest into agricultural fields is one of the few ways for family elders to bring additional land into production and thus to assure food security for their descendants (Keller 2008). The increasing scarcity of natural forests and expansion of protected areas might therefore incite land users to accelerate deforestation. Irrigated rice paddies and plots for cash crop cultivation are usually managed at the household level and passed on from parents to their children. New arrivals can rent or purchase such lands upon the approval of village authorities (Messerli 2004).

Research questions and methods

The starting point for this thesis was the realization that the widespread assumptions about small-scale land users destroying a global biodiversity hotspot through shifting cultivation were largely based on few spatially restricted case studies and much anecdotal evidence. While these assumptions have motivated many donors to invest in conservation and development interventions in Madagascar during the last 30 years, they triggered my interest to investigate the current state and past changes of shifting cultivation as well as to know more about the land users linked to the landscapes of north-eastern Madagascar. Available evidence on land change in this region focused entirely on deforestation without revealing anything about the agricultural land use trajectories at work. Therefore the main objective of this thesis was to better understand the dynamics and processes of land use change at the regional level as well as the links between land use and ES benefits to the local population. More specifically, the following research questions were addressed during the course of this thesis:

1) What were the main deforestation dynamics in north-eastern Madagascar between 1995 and 2011?
    a) How did the extent of forest and different agricultural land cover classes change?
    b) What were the main dynamics of change between different land cover classes?

2) What is the current extent of shifting cultivation and what were the main trajectories of land use and landscape change in north-eastern Madagascar between 1995 and 2011?
    a) What is the current extent of shifting cultivation and permanent land use systems?
    b) What were major changes in the extent of shifting cultivation and permanent land use systems between 1995 and 2011?
    c) What were the main landscape change trajectories in terms of intensification and extensification between 1995 and 2011 and where did they occur?

3) What are the links between land use and ES benefits to local land users in north-eastern Madagascar?
    a) Do different landscape types obtained through remote sensing reflect households' involvement in shifting cultivation and irrigated rice production?
    b) Do the bundles of ES linked to specific land uses vary across different landscape types?
    c) Do different landscape types correlate with household types in terms of key ES benefits they obtain?

The research approach I used to find answers to these questions is rooted in the domain of land system science, drawing on tools and methods from remote sensing as well as social sciences. In the absence of census or survey data I conducted extensive field research to obtain primary data required for the analysis. In the following, I give a brief overview of the methods used for the spatially explicit analysis of land change as well as for the investigation of ES benefits. The detailed description of methods can be found in the respective papers in Part II of the thesis.

Spatial analysis of land change

First, we developed medium-resolution land cover maps from Landsat satellite imagery for three different points in time. Availability of data for north-eastern Madagascar is low, as the area is often cloud covered. This makes it difficult to monitor land change in this region, and also posed challenges for this study. Moreover, to differentiate between permanent agriculture and burnt plots in a shifting cultivation cycle, we specifically required satellite images taken between December and March, when new fields are freshly burnt and irrigated rice fields still flooded. Eventually we were able to classify land cover for 1995, 2005, and 2011, distinguishing between forest and four agricultural land cover classes. To quantify land cover change we applied a post-classification pixel-to-pixel comparison in ArcGIS by overlaying the land cover maps from 1995, 2005, and 2011 to detect from–to transitions between different land cover classes (Braimoh 2006). To account for the different length of the two time intervals assessed and the different sizes of the land cover classes, we used the intensity analysis proposed by Aldwaik and Pontius (2012).

Second, we used the land cover maps for 1995 and 2011 as an input to the landscape mosaic approach, originally developed to investigate the extent of swidden cultivation in Laos (Messerli, Heinimann, and Epprecht 2009). This approach circumvents the challenge that land use cannot be inferred from pixel-based remote sensing images. For example, a patch of low-height vegetation, viewed in isolation, could represent several land uses, such as forest regrowth after a disturbance, a young fallow in the shifting cultivation cycle, or even a pasture. But if it is surrounded by burnt plots and forest, it is probably a young fallow in a shifting cultivation system. The landscape mosaic approach applies two steps to describe landscape types from land cover maps: first, the composition of neighbouring pixels is analysed for each pixel in a land cover map using a moving window approach in Arc-GIS; second, the different compositions are interpreted taking into account the socioecological context. Our classification of landscape types was guided by two land use issues that are important for conservation and development in the region (1) intensity of staple crop cultivation and (2) proportion of tree cover. The resulting landscape mosaic maps contain 15 different landscape types for the region of north-eastern Madagascar. To analyse landscape change we overlaid the two landscape mosaic maps for 1995 and 2011 and classified the change trajectories from one landscape type to another, according to changes in staple crop intensity and tree cover.

Household surveys to obtain socioecological data

We collected socioecological data through a stratified sampling of 45 villages distributed among the three most common landscape types (based on staple crop intensity) in the study region. These three landscape types present a gradient of intensification from less to more intensive agricultural landscapes. In each village we conducted face-to-face interviews with land users at household level, administering a standardized survey questionnaire. In total we interviewed 1,187 households. The questionnaire was structured according to the six distinct land use types present in the region: irrigated paddy rice fields, rain-fed hill rice plots, fallows (the latter two being integral parts of shifting cultivation), agroforests, pasture, and forest. It further contained three general sections about socio-demographic characteristics, households' well-being, and development aspirations. The questionnaire included open questions to allow respondents to explain what benefits and challenges they associated with each land use activity, and why they did not engage in certain land use activities. Questions about quantifiable household resources (e.g. kg of rice harvested, number of zebus, and revenue from cash crops) were included to indicate differences in the socio-economic status of households. We refrained from asking land users directly about ES, as we view the ES concept as a specific lens to examine the links between land use and human well-being, rather than a concept depicting land users' reality. Instead, our aim was to obtain a comprehensive understanding of households' land use activities and the associated benefits and challenges, and then frame the results according to the ES framework.

Integration of spatially explicit land use information with socioecological data

Each sampled village was assigned to one of the three landscape types, depending on its spatially explicit location. For a characterization of the three landscape types we applied descriptive statistics on quantitative and qualitative coded information related to land use and ES in the R statistical software (R Core Team 2015). More specifically, we tested for differences between the three landscape types using Wilcoxon-Mann-Whitney and Fisher's exact tests for numerical and categorical variables, respectively. For all variables we first controlled for differences at the level of villages before testing for differences between landscape types.

Key insights

The ES concept as a conceptual foundation

To highlight the benefits humans obtain from nature the ES concept was proposed almost two decades ago (Costanza et al. 1997; Daily 1997). As each actor perceives different benefits provided by land and natural resources, the ES concept is highly normative (Wiesmann and Hurni 2011). Since the Millennium Ecosystem Assessment (MEA 2005) the concept has experienced an exponential rise in use in different contexts and disciplines (Kull, Arnauld de Sartre, and Castro-Larrañaga 2015). Yet, there is still considerable critique from various different angles (for a good overview see Schröter et al. 2014). One of the challenges concerns the way in which the links between nature and the benefits should be classified. Some propose a classification that disentangles ecosystem processes from ES and relates them to specific categories of human values (Wallace 2007) while others argue for the importance of distinguishing between intermediate services, final services, and benefits (Fisher, Turner, and Morling 2009; Boyd and Banzhaf 2007). Furthermore, the goods and services provided by nature are also described as landscape functions (Bastian, Kronert, and Lipsky 2006; R. de Groot 2006; Haines-Young and Potschin 2010), land use functions (Perez-Soba et al. 2008), land functions (Verburg et al. 2009), or landscape services (Termorshuizen and Opdam 2009). For the present thesis we follow the 'cascading ES model' and classification proposed by Haines-Young and Potschin (2010) and modified by de Groot et al. (2010), which further distinguishes between benefits and values.

The first paper of this thesis extends the documentation of challenges associated with the ES concept, to systematically assess strengths and external factors that influence the concepts' uptake by different stakeholders.

Paper I: Strengths, Weaknesses, Opportunities and Threats: A SWOT analysis of the ecosystem services framework

As a group of early career researchers and practitioners (The Young Ecosystem Services Specialists YESS) we conducted a Strengths-Weaknesses-Opportunities-Threats (SWOT) analysis of the ES concept to derive strategies for the further development of the field. Strengths include the approach being interdisciplinary, and a useful communication tool. Weaknesses include an incomplete scientific basis, frameworks being inconsistently applied, and insufficient accounting for nature's intrinsic value. Opportunities include alignment with existing policies and established methodologies, and increasing environmental awareness. Threats include resistance to change, and difficulty with interdisciplinary collaboration. Considering the themes which have emerged through the SWOT, we propose five key strategies for furthering the concept.

The ES concept could improve decision-making related to natural resource use, and interpretation of the complexities of human–nature interactions. It is contradictory – valued as a simple means of communicating the importance of conservation, whilst also considered an oversimplification characterized by ambiguous language. Nonetheless, given sufficient funding and political will, the ES framework could facilitate interdisciplinary research, ensuring decision-making that supports sustainable development.

Land system science for generalizing from land cover to land use to landscape change

Adopting a sustainability perspective, land system science seeks to understand the causes and consequences of land cover and land use change applying socioecological systems thinking (Turner II, Lambin, and Reenberg 2007; Reenberg 2009; Verburg et al. 2015). Local land users' decisions are increasingly influenced by broad economic, political, and environmental processes (Lambin and Meyfroidt 2011; Verburg et al. 2009) leading to highly context-dependent outcomes (Ostrom 2007; Rindfuss et al. 2007). One of the main challenges, therefore, faced by land system science today is the production of generalized knowledge on place-based human–environmental interactions beyond a local case study level (Magliocca et al. 2014; Rindfuss et al. 2004).

Starting from a land centred view of land system science, north-eastern Madagascar is characterized by a lack of basic evidence regarding the dynamics of deforestation, despite the pronounced interest received from global conservation actors. This could partly be explained by the strong focus on forest by conservation researchers and practitioners, which has led to a number of regional or national level studies concentrating on the binary changes from forest to non-forest only (Sussman, Green, and Sussman 1994; Harper et al. 2007; ONE Office National pour l'Environnement et al. 2013; MEFT Ministère de l'Environnement, des Forêts et du Tourisme, USAID, and CI Conservation International 2009). Another reason may be the extremely humid context resulting in very frequent cloud cover, posing challenges for remote sensing.

In a first step towards understanding land system dynamics in north-eastern Madagascar, we have therefore taken on this challenge. We conducted a multi-temporal analysis of deforestation dynamics at the regional level, taking into account different agricultural land cover classes.

Paper II: Revealing Regional Deforestation Dynamics in North-Eastern Madagascar—Insights from Multi-Temporal Land Cover Change Analysis

Our study presents a first attempt to quantify changes in the extent of forest and different agricultural land cover classes, and to identify the main dynamics of land cover change for two intervals, 1995–2005 and 2005–2011.

The analysis revealed that during the 16-year period between 1995 and 2011 about 11% of the regions' forests disappeared. The rate of annual forest loss accelerated over the two intervals, with 1% of the initial forest area lost every year from 1995 to 2005 and 1.7% from 2005 to 2011. At the same time, the area used for planting hill rice in a shifting cultivation system remained almost stable, while the area used for irrigated paddy rice production slightly increased. This suggests that an intensification of rice production does not necessarily lead to reduced deforestation. This may be explained by differences in individual households' access to land on the one hand (some only have access to land for shifting cultivation), and diversification strategies on the other (households with access to both types of land will use both to reduce risks, e.g., of crop failure due to cyclones). Furthermore, under customary law, slashing and burning forests is the most commonly used means of securing land for future generations.

Shifting cultivation was mainly rotational i.e. fallow land was slashed and burnt to plant hill rice, although the establishment of new hill rice fields in forests increased during the study period. The forests targeted by shifting cultivation were mostly the small fragments outside today's core zones of protected areas. As the term "pioneering shifting cultivation" usually designates the establishment of new upland rice fields at the forest frontier, a new term might be needed to describe the process of landscape homogenization we observed in our study region. We therefore suggest the term "homogenizing shifting cultivation" to describe the process of shifting cultivation that removes the last forest fragments from the landscape.

We started with the pixel-based analysis of remotely sensed imagery for the land cover change analysis presented above, as is common in land system science. However, while we were able to identify burnt fields as indicators of shifting cultivation taking place, human use of land can generally not be directly inferred from land cover information obtained through remote sensing (Verburg et al. 2009). This is especially pertinent in the context of shifting cultivation systems, which are characterized by a combination of different land cover types showing high spatial and temporal dynamics (Schmidt-Vogt et al. 2009; Sirén and Brondizio 2009). In order to study shifting cultivation dynamics, one possibility is to rely on time series (e.g. Hurni et al. 2012). However, in humid tropical regions satellite image availability is often constrained by frequent cloud cover. In this case a landscape mosaic approach, taking into account the spatial composition of land cover categories, can be used to delineate shifting cultivation landscapes (Messerli, Heinimann, and Epprecht 2009; Hett et al. 2012).

To better understand the dynamics of land use and the main landscape change trajectories in our study region, we adopted the landscape mosaic approach originally developed in Laos (Messerli, Heinimann, and Epprecht 2009), and adapted it to the context of north-eastern Madagascar.

Paper III: Beyond deforestation monitoring in conservation hotspots: Analysing landscape mosaic dynamics in north-eastern Madagascar

Using the landscape mosaic approach, we assessed the changes between natural forests, shifting cultivation, and permanent cultivation systems in north-eastern Madagascar from 1995 to 2011. Our results showed that large continuous forest exists today only in the core zones of protected areas and that shifting cultivation is still being used to produce subsistence rice in 85% of the study region. At the same time landscapes in which rice is produced only through shifting cultivation were rare in 2011. Instead, mixed land use, in which rice is produced through both shifting and irrigated paddy cultivation, predominates in north-eastern Madagascar. Further, more than 80% of the region is still characterized by a high tree cover that includes both forest fragments and planted fruit trees.

The main trajectory of landscape change between 1995 and 2011 followed a trend of intensification, away from shifting cultivation towards irrigated rice production with stable tree cover. Another common trajectory, which occurred throughout the interior and more remote part of the region, was the loss of tree cover while staple crop production remained stable. As the two change processes of staple crop intensification and loss of tree cover hardly occurred together, this indicates that trade-offs between more intensive staple crop production and the maintenance of tree cover at the landscape level were limited.

The landscape mosaic approach allowed us to delineate shifting cultivation and permanent land use systems using basic land cover information. With this approach, although the precise land cover at the location of each single pixel is lost, knowledge is gained about land use by interpreting the spatial combination of different land cover pixels within a defined neighbourhood. Land use patterns delineated in this way are also easier to see than those in a standard land cover map. We have shown that the landscape mosaic approach enables identification of hotspots of land use change and thus provides evidence on which land use planning and forest conservation can build.

Linking land use to ES beneficiaries

While in spatial analysis new approaches for generalization and scaling up exist that allow a better representation of land use, they reveal only one side of the larger picture regarding the linkages between land use and ES benefits to humans. The integration of spatially explicit data on land use with social science information at regional to national level is crucial (Rindfuss et al. 2012; Rindfuss et al. 2007). So far, few examples exist from developing countries: the unavailability of census data at sufficient spatial resolution usually presents a major obstacle to such an endeavour. One exception is Lao PDR, where Messerli et al. (2015) combined national level spatial data on land use with village-level poverty indicators to explore trade-offs between poverty, agricultural intensification, and environmental integrity. Such spatially explicit knowledge can contribute to tailoring context-specific development interventions to maximize synergies and minimize trade-offs between environmental integrity and human well-being (Messerli et al. 2015; Verburg et al. 2015).

The ES concept provides a specific lens to study the connections between land use and the benefits to humans. It has therefore also received attention from scholars interested in the links between natural resources and poverty alleviation (e.g. J. A. Fisher et al. 2013; Daw et al. 2011; Dawson and Martin 2015). Whether ES can actually contribute to poverty reduction or rather support poverty prevention (Angelsen and Wunder 2003) is still under discussion (e.g. Fisher et al. 2013; Sunderlin et al. 2005). While the MEA and TEEB frameworks focus mainly on the ecological links between land and the provision of ES, existing conceptual frameworks from other science communities, such as the environmental entitlements concept (Leach M., Mearns R., and Scoones I. 1999) or political ecology (e.g. Forsyth 2008) highlight the important issues of access to ES and the need for social differentiation (Fisher et al. 2013). Daw et al. (2011) have also criticized that due to the aggregated view on human well-being used in the MEA framework, benefits to the poor – and thus opportunities for poverty alleviation – do not become evident. The disaggregation of ES benefits to different stakeholders is also crucial to acknowledge the existence of trade-offs, e.g. between different land uses and the ES linked to them. Another challenge is the common practice of selecting single ES for assessment, based on researchers' main interest and data availability.

In tropical forest regions – and especially in Madagascar – where ES research is often steered by land managers concentrating on biodiversity conservation, many studies focus on forests as a single land use type (Brown et al. 2013; Kari and Korhonen-Kurki 2013; Kramer et al. 1997; Wendland et al. 2010). However, especially in multifunctional tropical landscapes, human well-being depends on a range of land use activities and ES, and the interactions between them. To generate meaningful knowledge for the negotiation of trade-offs between conservation and human well-being, in the fourth paper of this thesis we try to embrace the whole set of land uses present in north-eastern Madagascar and the ES linked to them.

Paper IV: Navigating conservation–development trade-offs in biodiversity hotspots: landscape types, ecosystem services, and livelihoods in north-eastern Madagascar.

Integrating land use data obtained through remote sensing with socioecological data from a regional level household survey in north-eastern Madagascar, we characterized current landscapes in terms of ES bundles and key ES benefits to households. Our results confirmed that (1) the map of landscape types obtained through remote sensing and spatial analysis adequately reflects households' involvement in shifting cultivation and irrigated rice production, (2) the bundles of ES linked to specific land uses differ between landscape types, (3) each landscape type can be characterized by a certain composition of household types based on the key benefits they obtain from land use.

Such evidence is needed to support the negotiation of trade-offs between conservation of the biodiversity-rich forests and the provision of ES benefits to land users. Many challenges are linked to the current trend of landscape intensification in the region. Increased reliance on irrigated rice production does not automatically lead to higher food security and cash crop diversification does not necessarily result in higher income. Furthermore, the differences between households in terms of key ES benefits obtained need to be considered in devising development interventions that benefit all households equally.

With this we have shown that the ES concept provides a useful lens to study the links between people and the land they are using. Land users involved in the same land use activities might pursue them for different reasons. Some of these reasons can be explained by their demand for ES, which might differ between one household and the next. However, there are also other reasons pertaining to local land users' sociocultural realm of attitudes, motivations, and behaviour. While in the previous paper our aim was to embrace the complexity of different land uses and the bundles of ES linked to them, in the next step we take a different perspective, focusing on the complexity of local livelihoods. Using a Sustainable Livelihood Approach, as described in Högger and Baumgartner (2004) we explore how livelihood strategies leading to deforestation evolve and how deforestation and the loss of forest ES affects livelihoods. For this we focus on a case study in the Manompana forest corridor to the south of our study region. Household surveys and focus groups were conducted in four villages situated at differing distances to the forest massif and with varying forest resource availability.

Paper V: Understanding deforestation and forest fragmentation from a livelihood perspective

Applying a sustainable livelihood approach, we explored social-ecological systems in the Manompana forest corridor to understand: (i) how livelihood strategies leading to deforestation evolve and (ii) how the decrease of forest impacts on households' strategies. Results highlight the complexity of the environmental, cultural, and political context in which households' decision-making takes place. The current livelihood strategies of local households are based on shifting cultivation for subsistence rice production, which leads to deforestation and forest fragmentation. The opportunities arising from exploitable forest resources do not seem beneficial enough to make households change their livelihood strategies to preserve those resources for the future. Although there is an existing potential for the commercialization of precious woods and non-timber forest products, currently it cannot be exploited due to inexistent infrastructure, limited market access, the lack of an institutional framework, and the absence of regulations that would allow a legal, sustainable, and profitable trade in forest resources. Forest products are used as long as they are available. Once forest resources become scarce, people demonstrate the flexibility to adapt. Products are substituted and cultural values and rules are adapted accordingly. Our research shows that to counter the strategies leading to deforestation, changing one context factor or simply improving one sector of peoples' realities will not be sufficient.

Exploring ES trade-offs in a different forested landscapes context

The ES concept pursues a normative aim (Schröter et al. 2014). The presence or absence of ES and the bundles in which they commonly occur therefore depend on people's values and, as a result, are highly context specific (Wiesmann et al. 2011). So far, I have focused on one specific forest frontier context: the north-eastern escarpment of Madagascar. Although I have achieved a certain level of generalisation from the household to the landscape level, the north-eastern escarpment might still just represent one case in a tropical forested landscapes context. The eastern coast of Madagascar can be considered an exception to the current trend of large-scale tropical deforestation being increasingly driven by urban demands for food and energy crops in the global North (DeFries et al. 2010; Lambin et al. 2001; Meyfroidt et al. 2014). In the last part of this thesis I will therefore turn the focus onto a different tropical forested landscapes context in West Africa, to explore the similarities and differences with respect to the ES perceived by land users.

The coastal zone of Côte d'Ivoire harbours some of the last remnants of the humid Upper Guinean forest, another of the world's biodiversity hotspots. While in eastern Madagascar the protected areas are embedded in a highly biodiverse agricultural matrix, which produces crops primarily supporting subsistence needs as well as generating some income, the humid forests of Côte d'Ivoire are true biodiversity refuges in a sea of oil palm and rubber monocultures. What southern Côte d'Ivoire has in common with eastern Madagascar is a very hot and humid climate (Eldin 1971) and a shared history of French colonization. To study land users' perceptions of ES provided by protected areas, we selected three protected areas under different types of management as well as one control site without forest cover.

Paper VI: People, protected areas and ecosystem services: a qualitative and quantitative analysis of local people's perception and preferences in Côte d'Ivoire

Semi-structured interviews with key informants including village chiefs, leaders of community associations, and representatives from women's and youth groups, revealed that the most important ES perceived from protected forest areas were the regulation of microclimate, followed by medicinal plants. Further, the cultural ES of cultural heritage, maintenance of biodiversity for future generations and sacred places related to forests, were mentioned by several respondents. In the control site, which had virtually no forest cover left, several respondents perceived a decrease in ES which they related to the decrease in forest cover over the last ten years. The most important was again microclimate regulation (respondents perceived a decrease or perturbation of precipitation). The other ES, whose loss was deplored, were all provisioning ES such as large trees for the construction of canoes, firewood, wild animals, and wild fruits.

Despite the variety of ES linked to protected forest areas, respondents perceived a strong trade-off between forest conservation and alternative land use options. As one interviewee put it very clearly, "if it weren't for the conservation project we would all throw ourselves at this forest to exploit the wood, because it sells very well in [neighbouring] Ghana." However, trade-offs did not only occur between forest conservation and the need for forest resources and agricultural land within the protected area but, to a large extent, between the use of cultivable land for subsistence crop cultivation versus commercial crop plantations outside the protected area. Although cassava (*Manihot esculenta*) constitutes the dietary base for the population in this zone, the local land users' demand for land to grow commercial crops, especially rubber (*Hevea brasiliensis*), is so high that today there is only little space dedicated to the main subsistence crop. One woman phrased the problem very clearly "the men take all agricultural land for their commercial crop plantations and leave none for us to cultivate cassava, but if they come home from their work in the plantations they want to have a plate of Attiéke (local staple made from cassava) on the table". The discussion of trade-offs with the key informants suggests that although people are aware of the long-term benefits of forest conservation, especially with regard to microclimate regulation, provision of medicinal plants and cultural services, the pressure on land for both commercial and subsistence crop cultivation is so high that in the absence of protected areas, the remaining forest would most likely be transformed into agricultural land very quickly.

Comparing these results to the ES benefits obtained by people in the Malagasy forested landscapes context, in both locations the main ES benefit perceived from forest was the regulation of the hydrological cycle, which is important for the provision of irrigation water. However, as the forests in our study sites in Côte d'Ivoire were all included in protected areas, only one provisioning ES, medicinal plants, was mentioned. People living in the control site where no more forest cover is present, however, stated that they lacked several provisioning ES. While in north-eastern Madagascar even the most intensive paddy landscapes are still diverse in terms of different land uses and the products they provide, in southern Côte d'Ivoire landscapes are strongly dominated by rubber and oil palm monocultures. This might explain why in Côte d'Ivoire several provisioning ES provided by forests cannot be replaced with ES provided by other land uses. The example of Côte d'Ivoire might provide some indications about the future land use trade-offs in Madagascar, that might be expected, should forests only remain in protected areas with no access for the local population and the country become more exposed to global commodity chains. In this case the main land use trade-offs might no longer arise between forest and subsistence but between subsistence and commercial agriculture.

Synthesis and outlook

The papers discussed touch on a range of issues starting with the conceptual basis building on the ES concept. Subsequently, methodological contributions on scaling up from land cover to landscape change and on linking land use to ES benefits were presented. A more in-depth view on the drivers of deforestation in north-eastern Madagascar and a case study on ES benefits and land use trade-offs from a different tropical forested landscape context completed the work. To broaden the scientific evidence base regarding the current state and past trajectories of shifting cultivation and permanent land use systems in north-eastern Madagascar, we have leaned on remote sensing and spatial analysis, always taking into account the diverse and multifunctional production systems. A region-wide household survey to collect original socioecological data then allowed us to link the spatially explicit land use information with the ES benefits perceived by local land users. Our work contributes to the advancement of land system science, especially with respect to these two main aspects: 1) to apprehend land change dynamics from a coupled human–environment perspective, we need methods to link land use to land cover pixels (Rindfuss et al. 2004; Verburg et al. 2015), 2) to understand the impacts of human actions on the supply of ecosystem services, land system science requires spatially explicit land use to be linked with social science data (Crossman et al. 2013). In the context of north-eastern Madagascar, generalizing from land cover to landscape types allowed us to better understand the spatially explicit processes of landscape intensification and extensification. Information collected through household surveys revealed that the landscape types we classified from remote sensing data adequately represent land use. The characterization of these landscape types in terms of the key ES benefits to households and the ES bundles linked to different land uses, showed that the ES concept constitutes a useful framework to connect remotely sensed information with socioecological data from interviews.

Returning to the main goal of this thesis I would like to propose some hypotheses linked to the question that preoccupies conservation, development, and research actors alike in north-eastern Madagascar: How can we maintain the last remaining forests while simultaneously reducing people's poverty? In the absence of protected areas, the remaining continuous forests would most likely disappear. This is not because land users are ignorant about the manifold benefits forests provide; they are not. But in the trade-off between obtaining additional land to improve their own or future descendants' food security, and the maintenance of forest for the provision of said benefits, the former will always outweigh the latter. The land-sparing approach (Phalan et al. 2011), currently pursued by conservation actors in the region, may have led to accelerated deforestation of the small forest fragments scattered throughout the agricultural landscapes. However, this might also have happened without the presence of these protected areas, as the fragments constitute the last reserve of land that can be converted into hill rice fields for young people establishing a new household.

In terms of environmental justice, several problems are posed by protected areas and the strict enforcement needed to deter land users from taking possession of the land they consider their own under customary law. While we observed that in some areas (e.g. along the western border of the Masoala National Park) shifting cultivation was abandoned, most likely due to strong enforcement of the park boundaries and thus the closure of the agricultural frontier, we do not know how this has impacted on people's livelihoods and well-being. We can assume though that households without access to irrigated paddy fields – and thus fully dependent on shifting cultivation for rice production – had to find other means of obtaining rice (e.g. through working as wage labourers in other households' paddy fields). The in-depth studies of Keller (2008; 2015) in two of the villages along this border highlight these issues in more detail.

So, what is the way forward to protect the remaining forests without this being at the expense of the local land users' well-being? Irrigated rice plots are becoming smaller with every generation and crop-rotation cycles in shifting cultivation are already very short. For many newly established households, as well as for elders concerned with the food security of their descendants, bringing new land into production is often the only solution. Our results suggest that a focus on increasing production in irrigated rice fields alone will provide no benefits to a significant part of the population – people who today produce rice through shifting cultivation only. For those households to be able to benefit from investments in irrigated rice production, their access to irrigated rice fields needs to be improved. Currently, malfunctioning irrigation systems or the complete absence of canals and watergates leave some flat terrain, well suited for irrigated rice production, under-utilized. Diversifying cash crop production might reduce risks for households exposed to the high inter-annual variability of market prices. However, if cash crop diversification should lead to overall income increases, the severe constraints related to animal pests and plant diseases need to be diminished. Furthermore, even if households obtain more rice from irrigated rice fields or earn more money with cash crops, this does not mean that they will abandon shifting cultivation as there are also other benefits linked to this land use system (Kull 2000). Currently, there are almost no opportunities for young people to make a living outside of agriculture: thus, improving education and creating jobs is crucial to relieve the pressure on the remaining forests. For such general investments to have an effect on forest conservation, however, special attention must be directed towards the villages close to the forest frontier, which are often those that are least accessible. Allowing local communities to profit from commercially exploiting certain forest products (e.g. through sustainable timber production), and improving their access to markets for the sale of those products could provide some benefits. With the current level of infrastructure, tourism in this region remains underdeveloped and provides no income opportunities for many people.

With the landscape mosaic approach we obtained generalized and spatially explicit knowledge on landscape types for the entire region. Linking this map with socioecological data on ES benefits, we were able to generalize from the household to the landscape level. This knowledge should allow us to devise interventions and to direct them to places where they benefit more people. In terms of future research, furthering the evidence base on which development planning can build, I suggest the following lines: 1) having established the links between current land use and ES benefits, the next step would be to investigate the causal mechanisms that have led to the land use changes we have observed in the past. For this, quantitative methods to identify causal effects and qualitative methods to shed light on causal mechanisms should be combined (Meyfroidt 2015). This would allow the identification of drivers that present leverage points for change, 2) spatially explicit quantitative data on ES provision from land use would be needed to model future land use scenarios to assess trade-offs between biodiversity conservation and human well-being, 3) up to now we have focused on the ES demands of local land users only. However, we also have to understand the claims of other actors linked to land use in the study region in order to facilitate negotiation of ES trade-offs and future development options.

It will be a long process to bring people out of poverty in north-eastern Madagascar. The current multi-functional landscapes – combining shifting cultivation, irrigated rice production, agroforestry and cattle raising, and shaped by smallholders – hold many benefits, e.g. in terms of biodiversity, carbon sequestration, and cultural values. Especially if infrastructure improves, the current global rush on land, observed in many other parts of Africa, may in the long term also reach north-eastern Madagascar. This means that understanding the trade-offs between different land uses will be crucial for negotiating a sustainable development in this global biodiversity hotspot.

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Part II: Research papers

Paper I: Strengths, Weaknesses, Opportunities and Threats: A SWOT analysis of the ecosystem services framework

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Strengths, Weaknesses, Opportunities and Threats: A SWOT analysis of the ecosystem services framework

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ABSTRACT

The ecosystem services concept (ES) is becoming a cornerstone of contemporary sustainability thought. Challenges with this concept and its applications are well documented, but have not yet been systematically assessed alongside strengths and external factors that influence uptake. Such an assessment could form the basis for improving ES thinking, further embedding it into environmental decisions and management.

The Young Ecosystem Services Specialists (YESS) completed a Strengths–Weaknesses–Opportunities–Threats (SWOT) analysis of ES through YESS member surveys. Strengths include the approach being interdisciplinary, and a useful communication tool. Weaknesses include an incomplete scientific basis, frameworks being inconsistently applied, and accounting for nature's intrinsic value. Opportunities include alignment with existing policies and established methodologies, and increasing environmental awareness. Threats include resistance to change, and difficulty with interdisciplinary collaboration. Consideration of SWOT themes suggested five strategic areas for developing and implementing ES.

The ES concept could improve decision-making related to natural resource use, and interpretation of the complexities of human-nature interactions. It is contradictory – valued as a simple means of communicating the importance of conservation, whilst also considered an oversimplification characterised by ambiguous language. Nonetheless, given sufficient funding and political will, the ES framework could facilitate interdisciplinary research, ensuring decision-making that supports sustainable development.

1. Introduction

The term 'ecosystem services' (ES) was first introduced in the 1980s as an advocacy tool for biodiversity conservation, and has since been subjected to a variety of definitions and classifications

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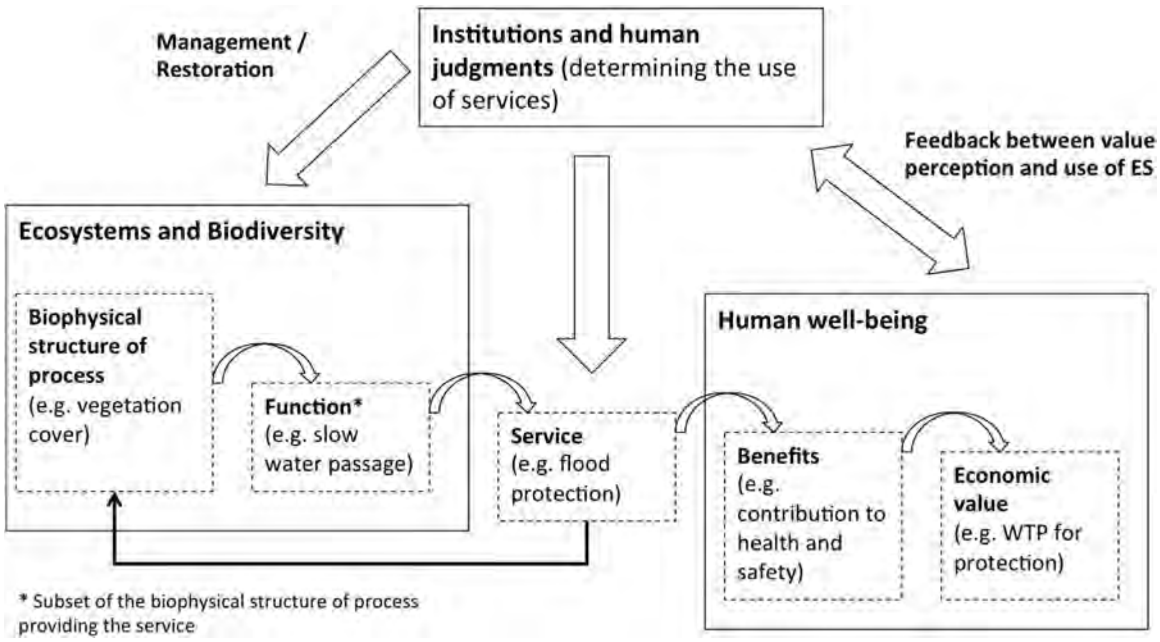

Fig. 1. Schematic representation of the conceptual thinking behind the ecosystem services framework (modified from: Braat and de Groot, 2012).

(Ehrlich and Ehrlich, 1981; Ehrlich and Mooney, 1983; Chan et al., 2007; Peterson et al., 2010). Since the 1990s, the continued evolution of ecosystem service definitions and classifications has been well documented (e.g. Costanza et al., 1997; Daily, 1997; Millennium Ecosystem Assessment, 2005; Boyd and Banzhaf, 2007; Wallace, 2007; Costanza, 2008; Fisher et al., 2009; TEEB et al., 2012; Böhnke-Henrichs et al., 2013). Whilst there is no one universal ecosystem services definition or framework, a recent and widely cited definition considers ES to be “the direct and indirect contributions of ecosystems to human well-being” (Braat and de Groot, 2012; TEEB et al., 2012; Fig. 1). Whilst critical voices have considered this a reflection of a utilitarian and anthropocentric view of nature, others emphasise that the concept of ES implies a worldview that humanity must be treated as part of nature rather than separate from it, and that we fundamentally rely upon functioning ecosystems – a view that has become increasingly recognised in recent decades (Mace, 2014). For the purposes of this paper, we define an ES framework to be “a framework by which ecosystem services are integrated into public and private decision making” (Ranganathan et al., 2008). Such an approach can include valuation of the goods and services provided by nature to society, thus enabling them to be incorporated into decisions regarding the governance of natural resources (Daily et al., 2000; Yousefpour et al., 2012). An ES framework is not restricted to economic valuation, and also allows the integration of multiple value domains (ecological, social, cultural and economic values), thus acknowledging the complexity of social–ecological systems in decision making (Martín-López et al., 2014) and the plurality of human values (Kenter et al., 2015).

Although the academic literature continues to debate the definition of ES, decision makers have increasingly implemented ES as part of environmental and natural resource policies and management frameworks. However, the viability of the ES framework has been challenged both conceptually and practically (McCauley, 2006; Norgaard, 2010; Peterson et al., 2010; Barbier, 2012; Beaudoin and Pendleton, 2012; Ressurreição et al., 2012; Sitas et al., 2014). A recent review by Schröter et al. (2014) highlights that the conceptual basis for ES may conflict with: biodiversity conservation; a fear of ‘selling out’ on nature; the commodification of nature; the vagueness of the concept; and, the power dynamics involved in ES research and management (see also Naidoo et al., 2008; Bullock et al., 2011; Sommerville et al., 2011). Knowledge gaps, specific to the connectivity between sustainability and human well-being, have also been highlighted as a challenge for the successful implementation of the ES concept (Nicholson et al., 2009; Chan et al., 2012), as have problems with existing tools, datasets and frameworks (Naidoo et al., 2008; Keeler et al., 2012).

In light of these concerns and challenges, significant research investment continues to seek the ‘best’ implementation pathways for the ES concept (Kremen and Ostfeld, 2005; Carpenter et al., 2009; Petz et al., 2012). As part of a collective endeavour to better understand how to operationalise the ES concept, an increasingly wide variety of implementation frameworks (Cowling et al., 2008; Nahlik et al., 2012; Petz and van Oudenhoven, 2012), payment structures (Gibbons et al., 2011; Sommerville et al., 2011; Bryan, 2013), ES tools (Nelson and Daily, 2010), and datasets (Schulp et al., 2012; Baral et al., 2013) have been developed and trialled globally.

Paralleling the proliferation of these disparate approaches, and despite concerns from some regarding the extent to which the ES concept can realistically deliver upon its objectives (e.g. Norgaard, 2010), the concept has begun to inform an increasingly wide range of national and international legislation and agreements (Perrings et al., 2010). Examples include the ecosystem-based management on which the European Marine Strategy Framework Directive is built (Long, 2011; Jobstvogt et al., 2014), the 14 Aichi Targets developed by the Convention on Biological Diversity (Strategic Goal D; CBD, 2010) and incorporation of ES in the CBD Ecosystem Approach, as well as the relatively new Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES; Larigauderie, Mooney (2010)).

Given the landscape of conceptual and intellectual debates, practical concerns, and increasing legislative consideration, it is important to continually and critically appraise the ES concept – searching for gaps, suggesting how any gaps might be filled, and considering to what extent the approach remains fit for purpose in a wider context. Here, we look critically at the ES concept through a Strengths–Weaknesses–Opportunities–Threats (SWOT) type analysis. Existing reviews have explored challenges to the successful implementation of the ES concept (Wallace, 2007; de Groot et al., 2010). Our SWOT assessment presents these challenges in a broader context – by providing an integrated, structured analysis of perceived strengths and weaknesses within the ES concept and its applications, as well as of the external opportunities and threats that may benefit or impede further development. Additionally, we use such analyses to begin developing strategies that might overcome existing or future challenges to the ES concept.

For the purposes of this paper, the authors surveyed an interdisciplinary group of ES researchers and practitioners – the Young Ecosystem Services Specialists (Böhnke-Henrichs et al., 2014) – eliciting their perceptions on the Strengths, Weaknesses, Opportunities and Threats of applying the ES concept for natural resource policy, planning, governance and management. YESS members are diverse, working across a wide range of ecosystems and disciplines, applying a variety of different methods and approaches to study and implement the ES concept (Böhnke-Henrichs et al., 2014). The rationale for relying upon early career ES researchers was to capture the perspectives of those who have a substantial, up-to-date understanding of the topic, but joined the field of ES research and implementation after its inception rather than being amongst those who first established it. Such researchers and practitioners are likely to critically think about established concepts, have cutting-edge experience of research on and implementation of the ES framework, and be actively engaged in innovation.

2. Material and methods

A mixed methods research strategy (Teddlie and Tashakkori, 2011) was employed, in the form of online surveys and face-to-face discussion groups, so as to elicit the perceptions from YESS members on the Strengths, Weaknesses, Opportunities and Threats of the ES framework. Applying a mixed methods approach allowed researchers to better capture the richness and complexities of the phenomena under study than by using a singularly qualitative or quantitative approach.

2.1. Survey respondents

Young Ecosystem Services Specialists (YESS) is an international network of early career doctoral and postdoctoral researchers, lecturers, and practitioners working on a variety of ES topics at a range of research, environmental and nature conservation organisations. At the time of the SWOT analysis, there were 67 active members of YESS. As members represent a range of expertise in the ES field, they were considered sufficiently well informed to complete a SWOT analysis of the ES framework. Respondents' backgrounds span the natural sciences and environmental and ecological economics, but other social sciences were under-represented and there was no participation from arts or humanities scholars. As such, the sample is not representative of the whole early career ES research community.

2.2. SWOT analysis and development of strategies

SWOT analyses derive their name from the assessment of the Strengths (S), Weaknesses (W), Opportunities (O), and Threats (T) faced by an industry, sector, company or any organisation (Gao and Peng, 2011). The idea of a SWOT analysis has its roots in strategic management research conducted in the 1960s and 1970s (Sevkli et al., 2012), and arises from the perspective that the performance of a given (typically economic) agent with respect to a particular objective depends upon the way in which the management of that agent interacts with both the *internal* characteristics of the agent, and the broader *external* context in which the agent must act (but over which the agent has no direct control in the short term) (Houben et al., 1999).

When applied to ES and its associated research fields, Strengths can be considered to be those features of the ES concept that underpin the ability of the concept and the field to achieve the implicit goals of:

a) increasing awareness of the extent to which human societies interact with and are dependent upon the environment;
b) better integrating the natural and social sciences and engaging and acknowledging stakeholder knowledge;
c) greater understanding of the impacts of environmental change and environmental policy on human wellbeing; and,
d) contributing towards achievement of sustainable relationships between human society and ecosystems.

By way of contrast, Weaknesses are attributes that can undermine the achievement of the goals (a–d) unless they are specifically addressed and improved. Here, Strengths and Weaknesses can be considered features of the ES concept itself, or 'internal' features. Conversely, Opportunities include the economic, technical, social, political, legal, and environmental features representing the context within which the ES concept is implemented, and that may facilitate or encourage the achievement of these goals. We thus consider Opportunities to be 'external' features. Threats are, similarly, external features that may prevent the accomplishment of the above goals (a–d).

The value of a SWOT analysis stems not only from its ability to highlight ways in which an agent's internal and external environments interact to affect its success (Houben et al., 1999), but also from its ability to be used in the development and implementation of long-term strategies to achieve particular objectives (Houben et al., 1999; Arslan and Er, 2008; Gao and Peng, 2011; Sevkli et al., 2012). There are various classes of strategies that can follow from a SWOT analysis: e.g. those that link Strengths and Opportunities ('SO Strategies'), those that link Weaknesses and Opportunities ('WO Strategies'), those that jointly focus on the Strengths and Threats ('ST strategies'), and those that arise from the joint assessment of Weaknesses and Threats ('WT Strategies'). For example, SO strategies utilise the fact that Strengths may help to capitalise upon external Opportunities, whereas WO strategies focus upon the pursuit of external Opportunities to lessen the severity of Weaknesses. Similarly, ST strategies focus on the potential for existing internal Strengths to mitigate the impact of external Threats, while WT strategies consist of actions intended to reduce both internal Weaknesses and external Threats simultaneously (Sevkli et al., 2012).

2.3. Analytical procedure

In conducting a SWOT analysis of the ES framework, an iterative approach was used. The first step of the process involved an online pilot survey (Survey 1) of 20 YESS network members, who were simply asked to share their perceptions about the Strengths, Weaknesses, Opportunities, and Threats (SWOT) of applying the ES framework in their work, as an open question. The pilot study was followed by two main surveys (i.e. Survey 2 and 3), where the framing of survey questions was refined based on pilot survey findings. The surveys took place in 2013: the pilot survey from January to March, Survey 2 from August to September, and Survey 3 from November to December.

A central research coordinator compiled the responses from the pilot survey, and attempted to identify themes for each SWOT characteristic, including the frequency with which the theme emerged.

The results of the pilot survey generated varied responses and fragmented agreement for each SWOT category – thus, the

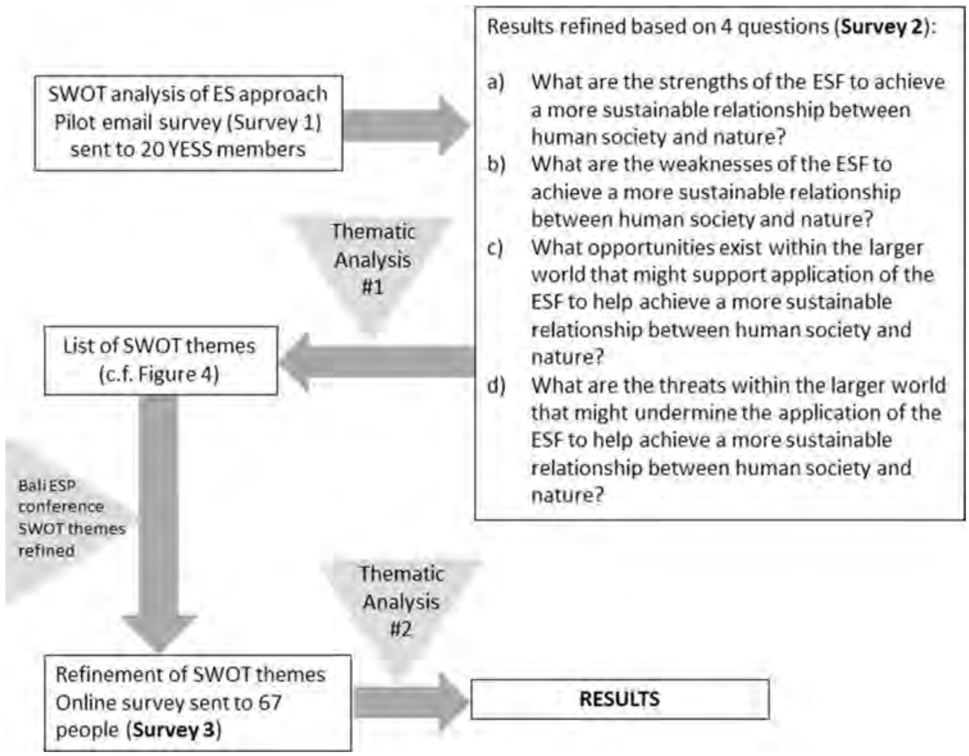

Fig. 2. The development and delivery of the ES SWOT research process.

outcomes were sent back to YESS members, who were asked to refine their responses based on the following, more structured questions (Survey 2), and considering the goals (a–d) outlined in Section 2.2: Fig. 2.

a) What are the Strengths of the ES framework to achieve a more sustainable relationship between human society and nature?
b) What are the Weaknesses of the ES framework to achieve a more sustainable relationship between human society and nature?
c) What Opportunities exist within the larger world that might support application of the ES framework to help achieve a more sustainable relationship between human society and nature?
d) What are the Threats within the larger world that might undermine the application of the ES framework to help achieve a more sustainable relationship between human society and nature?

A thematic analysis was carried out on the results of Survey 2 by two independent YESS researchers (Fig. 3). 'Themes' were considered to arise if similar suggestions were made by more than one respondent (e.g. 'the ES framework is interdisciplinary', as a Strength). The researchers identified between 10 and 13 themes per SWOT category with the requirement that both researchers had to reach consensus on the existence and wording of each

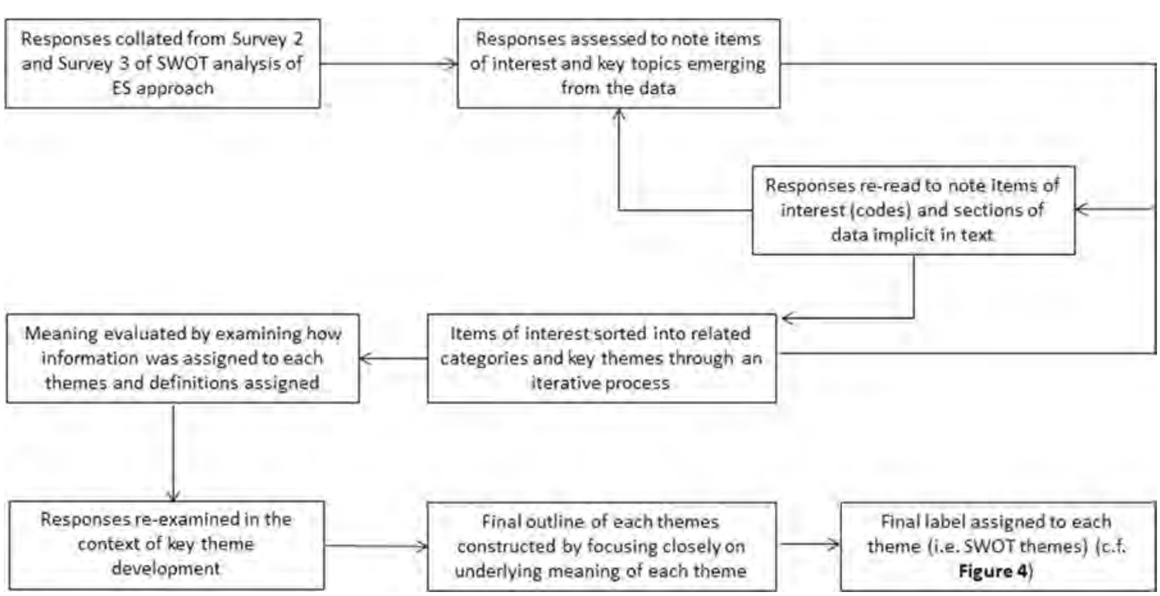

Fig. 3. The analytical process performed upon responses to Surveys 1 and 2, to develop SWOT themes.

theme. The results of that stage were presented, discussed and refined at the Ecosystem Services Partnership (ESP) conference in Bali in 2013[1], during a facilitated YESS workshop. Themes in all four SWOT categories were presented and explored in open discussion. Note that themes were not removed or added at this stage, as the goal was not to change the outcomes of the original survey; rather, their meaning was clarified as far as possible for a wider audience.

Following this refinement, a third online survey (Survey 3, Appendix) was developed and a link sent to all YESS members. Survey 3 required respondents to share their level of agreement on a 9-point scale from −4 ("strongly disagree") to +4 ("strongly agree") for each theme identified in the previous stage by the research coordinators, and refined at the Bali conference. 'Level of agreement' was then measured between 0% and 100%, corresponding to the percentage of respondents that agreed with the theme (i.e. rating on the agreement scale between +1 and +4) or disagreed with the theme (i.e. rating between −4 and −1).

Respondents then ranked the themes' respective perceived importance by selecting the three most important themes within each of the four SWOT categories. We used a weighted sum procedure for this part of the analysis (i.e. scores per respondent: 3 = most important; 2 = second most important; 1 = third most important) and presented the group result as the 'total importance score'. The maximum total importance score would have been 60, if all respondents chose the same theme as most important.

3. Results

3.1. Final survey respondent demographics

Following Surveys 1 (pilot) and 2, 20 YESS members participated in the final SWOT Survey 3 (~30% response rate). The average participant was 33 years old (min. 26 years, max. 45 years) with men and women equally represented. The sample covered researchers from 16 different countries. Participating YESS members were predominantly PhD students or postdoctoral researchers with an average of three years of ecosystem services research experience (min. one year and max. 9 years). The majority of participants stated that they had a background in environmental/conservation sciences (75%) or environmental/ecological economics (40%) (Table 1).

Table 1
Stated group affiliations of YESS survey participants (Survey 3).

Research/practice field	Frequency[a]
Environmental/conservation sciences	15
Environmental/ecological economics	8
Agriculture/forestry	5
Ecology/ecosystem sciences	5
Geography	4
Biological sciences	4
Environmental policy/governance studies	4
Sustainability studies	4
Others	5

[a] Multiple selections and open responses were possible. The number of participants was 20.

3.2. Breakdown of outcomes by SWOT category

3.2.1. Strengths

Amongst the key themes identified across all four SWOT categories (Fig. 4), the interdisciplinary approach was highlighted as the most important Strength of the ES framework (in this case a total importance score of 28 as a weighted sum). This was followed closely by the chance to improve accounting for nature (*score* = 24) and taking a holistic approach (*score* = 16). Raising societal awareness of ES benefits (*score* = 9), the ability of the ES framework to reconnect people to nature (*score* = 7) and the conceptual simplicity of the ES framework (*score* = 5) were noted as key strengths, but were ranked lower in importance in comparison to the founding purpose of the ES concept (i.e. as a communication and advocacy tool; *score* = 13). These findings indicate that survey respondents believe that fundamental Strengths of the ES framework lie in its interdisciplinary potential and in its ability to support improved decision-making. The respondent's agreement with the themes presented to them as Strengths ranged from 80% to 100% (Table 2).

3.2.2. Weaknesses

Survey respondents agreed that the two main Weaknesses in the ES framework are an incomplete scientific basis (*score* = 20) and inconsistencies in the application of a divergent range of available ES frameworks (*score* = 16) (Table 3). Questionable measures of the intrinsic value of nature (*score* = 14), the ambiguous language of the ES framework (*score* = 13), and an overemphasis on monetary values (*score* = 11), were also considered key weaknesses by survey respondents. The need for better tools (*score* = 3) and the scale-dependence of outcomes (*score* = 4) were the lowest ranked weaknesses of the ES framework. Overall, survey respondents highlighted the need for: greater methodological and terminological consistency; an overarching ES framework in the short term; further research; better understanding of ES supply; better understanding of the relationship of ES supply to maintaining or enhancing biodiversity in the long-term; and enhancing the influence of non-monetary methods to assess ES.

The respondents' agreement across themes ranged from 65% to 80%, i.e. lower than for the Strengths (Table 3).

3.2.3. Opportunities

A list of 11 themes within the Opportunities category reflects the positive outlook of survey respondents for future potential development in the ES framework. Alignment with policies and strategies (*score* = 24) and existing tools and methods (*score* = 18) were ranked as the top two opportunity themes. These were followed closely by increasing environmental awareness (*score* = 17), and opportunity for better realising sustainability ($n = 16$) (Table 4). Other themes within this quadrant have the potential to complement the top opportunities: for example, more funding (*score* = 7) could align with policies and strategies, technological advancements (*score* = 4) can advance existing tools and methods, and demand for ecosystem management (*score* = 14) can align with increasing environmental awareness.

3.2.4. Threats

Resistance to change in environmental practices (*score* = 32), difficulty of interdisciplinary work (*score* = 19) and insufficient funding (*score* = 14) were the top three Threats as selected by survey respondents. Interdisciplinarity of the ES framework (*score* = 19) was highlighted as a potential Threat due to different technical terminology and applications. The lack of institutional capability (*score* = 13) and loss of political interest (*score* = 13) were equally perceived as Threats for the ES framework.

An overall assessment of SWOT themes across all categories revealed that at least half of survey respondents were in agreement for most SWOT themes (Fig. 5). Only the Threat theme 'diversion from sustainability goals' received less than 50%

[1] http://previous.espconference.org/previous_editions/81764/5/0/60

Fig. 4. SWOT themes ranked according to their total importance score. The score is expressed as weighted sums (scores per respondent: 3 = most important; 2 = second most important; 1 = third most important; 60 = maximum group score). Symbols (○□◗+★) and shading indicate the 5 different strategy topics that emerged from the SWOT themes. For details see Section 3.3.

agreement from survey respondents. There was greater agreement across survey respondents within the Strengths quadrant (92%) as compared to Opportunities (82%), Weaknesses (72%) and Threats (69%) quadrants (Fig. 5). Broad agreement with themes was expected since they were derived from survey respondents' contributions in Survey 2.Table 5

3.3. Strategy development based upon the SWOT

Following on from the SWOT, the authors grouped themes into 5 different strategic areas (Fig. 4):

1. ES concept characteristics ○
2. Application of the ES concept □
3. Effects of ES concept application ◗
4. Demands of ES concept application +
5. User interface of the ES concept ★

Certain SWOT themes belong under more than one strategy. When counting the items per topic, it became clear that these are distributed irregularly in the different quadrants of the SWOT diagram (Fig. 6). While, for instance, Strategy 1 themes are concentrated within quadrants S, W and T, Strategy 5 themes have been identified only in quadrants O and T – perhaps unsurprisingly, given that the 'user interface' strategy might only be expected to be represented in the 'external' quadrants.

This distribution of themes across the SWOT quadrants was used as a starting point for identifying topic related strategies. These were considered useful under the assumption that a single overarching strategy may not be suited to capture the complexity of the problem and may also not be sufficiently tailored for those working in their respective context within the ES framework. Further, depending upon their expertise, survey respondents may have been interested in certain topics only – thus, topic-specific strategies would likely be more easily adopted.

3.3.1. Strategy 1 – ES framework characteristics

In Strategy 1 we consider a **strength–weakness (SW)** combination, and how to use identified Strengths to overcome Weaknesses. By contrasting the four highest scoring strengths with the five highest scoring weaknesses (Fig. 6), this strategy would focus upon the characteristics that form the ES framework via:

- extending the interdisciplinarity of ES research, with an emphasis on further strengthening links with the social sciences

Table 2
Strengths of the ES framework identified. 'Importance score' and 'agreement with theme' measured during survey 3, as specified in the Section 2.

Survey themes	Total importance score	Agreement with theme (%)
Interdisciplinary approach: The diversity of disciplines involved in ES research strengthens the framework. The ES framework is methodologically flexible; it invites methods stemming from different disciplines to be applied and new methods to be developed.	28	95
Improved accounting for nature: Ecosystem services valuation might improve environmental decision making by accounting for the freely available and often intangible services provided by nature.	24	100
Holistic approach: The ES framework takes a holistic perspective that brings social, ecological and economic values together and highlights trade-offs between and within the three dimensions.	16	100
Advocacy and communication tool: The ES framework provides a tool to advocate and communicate nature conservation, by adding social and economic reasoning to ethical arguments.	13	100
Increased societal engagement: The simplicity and anthropocentric perspective of ecosystem services facilitates its uptake by a wide range of actors and sectors e.g. policy makers, media, businesses and the general public. This might lead to larger engagement of these groups in nature conservation processes.	9	85
Equity in natural resource allocation: The ES framework could lead to more equity in natural resource allocation through improved accounting for ES and more equitable distribution of natural resources amongst stakeholders.	9	80
Reconnecting people to nature: The link between the biophysical and human dimensions of ecosystems is made explicit by the ES concept. The ES framework makes nature conservation about what matters to people.	7	80
Conceptual simplicity: The ES framework outlines the multifaceted way in which society benefits from ES and addresses the cause-effect relationship between environmental impacts and human well-being in an easy understandable manner.	5	90
Knowledge base: The ES framework enables us to categorize and organise our knowledge about the interconnectedness of humans and nature. This is an important pre-requisite to improving our understanding of the complexity of these connections.	5	95
Works on different scales: The ES framework enables the use of different geographical and temporal scales to account for ES. It can account for ES that are provided to distant areas or future generations and allows cross-comparison of local and global impacts.	3	90

and increasing involvement from the arts and humanities;

- creating holistic frameworks that contain clear and concise language so the approach can be consistently applied as communication and advocacy tools; and,
- increasing the representation and analysis of ES beyond utilitarian values to highlight broader shared and social values, and the intrinsic value of nature, including by highlighting synergies between intrinsic value and supporting and regulating services, and shared values and cultural services.

It is important to highlight that both the difficulty of interdisciplinary work and the variety of competing approaches within the Threat quadrant (Fig. 6) may not be reduced under the proposed **SW** strategy. Thus, a **strength–threat** strategy could be applied to reduce these threats. Pursuit of such a strategy should improve the ability of ES analyses to make progress on improving the sustainability of human-environment interactions.

3.3.2. *Strategy 2 – Application of the ES framework*

The second Strategy would concern the use of external Opportunities to overcome internal Weaknesses, with themes residing in the **weakness–opportunities (WO)** quadrants. Two of the

Table 3
Weaknesses of the ES framework identified. 'Importance score' and 'agreement with theme' measured during survey 3, as specified in the Section 2.

Survey themes	Total importance score	Agreement with theme (%)
Scientific basis incomplete: Our current understanding of the links between, biodiversity, ecosystem functioning and ecosystem services provision is poor.	20	70
Framework inconsistently applied: There are a range of ES frameworks in circulation, which do not entirely overlap. This might increase difficulties around data sharing and comparability of research results.	16	80
Disregarding intrinsic value of nature: The anthropocentric view of the ES framework and its application in decision making might cause an imbalance between biodiversity conservation targets and social and economic objectives, with dominance of the latter two.	14	70
Ambiguous language: The terminology used in the ES framework is open to interpretation.	13	70
Overemphasis on monetary values: An overemphasis of the monetary values of ecosystem services within ecosystem assessments might be contrary to the original objective of making ecosystems count.	11	80
Some ecosystem services poorly represented: The cultural, regulating and supporting services tend to be less well represented in ES research and assessments than provisioning services.	9	65
Large resources needed to apply framework: Implementing the ES framework in practice requires considerable resources (e.g. data, finance, expertise).	8	75
Inaccessible to non-specialists: Those who do not work in the ecosystem services field, or are not scientists, might find the ES framework terminology and methodology hard to understand.	6	65
Benefits poorly understood: It is non-trivial to aggregate, analyse and present the benefits received from ES. Many people might not necessarily acknowledge benefits of the ES identified by researchers.	6	75
Oversimplification: The ES framework is sometimes used in a way that oversimplifies ES to the extent that they are poorly represented and assessed. This might lead to misguided environmental decision making.	5	70
Difficult to apply: The ES framework is difficult to implement in practice. It is currently considered to be methodologically challenging to combine the large number of ES in one assessment.	5	75
Scale-dependence of outcomes: The ES framework is applied in different ways across different scales (local, regional, national etc.), with a range of possible outcomes at each scale.	4	70
Need for better tools: The ES assessment tools currently available to practitioners and researchers are inadequate and need to be improved.	3	75

Table 4
Opportunities identified for the ES framework. 'Importance score' and 'agreement with theme' measured during survey 3, as specified in the Section 2.

Survey themes	Total importance score	Agreement with theme (%)
Alignment with policies and strategies: Existing environmental policies and strategies already in place or currently under development are well suited to fit the ecosystem services concept, such as the CBD Strategic Plan for Biodiversity and the EU Biodiversity Strategy among others.	24	75
Alignment with existing tools and methods: ES framework can be easily integrated into existing tools and methods of environmental policy, such as environmental impact assessment and cost-benefit analysis.	18	95
Increasing environmental awareness: The ES framework fits into the growing global awareness of environmental issues, including climate change and its potential long-term impacts.	17	85
Operationalization of sustainability: There is a need to operationalise the term of 'sustainability' and reduce its vagueness. The ES framework with ecosystem services indicators and assessments could provide the framework to make sustainability more assessable and traceable.	16	95
Demand for ecosystem management: The demand to improve ecosystem based management, as well as the necessity to increase its acceptance might support the use of the ES framework.	14	85
Interest of societal actors: ES framework has received recognition and support from a wide range of actors within society, including public media, researchers, the business sector and stakeholders involved or affected by environmental management.	9	80
Policy awareness: Governments are aware of the ES framework as a result of the Millennium Ecosystem Assessment and The Economics of Ecosystems and Biodiversity initiative. Current demand for national assessments of natural resources is high.	8	75
More funding: Funding bodies are interested to support research with societal impact and interdisciplinary projects. There is also the opportunity to get more funding by highlighting the benefits that nature provides to humans.	7	85
Technological advancements: Fast increasing computing power allows us to use more complex system models to analyse data. Technological advancements also allow new ways of interacting with audiences through online media, video, games, and presentations.	4	85
Institutionalisation of nature's value: Establishment of legal requirements to protect the environment and the ES it provides. Incorporating the regulation of ES into laws and constitutions. Example set by Ecuador.	2	85
People's utility: People tend to value their self-regarding benefits higher than other-regarding values (including non-humans). The ES framework might benefit from this kind of thinking.	1	60

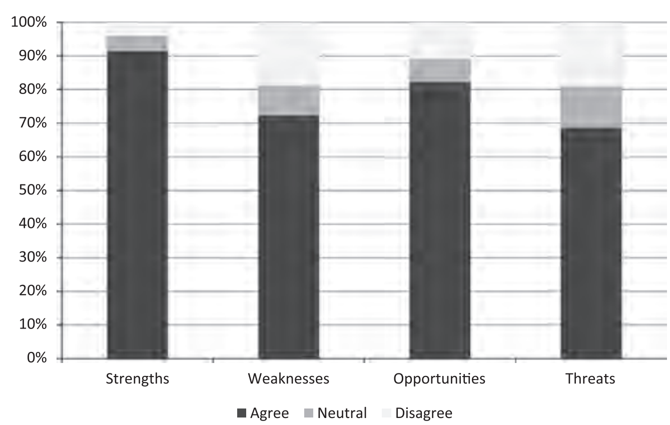

Fig. 5. Overall agreement with the themes developed for each SWOT category. Agree=rating between +1 and +4; neutral=rating 0; disagree=rating between −1 and −4.

highest scoring Opportunities acknowledge the potential alignment of the ES framework with existing agreements (e.g. the CBD Aichi targets, the UN Sustainable Development goals), and with existing tools (e.g. spatial conservation planning, environmental impact assessment, remote sensing). However, the Weaknesses suggest that this approach is inaccessible to non-specialists and difficult to apply. A **WO** strategy could focus on using the identified opportunities in two ways:

- Enhanced communication to elucidate how ES can be linked and add value to key performance indicators, and other measures that determine policy implementation success (e.g. measures of sustainable economic development). This broader picture could facilitate a better understanding of ES; and,
- ES specialists assisting and working with non-technical audiences in identifying and applying the most relevant and effective ES methods and tools for the required application. The result could be greater uptake and ownership of the ES framework.

3.3.3. Strategy 3 – Effects of an ES framework application

Thirdly, we consider the potential use of the ES framework to overcome Threats, given a combination of **strengths, opportunities and threats (SOT)**. Blending the existing Strengths of the ES framework (which includes improved accounting for nature, increased societal engagement, equity in natural resource allocation and reconnecting people with nature) with Opportunities (specifically an increase in environmental awareness and operationalization and institutionalisation of the ES framework) could offer scope for increasing environmental awareness and understanding (countering the identified threat of low awareness).

Equally, drawing upon these Strengths could ensure that implementation of the ES framework becomes or remains a political imperative (at the same time seeking to address any threat of a loss of political or researcher interest), and that the institutional application of the ES framework adds value.

A strategy containing these elements could also consider seeking to showcase the ES framework itself as a way of measuring the effects of resistance to change environmental practices (a third Threat theme).

3.3.4. Strategy 4 – Demands of an ES framework application

The fourth Strategy concerns dealing directly with barriers to the application of the ES, with a focus upon **weaknesses, threats** and some **opportunities (WTO)**. Overcoming Weaknesses and Threats is considered likely to be challenging. The strategic direction is heavily influenced by 8 Weaknesses, ranging from an incomplete scientific basis, to the fact that large resources are needed to apply frameworks, to the need for better tools. Insufficient funding is highlighted as a Threat, however, funding is also an identified Opportunity – so understanding exactly where the funding gap lies, and what causes it, would be a key challenge to deal with under this strategy.

Many of the identified Weaknesses – disregard for intrinsic value, oversimplification, ambiguous language, inaccessibility –

Table 5
Threats identified for the ES framework. 'Importance score' and 'agreement with theme' measured during survey 3, as specified in the Section 2.

Survey themes	Total importance score	Agreement with theme (%)
Resistance to change environmental practices: Even if understanding of human impacts and nature conservation benefits is considerably improved, changing environmental practices might not follow automatically.	32	85
Difficulty of interdisciplinary work: ES framework requires inter-disciplinary collaborations, which are hard to truly achieve in practice.	19	75
Insufficient funding: Funding for research might suffer severe cuts.	14	75
Loss of political interest: In the mid- to long-term future, policymakers might lose interest in promoting or implementing ES framework, if expectations for practical solutions of environmental management cannot be met by the ES framework.	13	80
Lack of institutional capability: Insufficient institutional capacity and expertise to implement treaties, agreements, conventions etc.	13	55
Competing approaches: Different approaches to biodiversity conservation and sustainable resource management divert interest away from ES research and assessments.	8	55
Loss of interest from researchers: Due to pressure of working at the cutting-edge of science and publishing novel approaches, scientists might lose interest in researching ES framework and move on to new approaches.	7	60
Misuse of environmental tools: Environmental tools can be incompletely or incorrectly applied, and therefore become ineffective or worsen the situation.	6	70
Lack of awareness across general public: Overall low understanding of ecosystems among general public including stakeholders and policy makers. These groups might be disengaged, if their interests are not sufficiently taken into account by the ES framework, or if low ecological understanding prevents buy-in to the ES framework.	5	85
Environmental ethics viewpoint: Approaches such as the ES framework, which put human values before nature's intrinsic value, might face opposition by some factions within the nature conservation field and the general public.	2	80
Diversion from sustainability goals: Society at large may lose interest in nature conservation and sustainability goals, thus removing the demand for the ES framework.	0	35

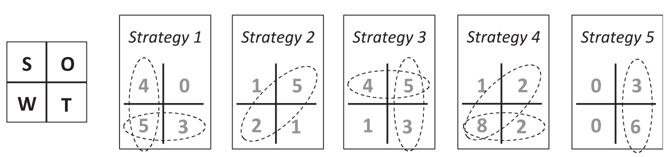

Fig. 6. Conceptual representation of strategy development and distribution of SWOT themes for each strategy topic. Far left: reminder of the four quadrants constituting the SWOT assessment. Dashed lines highlight the quadrants considered for each strategy 1–5. The number of SWOT themes identified within each quadrant is given for each strategy.

are perhaps at the root problems of conceptual convergence and communication. These Weaknesses are compounded by Threats such as loss of interest and lack of awareness. A strategy for resolving these challenges must involve collaboration between those researching and implementing the ES framework, as well as a focus on communication to non-specialists.

Although the Opportunity for technological advances through applying the ES framework was highlighted, it is endangered by the Threat of a lack of institutional capacity. The approach requires extensive support in terms of human and financial resources, to develop capacity, if it is to realise the opportunities it presents.

3.3.5. *Strategy 5 – Wider interface with the ES framework*

Finally, a strategy that focuses upon external issues, i.e. **opportunity–threat (OT)** quadrants, is necessary. This would concern the public face of the ES framework – specifically, how users (such as policy makers, researchers and the general public) engage with the approach.

Identified Opportunities highlight interest in and awareness of the ES framework on the part of a range of stakeholders. These are in contrast with a number of identified Threats such as: resistance to change in environmental practices, loss of political interest, lack of awareness across the general public and loss of interest by researchers. Building upon the topic of communication mentioned in Strategy 4, careful communication and dissemination measures would need to be designed that build upon existing interest and awareness – and, if the approach does prove successful in practice, ensuring that success is evaluated and publicised so as to avoid losing interest on the part of both researchers and policymakers. In turn, this latter requirement suggests the need for monitoring and detailed ex-post evaluation of the implementation of the ES framework.

A key Opportunity, as mentioned in Strategy 2, is alignment with existing policies. By seeking to support existing agreements and policies, and providing useful mechanisms for policy implementation rather than replacing them, it could perhaps be ensured that the ES framework circumvents the threat of resistance to change. The same reasoning could apply to the Threat of competing environmental approaches.

4. Discussion

The YESS group carried out a three-stage survey constituting a SWOT analysis of the ES framework. The aim of the assessment was to seek agreement on the perceived utility of an ES-based approach from a set of early career researchers and practitioners, and to offer the beginnings of some potential strategies for taking the framework forward based upon findings. In this way, we have extended the existing literature on the ES framework, which, whilst highlighting challenges to the use of ES concepts, is usually not structured around a SWOT analysis, and contains limited discussion around such strategies. While strategies to address challenges related with the application of the ES concept have been discussed elsewhere (see de Groot et al., 2010; Baker et al., 2013; Schröter et al., 2014), the strategies we identify emerge from a systematic approach to address perceived weaknesses and threats of ES-based approaches. The identified strategies should not be seen as exclusive, rather, they arise from focusing upon different combinations of the SWOT quadrants, and therefore can be complementary.

Numerous YESS members including 20 participants in the final survey (Survey 3), plus attendees at an ESP conference in Bali, gave input at the various stages of the SWOT analysis. There was very strong agreement by participants in relation to the most highly ranked Strengths, Weaknesses, Opportunities and Threats. The outcomes suggest that key Strengths include that the ES framework is interdisciplinary, provides a means for improved accounting for nature, is holistic, and is a useful advocacy and communication tool. Current Weaknesses include that the scientific basis for the approach is incomplete, ES frameworks are inconsistently applied and do not necessarily account for nature's 'intrinsic' value, and that the language of ES can be ambiguous. External Opportunities for the ES framework include alignment with different existing and emerging policies and strategies, the implementation of the approach through existing tools and methods, and the possibility that environmental awareness is increasing more generally. Finally, identified external Threats include general inertia regarding change in environmental practices, the broader difficulties with successful interdisciplinary collaboration, and insufficient funding to fully realise the potential of the ES framework.

Subsequent consideration of the themes coming out of the SWOT suggested five key strategic areas for furthering the ES framework: (1) approach characteristics; (2) application of the framework; (3) effects of application; (4) demands of application; and, (5) interface with the framework. Whilst the development of full strategies for improving and (if appropriate) embedding the ES framework into practice is beyond the scope of this article, we make some suggestions based on SWOT outcomes, and our findings here could influence the development of strategies.

4.1. Strategies

Strategy 1 is based around how existing Strengths with the approach might be used to overcome Weaknesses. Options include using the interdisciplinary nature of the ES framework, and the associated broad network of researchers working in the space, to further develop the currently incomplete scientific basis (see Bennett et al., 2015). Equally, since the approach has the Strength that it requires practitioners and policymakers to take a holistic view, it should readily be able to incorporate additional considerations that it currently lacks (e.g. inclusion of broader shared and social values; Kenter et al., 2015). Given the approach's potential Strength as an advocacy tool (Costanza et al., 2014), a focus upon this strength could result in the approach being used to leverage input from many more stakeholders than it currently does, to help ensure more equitable use of ES. However, there are also challenges: not least that interdisciplinary science is not easy, or that some stakeholders may remain unwilling to engage with the ES framework if they consider it to violate notions of intrinsic value of nature (Lang et al., 2012). The notion that the ES framework should go beyond utilitarianism to include broader values is now broadly recognised (Kenter et al., 2015), as reflected in explicit in the inclusion of shared or social values in major assessments (e.g. TEEB et al., 2012; UK National Ecosystem Assessment, 2011, 2014). The degree to which the ES framework is or may be able to incorporate non-anthropocentric values is more contentious. There has been debate around whether the concept of services to human-wellbeing is by definition anthropocentric, and not amenable to notions of intrinsic values (Gómez-Baggethun and Ruiz-Pérez, 2011; Braat and de Groot, 2012; Jax et al., 2013; Costanza et al., 2014; Schröter et al., 2014), and our survey suggests that most participants recognise the disregard of nature's intrinsic value as a weakness of the ES framework (Table 3). Nonetheless, notions such as habitat services (TEEB et al., 2012), and conceptualisations of cultural ecosystem services (e.g. Chan et al., 2012; Daniel et al., 2012) can provide a hook for bringing in biocentric values that go beyond the economic notion of existence value. Others have suggested a new ethical approach altogether that aims to transcend the intrinsic-instrumental, biocentrism–anthropocentrism divide (O'Neill et al., 2008). Although delving into this debate is beyond the scope of this article, it is useful to point out that survey participants also associated this issue with application of the ES framework in decision making, and thus broader institutional concerns around how the ES framework is applied. This runs parallel with two aspects of ES that, according to Gómez-Baggethun and Ruiz-Pérez (2011), are often neglected: (i) the role of the particular institutional setup in which environmental policy and governance is currently embedded; and (ii) the broader economic and socio-political processes that have governed the expansion of pricing into previously non-marketed areas of the environment.

Strategy 2 addresses the use of external Opportunities to overcome internal Weaknesses. Two key Opportunities involved the potential alignment of the ES framework with policies and strategies, and with existing tools and methods (e.g. spatial conservation planning, remote sensing, environmental and economic impact assessment). Meanwhile, one potential Weakness was that the approach can be inaccessible to non-specialists, and difficult to apply. Finding ways to align the ES framework more closely with existing policies, strategies and methods could facilitate a better understanding of ES for those not working directly in the field. This is a strategy that can be considered already in progress (e.g. incorporating ES into landscape planning; Albert et al., 2014), but it is nevertheless worth emphasising that doing so is likely to be productive, developing guidelines and providing examples of applied research on how this can be done, highlighting the ongoing need to communicate the basic ideas behind the ES framework (according to the Strengths identified, those ideas are essentially rather straightforward; Fig. 4), and developing knowledge exchange networks that bring together policy makers, research and practitioners (e.g. the UK Ecosystems Knowledge Network[2]). Focused efforts for ES specialists to work with non-technical audiences in identifying and applying the most relevant and effective ES methods and tools, for a given application, should result in greater uptake and ownership of the ES framework. Here transdisciplinary approaches, involving the co-production of knowledge offer much promise (Liu et al., 2010; Jahn et al., 2012; Reyersa et al., 2015) Encouraging the use of existing familiar tools and methodologies to implement the ES framework could equally support uptake, and help address the ongoing challenges around how best to operationalise the approach.

Strategy 3 targets the effects of applying the ES framework given a combination of the relevant Strengths, Opportunities and Threats. Blending the existing Strengths of the ES framework (e.g. conceptual simplicity, increased societal engagement, reconnecting people to nature) with Opportunities could well support an expanding general awareness of and willingness to engage with environmental issues (e.g. within industry; Bull et al., 2015), increasingly politicising the value of implementing the ES framework. Yet it must be considered that a 'loss of political interest' was identified as one of the major Threats to the ES framework. So long as the ES research community builds firmly upon the Strengths and Opportunities identified here, and given recent developments in ES policy – such as the potential incorporation of mandatory ES assessment into European environmental impact assessment requirements, and the recent establishment of IPBES – it would seem unlikely that political interest for the framework will fade in the short term. However, it cannot be taken for granted that this will perpetuate in the longer term, and so any strategic approach must contain measures to keep ES on the political agenda, and importantly ensure that ecosystem management activities are implemented on the ground in order to bridge

[2] http://ecosystemsknowledge.net

research-policy-implementation gaps. Another Threat to the ES framework is resistance to changing environmental practices – one can understand the potential for fatigue on the part of policymakers and the public, given how substantially concepts within conservation (and consequently policy development) have changed over recent decades (e.g. Mace, 2014). Arguments based on key Strengths with the ES framework, such as being characterised by conceptual simplicity and working on multiple scales, as well as explicit recognition and management of Weaknesses (e.g. perceived focus on monetary values) will continue to be required in order to overcome this overarching Threat. The fact that the ES framework provides a potentially strong advocacy and communication tool may be a useful asset in arguing for its wider implementation, especially with regards to engaging with the business sector (Reyersa et al., 2015). Here working with bridging agents can be powerful (Braat and de Groot, 2012; Ruckelshaus et al., 2013). However, ultimately the ES framework is only a means to diffuse ends, and it is conceivable that at some point the ES framework is superseded by other conceptualisations of sustainability and human-nature relations that prove more useful, persuasive or effective in terms of being embedded into practice.

Strategy 4 brings a focus upon Weaknesses, Threats and Opportunities. Research needs for the ES framework have been identified in the literature (e.g. Braat and de Groot, 2012; Bennett et al., 2015). Clearly, input of additional funding and resources to develop the ES framework would begin to address some of these challenges – and indeed insufficient funding has been highlighted as a Threat. But this does not constitute a strategy in itself, as the ES framework competes with many other fields for research funding. The strategy would be to use the identified Strengths and Opportunities to make the case for increased funding to develop and implement the ES framework: such as, e.g. on-going alignment with existing governmental or international policies and strategies. Equally, reducing the costs and efforts required for applying the ES framework will be important. Opportunities for reducing costs and efforts can include uptake of recent technological developments, utilising synergies between research projects and strengthening the networking and exchange of involved scientists rather than 're-inventing the wheel', and striking a balance between application of existing knowledge and methods based on agreed frameworks and protocols and ongoing debate and innovation. The Opportunity provided by technological advancements in terms of applying the ES framework (e.g. ES models and algorithms, hardware for monitoring components of ES), must be considered in the context of a lack of institutional capacity (as a Threat) in some cases. This might perhaps be mitigated through the open exchange of tools and knowledge, as well as key datasets. Further Opportunities could include the development and testing of less data-heavy tools and methods, for instance, by using proxies and existing datasets (e.g. Helfenstein and Kienast, 2014; Jacobs et al., 2015).

Themes informing Strategy 5 are within the Opportunities and Threats quadrants. This strategy relates to the 'public face' of the ES framework – specifically, how to encourage users (such as policy makers, societal actors, researchers and the general public) to engage with the approach. The Opportunities highlight interest and awareness of the ES framework on the part of a range of stakeholders. This can be used to promote the approach, but must be balanced with recognition of the difficulty in maintaining a consistent conceptual framing (Lamarque et al., 2011). Equally, public acceptance of the ES framework must overcome any future potential loss of political interest, resistance to change in environmental processes, lack of awareness across the general public and loss of interest by researchers. The ES framework and concepts behind it require clear communication across a range of audiences if the approach is to be successfully implemented, and the concept of ecosystem services should be mainstreamed across sectors, outlining the potential benefits of doing so (Cowling et al., 2008; Sitas et al., 2014). Note, finally, that a potential Threat that was raised in the pilot survey was the chance of societal diversion from sustainability goals more generally. This was not retained as a Threat to the ES framework by the last survey, perhaps as the respondents trust society will continue to pursue sustainability goals in some capacity (despite changing contextual conditions, e.g. austerity measures and economic crisis).

4.2. *Study limitations and further work*

The survey sample size (20 researchers in Survey 3) was small in absolute terms and thus cannot be assumed to represent the view of early career ES researchers generally. Nonetheless, there was a good degree of variety in the age, sex, nationality and experience with ES of those participating, which may have minimised potential biases in responses. As further research, it would be interesting to extend the survey more widely to other respondents and examine the extent to which the findings are in agreement with the broader ES community, especially of the opinions and perceptions of more long-established researchers in the field of ES.

The respondents to the survey were biased towards the natural sciences and environmental and ecological economics. Therefore, the outcomes may be different if the same survey approach was carried out using a more diverse academic sample (e.g. including more respondents with humanities and broader social science backgrounds), or decision makers. Similar future exercises could be undertaken to draw insights among and between different groups of ES users, stakeholders, researchers or practitioners. The strategies we have outlined should be seen as suggestive, rather than concrete guidelines for action. We offer them as a means for combining the findings of our surveys in a way that is practical and useful to future directions in the theory and practice of the ES framework.

Beyond potential biases associated with participants in the study, there are important linguistic uncertainties to consider. For a start, we consider a valuable component of the survey to be the variety in nationalities represented by respondents, but this same factor means that there is likely to be uncertainty introduced to the identification of themes resulting from subtleties in translation between different native languages. Such uncertainty extends to vaguely defined technical terms, and indeed, the definition of 'ecosystem services' itself. Here, we have used the TEEB definition, but others exist e.g. "the benefits people obtain from ecosystems" (Millennium Ecosystem Assessment, 2005); "the benefits provided by ecosystems that contribute to making human life both possible and worth living" (UK National Ecosystem Assessment, 2011), which are clearly rather different. ES can also be defined in more ecological terms, and in too many other ways to list here (Fisher et al., 2009). It is possible that the survey results would have been rather different with a different starting definition of ES – and therefore it should be considered that the very choice of definition encapsulates a certain perspective into the findings here.

Although SWOT analysis stands out for its simplicity and value in focusing attention on key issues, it entails limitations – for example unclear classification of items as strengths, weaknesses, opportunities or threats, or over-subjectivity in the generation of themes due to compiler bias (Pickton and Wright, 1998). Nevertheless, the results of the SWOT analysis we conducted here allow assessing the relative importance of different themes under the four SWOT categories, from the perspective of a group of ES early career researchers and practitioners. The key utility in the research presented here is thus to review and capture, in a structured way, a variety of considerations relevant to the strategic development of the ES framework that are otherwise not collated within the literature. Another important aspect of conducting such a SWOT analysis is the process itself (Pickton and Wright, 1998). In this research, it provided a platform to exchange ideas and find agreement or otherwise among the YESS community, and contributed to building the community itself.

5. Conclusion

Critical analysis of the ES framework can already be found in literature, however, the innovative character of this research was that such analysis was systematically structured using a SWOT characterisation, allowing us to derive strategies for further development of the ES field. Another important feature of this research is that it reflects the views and perceptions of early career researchers and practitioners, who will help shape the ES field in the future. Our work emphasises that the ES framework can be viewed not only as a way of improving decision-making, but also as a means for more widely interpreting and communicating the complexities of the interaction between humanity and nature. Further, it is suggested that the ES framework is only likely to truly find traction in implementation when more deeply merged with existing policies and incorporating existing tools. Interestingly, the ES framework appears in some senses contradictory – being valued by specialists as a simple means of communicating the importance of nature conservation, whilst also being potentially an oversimplification and characterised by ambiguous language, and this tension suggests its relevance as a bridge between research and practice. Provided sufficient funding and political will is maintained, e.g. through initiatives such as IPBES, the ES framework may yet provide a powerful means for facilitating interdisciplinary research, and for better incorporating sustainability into policy and practice.

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Appendix A. Supplementary Information

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.ecoser.2015.11.012.

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Paper II: Revealing regional deforestation dynamics in north-eastern Madagascar —insights from multi-temporal land cover change analysis

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Article

Revealing Regional Deforestation Dynamics in North-Eastern Madagascar—Insights from Multi-Temporal Land Cover Change Analysis

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Abstract: The north-eastern escarpment of Madagascar harbours the island's last remaining large-scale humid forest massifs surrounded by a small-scale agricultural mosaic. There is high deforestation, commonly thought to be caused by shifting cultivation practiced by local land users to produce upland rice. However, little is known about the dynamics between forest and shifting cultivation systems at a regional level. Our study presents a first attempt to quantify changes in the extent of forest and different agricultural land cover classes, and to identify the main dynamics of land cover change for two intervals, 1995–2005 and 2005–2011. Over the 16-year study period, the speed of forest loss increased, the total area of upland rice production remained almost stable, and the area of irrigated rice fields slightly increased. While our findings seem to confirm a general trend of land use intensification, deforestation through shifting cultivation is still on the rise. Deforestation mostly affects the small forest fragments interspersed in the agricultural mosaic and is slowly leading to a homogenization of the landscape. These findings have important implications for future interventions to slow forest loss in the region, as the processes of agricultural expansion through shifting cultivation *versus* intensified land use cannot *per se* be considered mutually exclusive.

Keywords: land cover changes; Landsat; meso-scale; humid forest; shifting cultivation; land use intensification; deforestation; Analanjirofo

1. Introduction

Human needs for food, fibre, and other services from natural and cultivated ecosystems are driving worldwide land cover (LC) changes [1]. Combined, the resulting LC changes have tremendous impacts on the planet's climate system, water and nutrient cycles, and human societies [2]. The most widely discussed LC change of global importance is probably deforestation. In the tropics, forest was the most important source of agricultural land expansion towards the end of the 20th century, raising concerns about the loss of ecosystem services and biodiversity [3]. Despite a surge in conservation actions around the globe, tropical forest loss has still increased during the last decade [4]. Local smallholders and their subsistence food production systems, often based on shifting cultivation, have long been held accountable for tropical deforestation [5,6]. More recently, indirect factors such as economic incentives [7] and globalized demands for commercial crop cultivation have been identified as increasingly important factors of tropical deforestation [8–10]. This global trend of land use intensification has led to the demise of shifting cultivation in many places, mostly in South-East Asia and East Africa [11].

One prominent exception to this trend is Madagascar. In Madagascar, agriculture along the humid forest frontier is still dominated by traditional smallholder systems. While concern about deforestation and shifting cultivation dates back to colonial times [12], surprisingly little is known about the dynamics between forest and shifting cultivation systems at a regional level. These dynamics are most obvious along the north-eastern escarpment, which harbours the island's last remaining large-scale humid forest massifs, surrounded by a matrix of small-scale agricultural patches. The few studies focusing on shifting cultivation in this area [13–15] and the general deforestation discourse [16,17] point to the persistence or even expansion of shifting cultivation. A wide range of stakeholders from various levels and sectors have therefore been involved in trying to slow deforestation, mainly by establishing protected areas and promoting intensification of other land use practices such as irrigated permanent rice production and agroforestry (e.g., [18–20]).

Due to the strong global empathy with Madagascar's largely endemic fauna and flora, for which the island was labelled one of the "hottest" global biodiversity hotspots [21], national-scale LC change analysis has so far focused strongly on deforestation rates [22], which were found to be decreasing (e.g., [23–26]). By contrast, local-scale deforestation studies from the north-east found increased forest loss [27,28]. However, both types of study—national and local-scale—have limited their analysis of changes from forest to non-forest LC classes. What is missing so far are LC change studies on a regional scale, which would consider various agricultural classes and thus enable us to better understand deforestation dynamics. This knowledge could then be used to plan more sustainable interventions to slow forest loss.

This study seeks to fill the important gap between local and national-scale LC change studies. It provides new information on deforestation dynamics along the north-eastern escarpment of Madagascar, based on a regional-scale assessment of multi-temporal LC change dynamics between 1995 and 2011. The main objectives of the study were (i) to quantify major changes in the extent of forest and different agricultural LC classes; and (ii) to identify and understand the main dynamics between different LC classes.

2. Materials and Methods

2.1. The Study Region

The 24,200 km^2 study region is located in north-eastern Madagascar (Figure 1) and comprises the hilly escarpment between the highlands in the west and the Indian Ocean in the east. It corresponds largely to the administrative region of Analanjirofo plus the Masoala peninsula, although the eastern coastline of the Masoala peninsula is not included as the available satellite images did not extend this far.

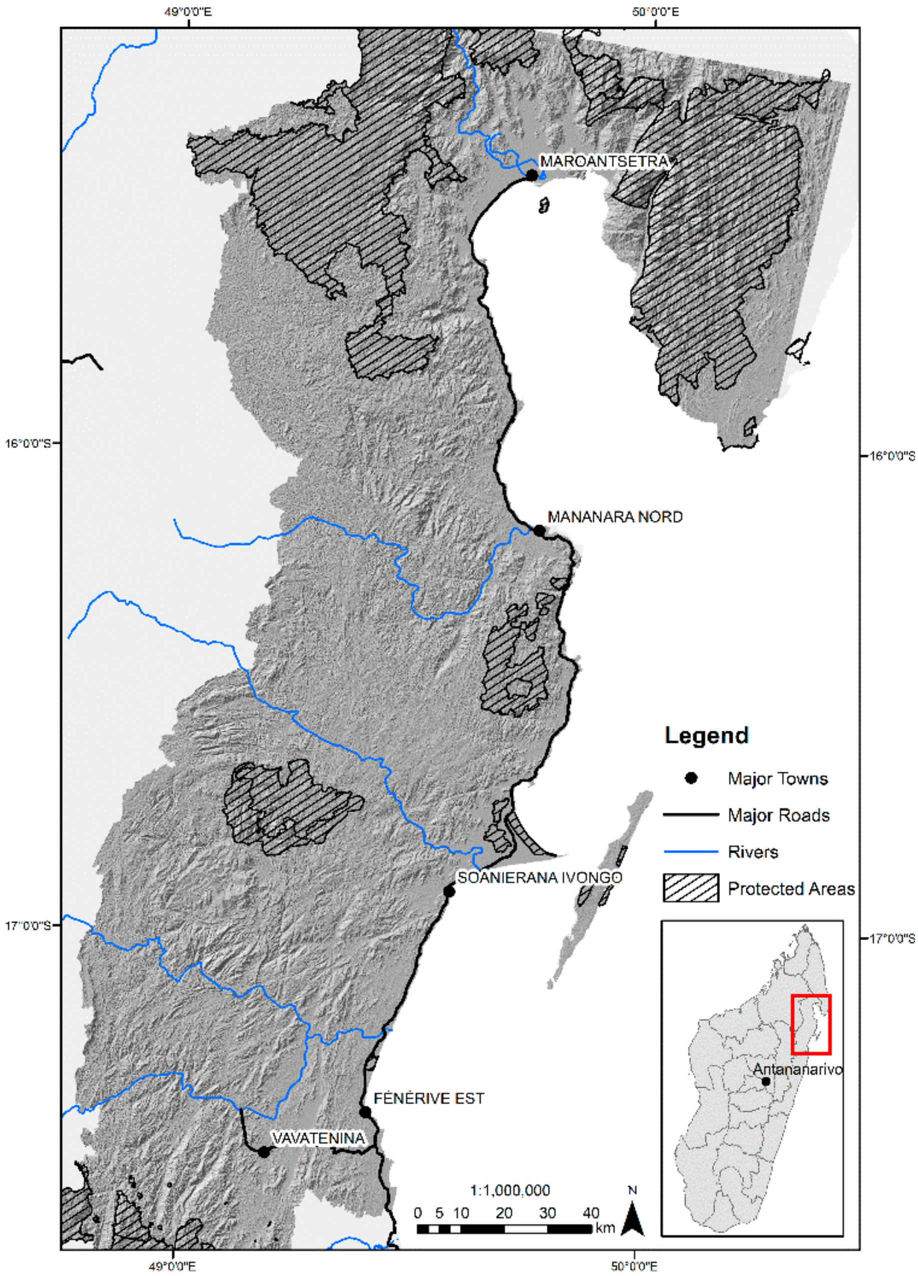

Figure 1. Study region location in north-eastern Madagascar showing major towns, roads, rivers, and protected areas.

The study region has a humid climate with 3600 mm of rainfall per year and an average annual temperature of 24 °C [29]. Its landscape consists of a few large forest massifs surrounded by a mosaic of small patches, reflecting diverse land use activities. The rural population, ethnically dominated by the Betsimisaraka people, applies a mixed production system, cultivating both rain-fed and irrigated rice mainly for subsistence, and commercial crops such as clove, vanilla, coffee, and lychee for income generation [30]. Large annual fluctuations in producer prices present an important challenge to local land users [31]. Rain-fed upland rice cultivation takes place on moderate to steep slopes through shifting cultivation. While there are several terms to describe this land use system in the literature, e.g., slash-and-burn or swidden agriculture, we use the relatively neutral term "shifting cultivation", to emphasize its spatially dynamic character. Through this system, small plots are cleared, burned, and planted for a single year and then left fallow for several years. While the rice can be intercropped with other annuals (mainly maize), tuber crops such as cassava or sweet potatoes are often planted as a second season crop after the rice harvest [14]. Irrigated rice is cultivated in paddies at the valley bottoms: depending on need, labour availability, and fertility, this may be once or twice a year, or paddies may be left fallow for one or several years. This form of rice cultivation is generally limited by lack of flat terrain and access to water for irrigation [30]. Cultivation of clove trees, coffee, and lychee can either be in the form of dense agroforests combined with a diverse mix of other fruit trees and tuber crops for subsistence, or in the form of monocultural stands (mainly for clove). Vanilla is usually cultivated within agroforests shaded by a few large trees. Land use as pasture is rare in this region. Zebu cattle rearing is of little importance and mainly concentrated in the plains around the city of Maroantsetra, where zebus usually graze on clove fields, in irrigated rice paddies after harvest, and along footpaths.

In the study region, a mixed ownership system prevails for agricultural land. Land rights for shifting cultivation are traditionally lineage based: the person who first cuts a piece of forest enables all their descendants to hold the right to use this land for shifting cultivation. Elders allocate plots for rice cultivation to individual households within their extended family on a year-by-year basis [32]. Rights to permanent agricultural land such as irrigated rice paddies or agroforests can be individual or family-based; they are usually inherited and sometimes purchased [14]. Land zoning for forest conservation is very common: protected areas cover 23% of the study region, the largest being Makira Natural Park (since 2005), Masoala National Park (since 1997), Ambatovaky Special Reserve (since 1958), and Mananara Nord National Park (since 1989) [33]. While local land users have restricted access to these protected areas, enforcement is generally weak due to limited accessibility and lacking funds. Outside protected areas, community-managed "sacred forests" and family-owned forests consisting of small fragments are common [32].

2.2. Satellite Data Preprocessing and Classification

Landsat 5 Thematic Mapper (TM) and Landsat 7 Enhanced Thematic Mapper+ (ETM+) satellite data were ordered from the US Geological Survey (USGS) Earth Explorer website (available at http://earthexplorer.usgs.gov). Availability of data for north-eastern Madagascar is low, as the area is often cloud-covered. This makes it difficult to monitor land change in this region, and also posed challenges for our study. Moreover, to differentiate between permanent agriculture and burnt plots in a shifting cultivation cycle, we specifically required satellite images taken between December and March, when new fields are freshly burnt and irrigated rice fields still flooded. In the long-term Landsat data archive we located four-albeit, partially clouded-pairs of Landsat 5 TM and Landsat 7 ETM+ scenes that represent the study area in 1995, 2005, and 2011. For 2005, we classified and merged a Landsat TM and Landsat ETM+ (SLC-off) data set acquired within less than a month of each other: despite large cloud-covered areas in both, they complemented the majority of the areas covered by the Landsat TM scene. We downloaded Landsat Level 1T products, whose processing includes radiometric calibration and geometric correction incorporating ground control points and a digital elevation model [34]. The satellite scene pairs we used are listed in Table 1.

Table 1. Acquisition dates, sensor, and coverage of the used satellite scenes.

Acquisition Date	Path/Row	Sensor	Reference Data
24 January 1995	158/71, 158/72	Landsat 5 TM	visual interpretation
8 March 2005	158/71, 158/72	Landsat 5 TM	Google Earth
12 February 2005	158/71, 158/72	Landsat 7 ETM+ (SLC-off)	Google Earth
21 February 2011	158/71, 158/72	Landsat 5 TM	field data, Google Earth

For radiometric correction we used the ATCOR3 procedure developed by Richter [35], correcting topographic influences as well as atmospheric absorption and scattering using the Shuttle Radar Topography Mission (SRTM) digital elevation model. After radiometric preprocessing, we mosaicked the scenes and checked for geometric matching. To correct a shift in the 2005 and 2011 TM mosaic, we applied a third order polynomial adjustment to the other well-matching mosaics. Finally, we projected all mosaics obtained from UTM Zone 39S into the Laborde map projection used in Madagascar.

The classification scheme (Table 2) was defined according to the present LC in the study region and, partly, to local communities' specific land use. At this point, we would like to stress the importance of differentiating between LC and land use. While LC can be derived from the analysis of satellite images, land use reflects human-environment interactions and requires other methods of detection, representing a challenge for the understanding of land change processes [36]. By opting to use the neutral terms "low-height" or "medium-height" vegetation for two of the LC classes, our aim was to avoid a premature interpretation of changes in land use that the terms "fallow" or "secondary" vegetation might imply. Low-height vegetation represents primarily non-woody vegetation such as grasses, herbaceous plants, and ferns, while medium-height vegetation represents medium-growth stands of trees mixed with shrubs and large herbaceous plants. These different statuses in vegetation cover result in different spectral signatures.

Through field work in 2013, we obtained training and verification data for the supervised classification and verification of the 2011 mosaic. Additionally, we digitized samples from Google Earth imagery acquired in 2011 and a WorldView-2 scene acquired in December 2012, selecting stratified random sampling. Training and verification data for the 2005 mosaic were digitized from Google Earth imagery acquired in 2005. The high-resolution imagery for 2011 and 2005 cover two representative LC and land use subsets to the north and south of the study region. All four subsets have a size of about 20 km by 12 km. To guarantee the independence of training and verification data, half of the obtained reference samples for each year were used to train the maximum likelihood classifier, and the other half to verify the classification results. For the 1995 data set, we defined classification samples through visual interpretation of the Landsat satellite data itself and local expert knowledge, since no independent reference data such as aerial photos exist for 1995.

Table 2. LC classification scheme and possible attribution to land use.

LC Class	Description	Possible Attribution to Land Use
Forest	Primary and degraded or disturbed dense high-growth tree stands, mainly big forest massifs but also fragments	Different protection/management status and use rights: from governmental to non-governmental to customary, communal, or family
Flooded vegetation	Flooded low-growth and non-woody vegetation	Cultivation of irrigated rice once/twice a year
Burnt plots	Recently cleared and burnt plots with little or no vegetation cover	Agricultural fields that are part of the shifting cultivation cycle: after burning they are usually cultivated with rain-fed rice and often abandoned to fallow after one year of cultivation
Low-height vegetation	Low-height, non-woody vegetation such as grasses, herbaceous plants and ferns	Mainly used as fallows in the shifting cultivation cycle. They can be transformed into clove tree plantations which, in a few cases, are simultaneously used as pastures
Medium-height vegetation	Medium-height stands of trees often mixed with shrubs and large herbaceous plants	Mainly agroforests with a diverse mix of planted trees and shrubs as well as monocultural clove tree plantations. Could in some cases also represent secondary or degraded forest
Bare land	Bare soil areas, rocks	Villages, roads, beaches, empty riverbeds
Grassland	Grassland (only in the dry transition zone towards the highlands)	Pastoral use
Water	Water bodies and wetlands	
No data	Clouds and cloud shadows	

Next, we performed supervised maximum likelihood classification, inputting all spectral bands of our satellite data as well as the Normalized Difference Vegetation Index (NDVI). We further improved and confirmed classification of the large forest areas and the many smaller forest fragments by reclassifying areas within a threshold-based forest mask based on bands 4, 5, and 7. We visually checked the forest masks in detail before reclassifying the areas into (a) forest; (b) medium-height vegetation; and (c) low-height vegetation. All classification results were sieve-filtered with a minimum homogeneous patch size of three four-connected pixels. The filter replaces those pixel class values with their largest neighbouring class value to reduce the salt-and-pepper effect [37] caused by mixed pixel values leading to classification errors. The minimum patch size was defined based on visual comparison with landscape field sizes clearly visible in Google Earth imagery. Areas with cloud cover or shadow were generously masked in all three mosaics. We also masked and manually corrected inconsistent class assignments, in view of our main goal of generating highly accurate LC maps for later spatial analysis at landscape level.

2.3. Assessing Map Accuracy

To assess the accuracy of the two classification results for 2005 and 2011, we used the reference samples which were not used for training of the classification. The 2011 verification data set consisted of about 10,800 pixels covering an area of about 10 km^2. The 2005 verification data set consisted of about 26,400 pixels covering an area of about 24 km^2. For the 1995 classification, no verification data set was available, but we estimated the accuracy to be similar to that of the 2005 and 2011 classifications, as we used the same classification algorithm. To account for the different sampling intensities in our differently sized LC categories, we weighted the accuracies with the proportion of the LC categories in the respective maps. We then calculated producer accuracy (PA), user accuracy (UA), and overall accuracy (OA) directly from the resulting error matrices, presenting stratified estimators incorporating area proportions as recommended by Olofsson *et al.* [38]. For comparison, we also computed the unweighted PA and OA from the error matrices based on sample counts [39].

2.4. Quantifying LC Change

To capture the full dynamics and underlying processes of LC change, analysis must include cross-tabulation matrices and not only net-change proportions of LC classes [40]. Therefore, we applied a post-classification pixel-to-pixel comparison in ArcGIS by overlaying LC maps from 1995, 2005, and 2011 to detect from–to transitions between different LC classes [41]. In the resulting cross-tabulation matrices for the 1995–2005 and 2005–2011 intervals, rows show the LC classes from the first time point while columns show classes from the subsequent time point. As the two intervals varied in length, changes were always presented as a percentage of the analysed area per year. The rather long intervals analysed mean that certain changes occurring within those intervals may have been missed.

When trying to detect the most systematic LC changes, it is also necessary to account for the different sizes of LC classes. A large transition between two large classes does not necessarily imply the most systematic LC change, as a large transition would be expected even under a random process of change. Aldwaik and Pontius Jr. [42] therefore propose analysing annual transition intensities, as this method provides a means to account for the different proportions of LC classes. Transition intensities are first calculated relative to the size of the LC class in the initial year (*i.e.*, from a perspective of gains) and then relative to the size of the LC class in the subsequent year (*i.e.*, from a perspective of losses). The obtained value is called the observed annual transition intensity. To detect if a certain transition can be considered systematic, the observed annual transition intensity is compared to the uniform annual transition intensity. Uniform intensity is what would be observed if the gain of a class in the subsequent year were distributed uniformly across the available LC classes in the initial year, or the loss of a class in the initial year were distributed uniformly across the available LC classes in the subsequent year [42]. In our case, forest and low-height vegetation are the two largest classes and therefore even a uniform process of LC change would result in a large transition from forest to low-height vegetation. The difference between observed and uniform intensity indicates whether an observed change between two classes can be considered rather uniform (the closer the value is to zero) or systematic (the further the value is from zero). To detect the most dominant signals of change, we added the difference between observed and uniform transition intensities from the perspective of gains and the perspective of losses.

For the assessment of LC change, we only used the part of the study region that was cloud-free during all three years. Further, we assumed the three LC classes of bare land, grassland, and water to be relatively stable and of no specific interest for our study. We therefore excluded them from the change analysis as well as from the accuracy assessment. The total area for which LC change was assessed thus comprised 14,842 km^2, which corresponds to about 61% of the entire study region (Figure 1) and will be referred to as the “analysed area” in this paper.

3. Results

3.1. Classification Accuracy

The error matrices of the estimated area proportions are presented in Table 3. For each year, PA and OA as calculated from the estimated area proportions [38] are compared to the PA and OA derived from the error matrix based on sample counts.

Table 3. Error matrices with cell entries expressed as the estimated proportion of area for the 2005 **(above)** and 2011 classifications (**below**). For comparison, the last row in each matrix presents PA based on sample counts.

2005		Reference Categories					Total	UA	
		For	Fld	Bur	Lhv	Mhv			
Map categories	For	0.4965	0.0000	0.0050	0.0066	0.0000	0.51	0.98	
	Fld	0.0002	0.0523	0.0091	0.0032	0.0000	0.06	0.81	
	Bur	0.0000	0.0006	0.0190	0.0019	0.0001	0.02	0.88	
	Lhv	0.0005	0.0030	0.0216	0.2418	0.0002	0.27	0.91	
	Mhv	0.0000	0.0044	0.0001	0.0008	0.0445	0.05	0.89	
Total		0.50	0.06	0.05	0.25	0.04			
PA (strat. estim.)		1.00	0.86	0.33	0.96	0.99		OA	0.85
PA (sample count)		1.00	0.84	0.71	0.61	0.97		OA*	0.91
2011									
Map categories	For	0.4476	0.0004	0.0000	0.0149	0.0245	0.49	0.92	
	Fld	0.0000	0.0661	0.0006	0.0049	0.0007	0.07	0.91	
	Bur	0.0000	0.0008	0.0289	0.0030	0.0005	0.03	0.87	
	Lhv	0.0005	0.0074	0.0064	0.2591	0.0347	0.31	0.84	
	Mhv	0.0000	0.0006	0.0006	0.0243	0.0726	0.10	0.74	
Total		0.45	0.08	0.04	0.31	0.13			
PA (strat. estim.)		1.00	0.88	0.79	0.85	0.55		OA	0.87
PA (sample count)		1.00	0.88	0.83	0.88	0.56		OA*	0.86

LC classes: For = Forest, Fld = Flooded vegetation, Bur = Burnt plots, Lhv = Low-height vegetation, Mhv = Medium-height vegetation. * OA based on sample counts.

In the 2005 map, the lowest UA was obtained for the flooded vegetation class, as it was difficult to tell flooded vegetation apart from burnt plots and low-height vegetation. PA based on the stratified estimator was very low for the burnt plot class, as this class covers only 2% of the 2005 map and therefore greatly reduces the accuracy when used as a weighting factor. The PA based on sample count yielded a much better result for this class, which shows that it is important to account for the different sizes of LC categories in the accuracy assessment. For a very small class such as burnt plots, the omission of even relatively small areas has a much larger effect on the map area of this class than in the case of a large class. It should therefore be kept in mind that the area of burnt plots in 2005 was probably largely underestimated. The lowest PA based on sample counts was found for low-height vegetation. In 2011 both UA and PA were lowest for the class of medium-height vegetation which was mistaken for low-height vegetation. There were only small differences between the PA based on the stratified estimator *versus* sample count. The large omission error associated with medium-height vegetation signifies that the area of medium-height vegetation was underestimated because part of it was classified mainly as low-height vegetation and sometimes as forest. PA for forest was very high for both years, since most forest samples lie within large forest massifs which were also classified as such.

3.2. Observing Net LC Changes

Table 4 presents LC shares of the analysed area in 1995, 2005, and 2011. Forest comprised the largest share in each year, followed by low-height vegetation. In 1995, the study area was dominated by forest whereas the rest of the area was under agricultural use. Among the non-forest classes, low-height vegetation had the largest share, followed by medium-height vegetation. Flooded vegetation and burnt plots covered only relatively small parts of the analysed area.

Table 4. LC shares (in km^2 and percentage of total analysed area) and net area of change (as percentage of total analysed area) for the years 1995, 2005, and 2011.

LC Class	1995		2005		2011		Net Area of Change (%)		
	km^2	%	km^2	%	km^2	%	1995–2005	2005–2011	1995–2011
Forest	8894	59.9	8030	54.1	7234	48.7	−5.8	−5.4	−11.2
Flooded vegetation	810	5.5	964	6.5	1077	7.3	1.0	0.8	1.8
Burnt plots	465	3.1	331	2.2	492	3.3	−0.9	1.1	0.2
Low-height vegetation	2948	19.9	4774	32.2	4576	30.8	12.3	−1.3	11.0
Medium-height vegetation	1724	11.6	743	5.0	1462	9.9	−6.6	4.8	−1.8
Total	**14,842**	**100**	**14,842**	**100**	**14,842**	**100**			

From 1995 to 2005, forest and medium-height vegetation decreased, while low-height vegetation experienced a large increase. Very little net change was observed for flooded vegetation (slight increase) and burnt plots (slight decrease). During the second interval, from 2005 to 2011, forest area further decreased. However, contrary to the first interval, low-height vegetation also somewhat decreased, while medium-height vegetation experienced a large increase. Flooded vegetation and burnt plots both experienced small net increases.

Overall, from 1995 to 2011, only forest decreased consistently while flooded vegetation increased. The largest net decrease in forest was compensated for by a net increase in low-height vegetation. Net LC shares of the three other classes remained almost unchanged during the entire study period. Although by 2011 forest still represented the largest single LC class, agricultural LC classes covered more than half of the analysed area. In the next section we examine the change dynamics of the different LC classes, in order to reveal the underlying processes behind the observed net LC changes.

3.3. Assessing Detailed LC Change Dynamics

Figure 2 reveals the overall change dynamics of each LC class.

During the first interval, the largest loss was experienced by medium-height vegetation followed by forest, and the largest gain by far was made by low-height vegetation. Low-height vegetation experienced, simultaneously, the largest loss and gain during the second interval. This type of change is referred to as a “swap”, and depicts vegetation loss occurring in one location while gain occurs in another [43]. The classes of flooded vegetation and burnt plots were also characterized by a swap rather than by net change.

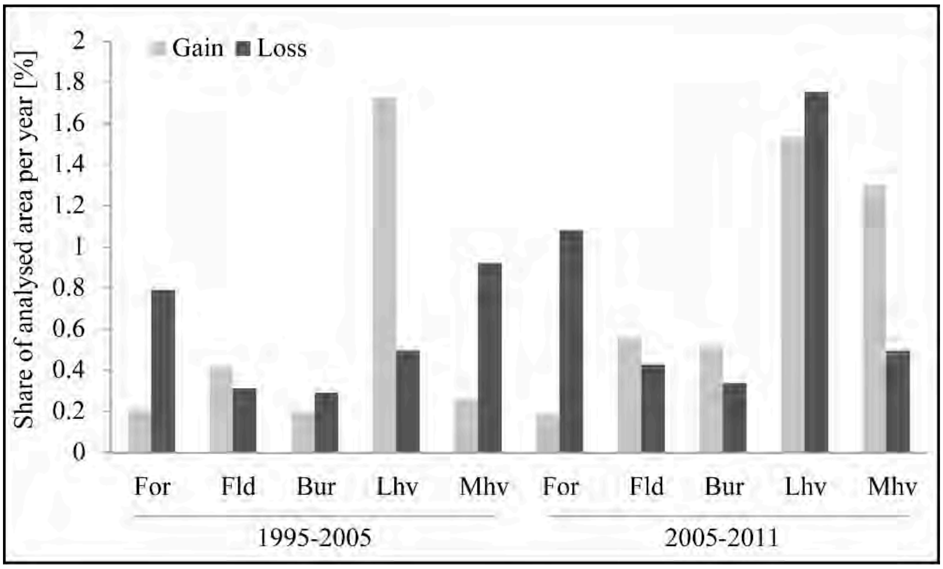

Figure 2. Gain and loss for each LC class as percentage of analysed area per year from 1995–2005 (**left**) and 2005–2011 (**right**). LC classes: For = Forest, Fld = Flooded vegetation, Bur = Burnt plots, Lhv = Low-height vegetation, Mhv = Medium-height vegetation.

Next, we distributed the gains and losses of every LC class among the remaining classes, to detect the dynamics of change between LC classes (Table 5). The LC change matrix reveals that the two classes with the largest losses during the first interval (Figure 2)—medium-height vegetation and forest—were transformed mainly into low-height vegetation. The large gain experienced by low-height vegetation originated almost equally from medium-height vegetation and forest area. Flooded vegetation experienced the second largest gain, mainly from low-height vegetation and medium-height vegetation.

Table 5. LC change matrix for two intervals: 1995–2005 (**left**) and 2005–2011 (**right**), in percentage of the total analysed area per year.

	2005	**Class n**						**2011**	**Class j**				
	1995	**For**	**Fld**	**Bur**	**Lhv**	**Mhv**		**2005**	**For**	**Fld**	**Bur**	**Lhv**	**Mhv**
Class i	For	5.20	0.07	0.06	0.63	0.03	**Class m**	For	7.94	0.10	0.13	0.56	0.29
	Fld	0.03	0.23	0.02	0.22	0.04		Fld	0.01	0.65	0.03	0.32	0.06
	Bur	0.02	0.04	0.02	0.22	0.02		Bur	0.01	0.03	0.03	0.26	0.04
	Lhv	0.07	0.18	0.08	1.49	0.17		Lhv	0.15	0.36	0.33	3.61	0.91
	Mhv	0.09	0.13	0.04	0.66	0.24		Mhv	0.02	0.06	0.03	0.39	0.34

LC classes: For = Forest, Fld = Flooded vegetation, Bur = Burnt plots, Lhv = Low-height vegetation, Mhv = Medium-height vegetation.

During the second interval, however, the large gross loss experienced by low-height vegetation was transformed mainly into medium-height vegetation. The second largest loss was again experienced by forest, which, as during the previous interval, lost mostly to low-height vegetation. In terms of gains, low-height vegetation gained mainly from forest while medium-height vegetation gained mainly from low-height vegetation. Although some gain was observed for forest during both intervals, this can mostly be attributed to regrowth of Traveller's Palm (*Ravenala madagascariensis*) in the floodplain north of Maroantsetra.

3.4. Assessment of LC Transition Intensities from the Perspective of Gains and Losses

While the LC change matrix in Table 5 gives some indication of key patterns of change, it remains unclear whether the observed transitions from one class to another occurred as a result of processes that are systematically more or less intensive than uniform processes [42]. Therefore, we have to consider differences in class size when trying to identify the most systematic LC transitions [43]. With this purpose, we applied the intensity analysis proposed by Aldwaik and Pontius Jr. [42] to transitions between different LC classes.

Table 6 presents three values for every transition: observed intensity (row i), uniform intensity (row ii), and the difference between observed and uniform intensity (row iii). To detect for each class from which other class it gained most intensively, we compared the values in row (iii) within every class column. During both intervals, the most intensive transition was for low-height vegetation, which gained most intensively from burnt plots. Low-height vegetation also gained intensively from medium-height vegetation and flooded vegetation. Only during the second interval did medium-height vegetation also gain intensively from low-height vegetation. All other gains were far less intensive, and no class systematically gained from forest.

Table 6. Transition intensity analysis from the perspective of gains for the intervals 1995–2005 (**left**) and 2005–2011 (**right**): (i) Observed intensity: annual area of gain of class n from class i relative to the size of class i in 1995 (left table) and of class j from class m relative to the size of class m in 2005 (right table); (ii) Uniform intensity: area of gross gain of class n relative to the area of all non-n classes in 1995 (left table) and of class j relative to the area of all non-j classes in 2005 (right table); (iii) difference between observed and uniform intensity.

	2005		**Class n**				
	1995		**For**	**Fld**	**Bur**	**Lhv**	**Mhv**
Class i	**For**	(i)		0.12	0.10	1.05	0.05
		(ii)		0.44	0.21	2.15	0.30
		(iii)		−0.32	−0.11	−1.1	−0.25
	Fld	(i)	0.58		0.42	3.94	0.77
		(ii)	0.52		0.21	2.15	0.30
		(iii)	0.06		0.21	1.79	0.47
	Bur	(i)	0.54	1.15		6.92	0.73
		(ii)	0.52	0.44		2.15	0.30
		(iii)	0.02	0.71		4.77	0.43
	Lhv	(i)	0.34	0.89	0.43		0.85
		(ii)	0.52	0.44	0.21		0.30
		(iii)	−0.18	0.45	0.22		0.55
	Mhv	(i)	0.79	1.10	0.32	5.72	
		(ii)	0.52	0.44	0.21	2.15	
		(iii)	0.27	0.66	0.11	3.57	

	2011		**Class j**				
	2005		**For**	**Fld**	**Bur**	**Lhv**	**Mhv**
Class m	**For**	(i)		0.19	0.23	1.04	0.53
		(ii)		0.59	0.53	2.26	1.37
		(iii)		−0.4	−0.3	−1.22	−0.84
	Fld	(i)	0.17		0.51	5.00	0.93
		(ii)	0.41		0.53	2.26	1.37
		(iii)	−0.24		−0.02	2.74	−0.44
	Bur	(i)	0.37	1.41		11.55	1.80
		(ii)	0.41	0.59		2.26	1.37
		(iii)	−0.04	0.82		9.29	0.43
	Lhv	(i)	0.47	1.12	1.03		2.84
		(ii)	0.41	0.59	0.53		1.37
		(iii)	0.06	0.53	0.50		1.47
	Mhv	(i)	0.37	1.24	0.57	7.71	
		(ii)	0.41	0.59	0.53	2.26	
		(iii)	−0.04	0.65	0.04	5.45	

LC classes: For=Forest, Fld = Flooded vegetation, Bur = Burnt plots, Lhv = Low-height vegetation, Mhv = Medium-height vegetation.

Second, we calculated transition intensities with respect to losses (Table 7). By comparing the values of row (iii) within each class row, we can detect the most intensive transitions in terms of losses for each class. The most intensive transition during both intervals was from low-height vegetation to burnt plots. During both intervals, low-height vegetation also lost intensively to medium-height vegetation and flooded vegetation. The only other relatively intense transitions in terms of loss were from medium-height vegetation to low-height vegetation during the first interval and from forest to burnt plots during the second. The other transitions were much less intensive.

At this stage, we would like to point to the additional insights provided through the intensity analysis as compared to the conventional change matrix (Table 5) alone. By taking into account the large size differences of land cover categories, especially those of forest and burnt plots, the intensity analysis with respect to losses (Table 7) reveals that forest lost most intensively to burnt plots during both intervals. From the change matrix alone, we would conclude that the transition from forest to burnt plots was less important, as in terms of area, forest lost much more to low-height vegetation and to flooded vegetation. The intensity analysis further shows that low-height vegetation experienced the most gain from burnt plots, whereas in terms of area, low-height vegetation gained mostly from medium-height vegetation in the first interval and from forest during the second.

Table 7. Transition intensity analysis from the perspective of losses for the intervals 1995–2005 (l**eft**) and 2005–2011 (**righ**t): (**i**) Observed intensity: annual area of loss from class i to class n relative to the size of class n in 2005 (left table), and from class m to class j relative to the size of class j in 2011 (right table); (**ii**) Uniform intensity: area of gross loss of class i relative to the area of all non-i classes in 2005 (left table) and of class m relative to the area of all non-m classes in 2011 (right table); (**iii**) difference between observed and uniform intensity.

	2005		**Class n**				
	1995		**For**	**Fld**	**Bur**	**Lhv**	**Mhv**
Class i	**For**	(i)		1.15	2.57	1.96	0.56
		(ii)		1.72	1.72	1.72	1.72
		(iii)		−0.57	0.85	0.24	−1.16
	Fld	(i)	0.06		1.02	0.67	0.84
		(ii)	0.33		0.33	0.33	0.33
		(iii)	−0.27		0.69	0.34	0.51
	Bur	(i)	0.03	0.55		0.67	0.46
		(ii)	0.30	0.30		0.30	0.30
		(iii)	−0.27	0.25		0.37	0.16
	Lhv	(i)	0.12	2.72	3.78		3.35
		(ii)	0.73	0.73	0.73		0.73
		(iii)	−0.61	1.99	3.05		2.62
	Mhv	(i)	0.17	1.96	1.69	2.07	0.17
		(ii)	0.97	0.97	0.97	0.97	0.97
		(iii)	−0.80	0.99	0.72	1.10	−0.80

	2011		**Class j**				
	2005		**For**	**Fld**	**Bur**	**Lhv**	**Mhv**
Class m	**For**	(i)		1.41	3.80	1.83	2.92
		(ii)		2.11	2.11	2.11	2.11
		(iii)		−0.70	1.69	−0.28	0.81
	Fld	(i)	0.02		1.00	1.05	0.61
		(ii)	0.46		0.46	0.46	0.46
		(iii)	−0.44		0.54	0.59	0.15
	Bur	(i)	0.02	0.43		0.84	0.41
		(ii)	0.35	0.35		0.35	0.35
		(iii)	−0.33	0.08	−0.35	0.49	0.06
	Lhv	(i)	0.31	4.95	9.97		9.28
		(ii)	2.54	2.54	2.54		2.54
		(iii)	−2.23	2.41	7.43		6.74
	Mhv	(i)	0.04	0.86	0.87	1.25	0.04
		(ii)	0.55	0.55	0.55	0.55	0.55
		(iii)	−0.51	0.31	0.32	0.70	−0.51

LC classes: For = Forest, Fld = Flooded vegetation, Bur = Burnt plots, Lhv = Low-height vegetation, Mhv = Medium-height vegetation.

3.5. Revealing the Most Dominant Signals of Change

Combining the intensity of gains (Table 6) with the intensity of losses (Table 7), we can reveal the most dominant signals of change (Table 8). The farther the numbers are from zero, the more systematic the transition.

Table 8. Transition matrix for two intervals, 1995–2005 (**left**) and 2005–2011 (**right**), showing added differences between observed and uniform intensity for gain (Table 6) and loss (Table 7).

	2005			**Class n**				**2011**			**Class j**		
	1995	**For**	**Fld**	**Bur**	**Lhv**	**Mhv**		**2005**	**For**	**Fld**	**Bur**	**Lhv**	**Mhv**
Class i	**For**		−0.89	0.74	−0.86	−1.41	**Class m**	**For**		1.10	1.39	−1.50	−0.03
	Fld	−0.21		0.9	2.13	0.98		**Fld**	−0.68		0.52	3.33	−0.29
	Bur	−0.25	0.96		5.14	0.59		**Bur**	−0.37	0.90		9.78	0.49
	Lhv	−0.79	2.44	3.27		3.17		**Lhv**	−2.17	2.94	7.93		8.21
	Mhv	−0.53	1.65	0.83	4.67			**Mhv**	−0.55	0.96	0.36	6.15	

LC classes: For = Forest, Fld = Flooded vegetation, Bur = Burnt plots, Lhv = Low-height vegetation, Mhv = Medium-height vegetation.

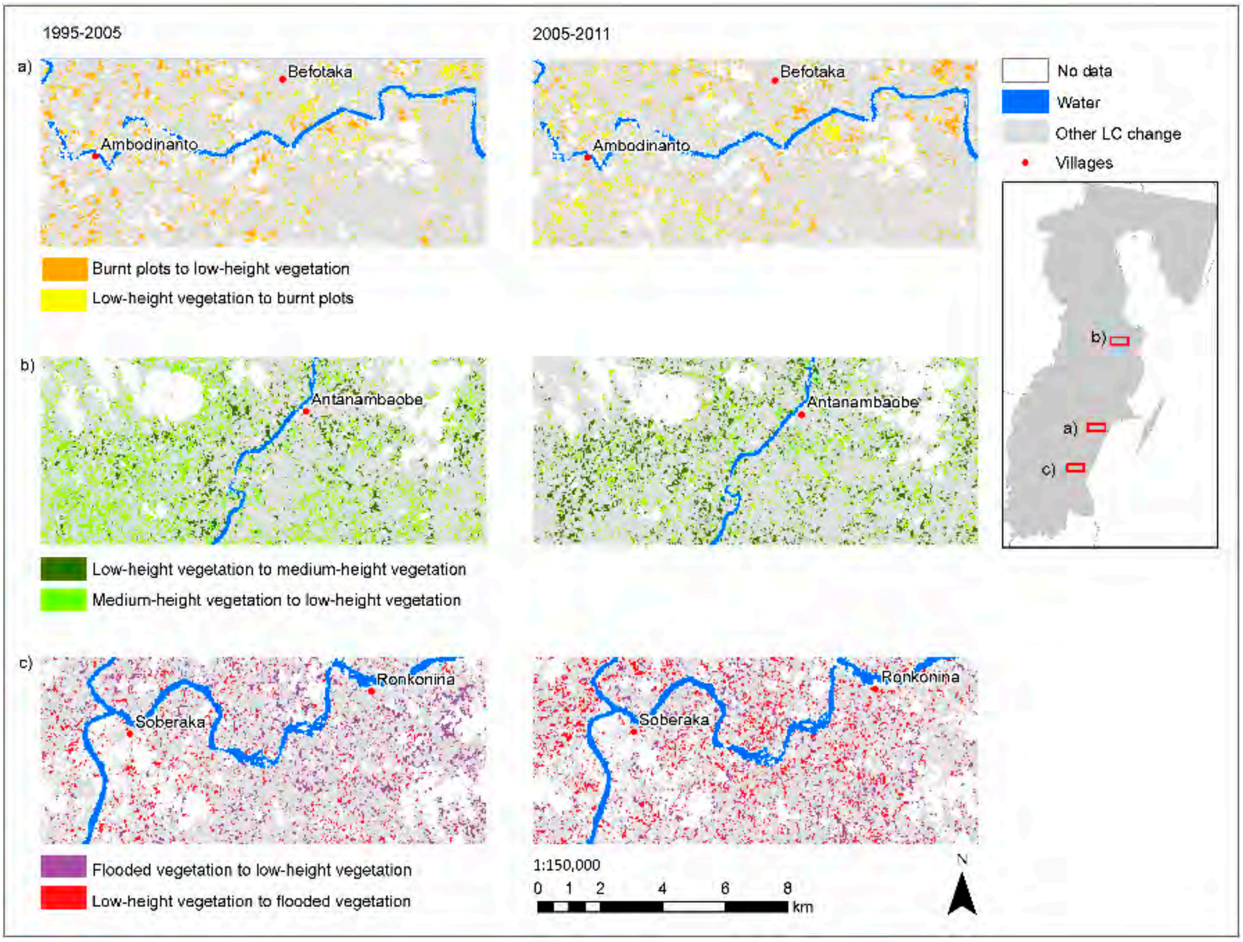

Figure 3. The most dominant LC transitions during both intervals: (**a**) between burnt plots and low-height vegetation; (**b**) between low-height and medium-height vegetation; (**c**) between flooded and low-height vegetation.

The most dominant signal of change during both intervals was the simultaneous transition between low-height vegetation and burnt plots and *vice versa*. This transition indicates a rotational shifting cultivation system where every year fallow plots are slashed and burned for upland rice cultivation in some locations, while in other locations upland rice fields are abandoned to fallow. Another simultaneous transition was observed between medium-height and low-height vegetation and *vice versa*. During the first interval, the decrease in biomass from medium-height to low-height vegetation was more intensive, while during the second interval the opposite process was more dominant. The third dominant transition during both intervals was from low-height vegetation to flooded vegetation and *vice versa*.

To illustrate the small-scale but highly dynamic character of these six transitions, three selected areas are shown in Figure 3.

Another three transition types were dominant mainly during one of the two intervals. During the first interval, medium-height vegetation was systematically transformed into flooded vegetation. During the second interval, deforestation to burnt plots and to flooded vegetation were also dominant transitions.

4. Discussion

4.1. Overall Trends in LC Change: Deforestation and Expansion of Agricultural Land

Deforestation on the eastern escarpment of Madagascar has long attracted the attention of scholars and conservation practitioners (e.g., [22,44]). Our analysis of net LC changes (Table 4) revealed that during the 16-year study period from 1995 to 2011, forest area decreased by about 11% and low-height vegetation, mainly representing fallow land, increased. The rate of annual forest loss accelerated over the two intervals, with 1% of the initial forest area lost every year from 1995 to 2005 and 1.7% from 2005 to 2011. Both increase and magnitude of our observed annual deforestation rate are in line with more local-scale studies conducted within our study region. In one of these studies, conducted in the northern part of Masoala National Park, Allnutt *et al.* [27] found that the annual rate of forest change increased from 0.99% during 2005 and 2008 to 1.27% from 2010 to 2011. In another, carried out in the Manompana forest corridor, the annual deforestation rate remained almost stable with 1.07% between 1991 and 2004 and 1.09% between 2004 and 2009 [28]. It should be noted though, that such averaged rates of change are of limited value for this study, as they conceal the high variability of change between the analysed time points. During both intervals of our study, forest loss occurred mainly outside today’s core zones of protected areas (92% from 1995 to 2005 and 88% from 2005 to 2011) and targeted mostly the small forest fragments that are part of the diverse landscape mosaic typical of north-eastern Madagascar. Although the importance of those fragments for the provision of forest products and services is acknowledged by local land users, they are primarily perceived as a land reserve for future cultivation and thus deforested once additional land is needed [32]. Since the majority of protected areas in our study region were established before 1995, we did not further investigate if those protected areas had any impact on forest change. However, for Makira Natural Park, established in 2005, we observed that in the valley of Maitsoarongana intense forest loss occurred between 1995 and 2005 but was no longer the case between 2005 and 2011 (Figure 4). Nonetheless, such local examples should be treated with caution, as they are not necessarily representative of broader trends.

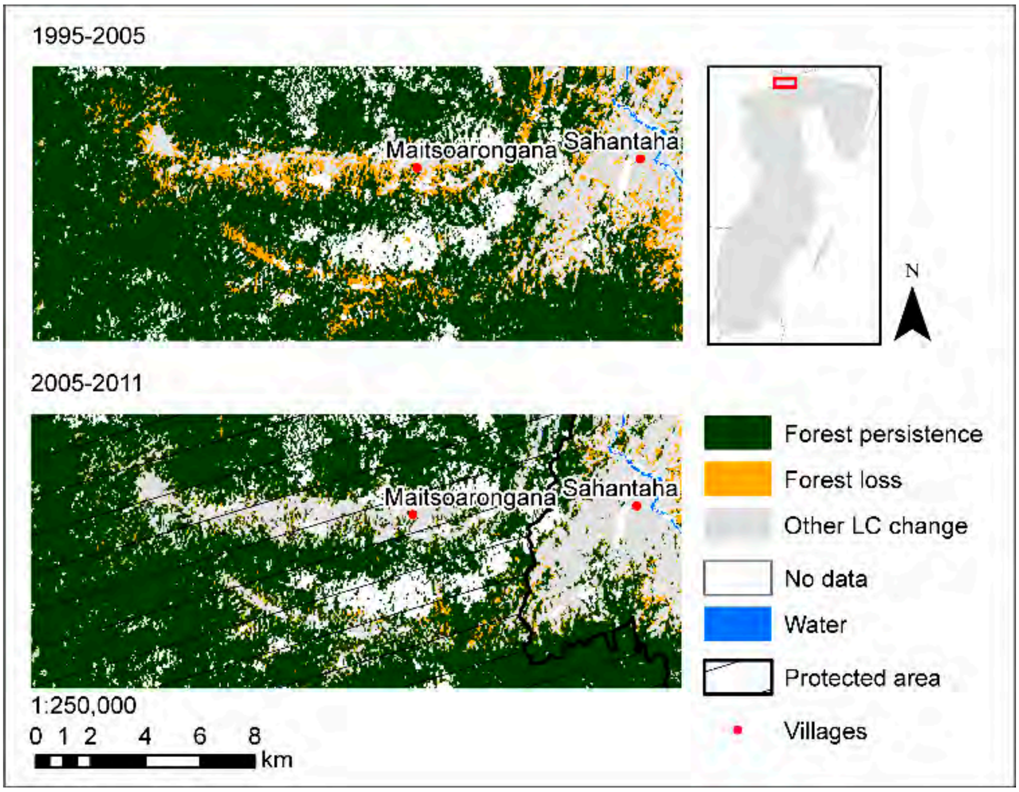

Figure 4. Example of forest loss before and after establishment of Makira Natural Park in 2005.

By considering agricultural LC classes in our analysis, we are able to add evidence to the scarce knowledge base on the development and current state of shifting cultivation on the north-eastern escarpment. The total area of burnt plots increased very little during the overall study period. This indicates that the area used for rain-fed rice production through shifting cultivation has remained at almost the same level as in 1995. The smaller area of burnt plots observed in early 2005 as compared to 1995 and 2011, however, should be regarded as a one-time phenomenon rather than as a manifestation of more profound changes. With very few fires, 2004 was an extreme outlier: Madagascar's total burnt surface amounted to less than 10% of the average surface burnt between 1992 and 2007 [45]. The low occurrence of fires in 2004 was confirmed also by MODIS fire observations of the Analanjirofo region [46]. This might be explained by inter-annual rainfall variability: during periods of excessive rainfall, land users are unable to light the slashed vegetation. As December 2004 was the wettest December during our entire study period [47], this might have caused some land users to skip upland rice cultivation for one year and rely on irrigated rice harvests complemented by rice bought on the market, spending income from cash crops or wage labour. Furthermore, our accuracy assessment based on the stratified estimator indicates that the area of burnt plots in 2005 was underestimated on the map.

Low-height vegetation experienced by far the largest increase in net area during the study period. Assuming that low-height vegetation to a large part represents agricultural land under fallow (see Table 2 for the link between land cover and land use), this suggests that land users expanded their fallow land while the total area of burnt plots between 1995 and 2011 remained more or less stable. As a fallow is always preceded by a burnt plot, this result implies that at some point between 1995 and 2011 there was a peak in burnt plots which was omitted by our analysis (see Section 2.4.). A probable explanation for the expansion of fallows is that this constitutes the only option for land users to hold off shortening crop rotation cycles, and thus counteract fertility decline, in the absence of access to agricultural inputs and restricted time and labour availability [48]. Yet, shortened fallow cycles might also occur in some locations, as this aggregated result probably masks large differences among individual households' access to land. Another possible explanation relates to the traditional land rights system which grants ownership to the person who first deforests a parcel of land for cultivation [32,49]. With increasing physical scarcity of forests as well as access restrictions in the study region, land users might engage in deforestation not only to bring land into production to cover immediate food requirements, but also to secure it for their descendants.

4.2. Detailed LC Change Dynamics

The most dominant change process in the analysed area was observed between low-height vegetation and burnt plots. While low-height vegetation regrew on formerly burnt plots, elsewhere low-height vegetation was burnt. Burnt plots gained more intensively from low-height vegetation than from forest (Table 6), especially during the second time interval. This exchange between the two classes reflects the rotational character that is typical of the shifting cultivation system along the north-east coast as opposed to a pioneering shifting cultivation system, where new rice fields are established in forest [50].

Nevertheless, pioneering shifting cultivation is still very widespread in the analysed area. In terms of area, forest was mainly transformed into low-height vegetation, but when taking into account the highly different sizes of the individual LC classes, the most intensive transition occurred from forest to burnt plots (Table 8). Additionally, the area of transition from forest to low-height vegetation can to a large extent also be attributed to agricultural expansion for shifting cultivation. The pixels classified as burnt plots in one year will be covered with low-height vegetation the next, and thus be missed by our analysis with intervals of 10 and six years. As we assume that the majority of burnt plots in the analysed area are indicative of shifting cultivation rather than logging, this result suggests that current deforestation in the analysed part of our study region occurs mainly to clear land for shifting cultivation. We do not mean to imply that the logging of precious timber species is of little concern in the study region, but this process of forest change was omitted by our analysis, as the logging of single trees requires higher-resolution spatial data for detection [27]. However, while the current illegal selective logging practices in our study region may have severe impacts on the forest's biodiversity value [51], their contribution to large-scale LC change as analysed by our regional-level study is probably negligible. Contrary to most other shifting cultivation hotspots around the globe [11], in north-eastern Madagascar, shifting cultivation persists and its contribution to deforestation has probably even increased between 1995 and 2011.

Another important change process observed concerns the decrease in biomass from medium- to low-height vegetation during the first interval, and *vice versa* during the second. This might in part be related to extreme changes in producer prices for the main tree cash crops of coffee and clove in the study region. While producer prices for cloves in Madagascar experienced about a 10-fold increase between 1995 and 2002, the opposite trend was recorded for coffee prices during this period [31]. This might have incited some land users to uproot their coffee plantations and plant clove trees instead. A transformation such as this would have shown up in our analysis as a change from medium- to low-height vegetation and back again to medium-height. It should be noted though that the accuracy of the 2011 LC map is lowest for the class of medium-height vegetation, and that at least during the second interval part of this change might be attributable to confusion with low-height vegetation.

Lastly, the mutual transformation between flooded and low-height vegetation during each of our study intervals points to the importance of sociocultural factors influencing the dynamics of agricultural production systems in the region. Land users can only maintain irrigated rice production if they have access to irrigation water, and conflicts concerning the distribution of irrigation water as well as labour investments into irrigation infrastructure are very common in the region [14,30]. As a result, land users might let their irrigated rice fields lie fallow for some years until the conflict is resolved. While this could explain part of the swap between flooded and low-height vegetation, part of this change can be attributed to flooded vegetation being misclassified as low-height vegetation, due to annual differences in water levels during the three study years (see Table 3).

5. Conclusions

North-eastern Madagascar receives much international attention due to the extraordinary biodiversity and high carbon levels preserved in its shrinking humid rainforests. In this context, our analysis presents the first attempt to identify and understand the main dynamics of LC change at a regional scale. Overall, our results appear to confirm the general assumption that land use is intensifying in the study region. The total area under upland rice cultivation remained almost stable over the 16-year study period, while the area of irrigated rice fields slightly increased. However, our observations do not confirm the often-held assumption that land use intensification leads to less deforestation. On the contrary, we found that the rate of forest loss had increased between 1995 and 2011, with forest largely replaced through low-height vegetation. This contradictory trend suggests that even if more rice is produced in irrigated paddies, shifting cultivation will continue. This may be explained by differences in individual households' access to land on the one hand (some only have access to land for shifting cultivation), and diversification strategies on the other (households with access to both types of land will use both to reduce risks, e.g., of crop failure due to cyclones). Furthermore, under customary law, slashing and burning forests is the most commonly used means of securing land for future generations.

The main cause of deforestation between 1995 and 2011 was shifting cultivation. While the large forest massifs enclosed by protected areas seemed to be comparatively well protected, deforestation predominantly occurred in the smaller forest fragments interspersed in the agricultural landscape. As the term "pioneering shifting cultivation" usually designates the establishment of new upland rice fields at the forest frontier, a new term might be needed to describe the process of landscape homogenization we observed in our study region. We therefore suggest the term "homogenizing shifting cultivation" to describe the process of shifting cultivation that removes the last forest fragments from the landscape. This may well be an outcome conservation organizations are prepared to accept as a side effect of preserving the few remaining forest massifs in strictly protected areas. However, little is known about the socio-economic, sociocultural, and ecological consequences should those fragments disappear.

To conclude, we would like to stress the importance of analysing and understanding the links between the different land use components of shifting cultivation, irrigated rice production, cash crop cultivation, animal husbandry, and forest use in an integrative way. To support the planning of more comprehensive interventions to slow forest loss in north-eastern Madagascar, it will be necessary to link the present LC information with land users' socioecological interactions. A deepened understanding of land use processes and the actors influencing them could serve as a first step to negotiating land use trade-offs and ensuring the long-term existence of highly diverse landscapes fulfilling both ecological and sociocultural goals.

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Author Contributions

Land cover classification was performed by Sandra Eckert. Main data analysis was performed by Julie G. Zaehringer. Sandra Eckert contributed to the materials and methods. Peter Messerli contributed to the discussion and conclusion. Julie G. Zaehringer wrote the paper.

Conflicts of Interest

The authors declare no conflict of interest.

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Paper III: Beyond deforestation monitoring in conservation hotspots: Analysing landscape mosaic dynamics in north-eastern Madagascar

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Beyond deforestation monitoring in conservation hotspots: Analysing landscape mosaic dynamics in north-eastern Madagascar

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ABSTRACT

Due to its extraordinary biodiversity and rapid deforestation, north-eastern Madagascar is a conservation hotspot of global importance. Reducing shifting cultivation is a high priority for policy-makers and conservationists; however, spatially explicit evidence of shifting cultivation is lacking due to the difficulty of mapping it with common remote sensing methods. To overcome this challenge, we adopted a landscape mosaic approach to assess the changes between natural forests, shifting cultivation and permanent cultivation systems at the regional level from 1995 to 2011. Our study confirmed that shifting cultivation is still being used to produce subsistence rice throughout the region, but there is a trend of intensification away from shifting cultivation towards permanent rice production, especially near protected areas. While large continuous forest exists today only in the core zones of protected areas, the agricultural matrix is still dominated by a dense cover of tree crops and smaller forest fragments. We believe that this evidence makes a crucial contribution to the development of interventions to prevent further conversion of forest to agricultural land while improving local land users' well-being.

1. Introduction

Tropical forest landscapes have been modified by humans for tens of thousands of years with increasing intensity (Malhi, Gardner, Goldsmith, Silman, & Zelazowski, 2014). The expansion of agricultural land is a main driver of forest conversion (Gibbs et al., 2010), ranging from large-scale agribusinesses to smallholder subsistence farms (Laurance, Sayer, & Cassman, 2014). In many countries the concern has now shifted to large-scale forest clearance linked to the engagement in international agricultural markets and the growth of urban populations (DeFries, Rudel, Uriarte, & Hansen, 2010; Lambin & Meyfroidt, 2011; van Vliet et al., 2012). Madagascar seems to be an important exception to this trend, with the retraction of its humid forest frontier still due to smallholders' expansion of agricultural land to produce subsistence rice through shifting cultivation (van Vliet et al., 2012). In Madagascar, as in other shifting-cultivation hotspots around the globe (Ickowitz, 2006; Mertz et al., 2009), shifting cultivation has since colonial times been considered irrational and unsustainable, leading to the destruction of biodiversity-rich forests (e.g., Humbert, 1927 in Kull, 2000).

Land change science offers a strong conceptual framework to analyse transitions in land use systems dominated by smallholders (Turner, Lambin, & Reenberg, 2007). Adopting a sustainability perspective, it seeks to understand the dynamics of land cover and land use as a coupled human–environment system (Global Land Project, 2005; Reenberg, 2009). The resulting knowledge should help policy-makers to steer land change processes towards sustainable outcomes, ensuring the provision of ecosystem services for stakeholders at different levels.

A major challenge arises if the investigation of land change starts with the analysis of remotely sensed imagery. This makes it difficult to link land cover information to human influence and thus to understand land use processes (Verburg, van de Steeg, Veldkamp, & Willemen, 2009). This is especially pertinent in the context of shifting cultivation systems, which are characterized by a combination of different land cover types showing high spatial and temporal dynamics (Schmidt-Vogt et al., 2009; Sirén & Brondizio, 2009). Another challenge involves the discrepancy between the different levels at which land use decisions are made. Local land

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users' decisions are increasingly influenced by broad economic, political and environmental processes (Lambin et al., 2001; Verburg et al., 2009) leading to highly context-dependent outcomes (Ostrom, 2007; Rindfuss et al., 2007). The uniqueness of local information makes upscaling and generalization difficult (Magliocca et al., 2014), which hinders its use by policy-makers (Messerli, Bader, Hett, Epprecht, & Heinimann, 2015). In light of these two challenges, it is not surprising that shifting cultivation in eastern Madagascar does not appear on regional or national maps.

Most regional and national land change studies have limited their focus to the binary analysis of changes from forest to non-forest land cover (Grinand et al., 2013; Harper, Steininger, Tucker, Juhn, & Hawkins, 2007; Ministère de l'Environnement, des Forêts et du Tourisme (MEFT), United States Agency for International Development (USAID), & Conservation International (CI), 2009; Office National pour l'Environnement (ONE), Direction Générale des Forêts (DGF), Foiben-Taosarintanin'i Madagasikara (FTM), Madagascar National Parks (MNP) & Conservation International (CI), 2013). The scarce scientific knowledge on the current extent and trajectories of shifting cultivation in this zone is almost exclusively based on a few case studies clustered between the capital, Antananarivo, and the port of Toamasina (Klanderud et al., 2010; Messerli, 2004; Styger, Rakotondramasy, Pfeffer, Fernandes, & Bates, 2007). This presents a considerable omission given the large attention shifting cultivation has received from conservation and development stakeholders (Conservation International, 2011; Freudenberger, 2010; Holmes, Ingram, Meyers, Crowley, & Victurine, 2008; World Bank, 2013; World Wildlife Fund, 2007).

The eastern escarpment of Madagascar holds some of the most biodiversity-rich forests on earth and is therefore a global conservation priority (Myers, Mittermeier, Mittermeier, da Fonseca, & Kent, 2000). Theoretically, the establishment of two large protected areas in 1997 and 2005 (Masoala National Park and Makira Natural Park, respectively) has closed most of the agricultural frontier in the region. Conservation and development strategy has mainly been directed at the intensification of land use away from shifting cultivation towards permanent irrigated rice production. However, little is known about the success of this approach, and the focus on single components of the agricultural production system has been questioned (Brimont, Ezzine-de-Blas, Karsenty, & Toulon, 2015; Messerli, 2004; Zaehringer, Eckert, & Messerli, 2015). While shifting cultivators are held responsible for rapid deforestation, spatially explicit evidence for this claim is lacking due to the abovementioned difficulty of detecting shifting cultivation on land cover maps. The either/or focus on changes from forest to nonforest also limits our understanding of the processes at work and of how to slow forest loss and lift the local population out of poverty.

The goal of this study was thus to spatially delineate shifting cultivation and permanent land use systems in north-eastern Madagascar and to assess their changes at a regional level; to the best of our knowledge, it is the first such effort. For this study we defined landscape as a spatially heterogeneous area composed of interacting land use systems. We mapped current landscape types, quantified major changes in their extent from 1995 to 2011 and identified the location and magnitude of intensification and extensification at the landscape level. This offers a crucial contribution to policy-making for a more sustainable development of this resource-rich but poverty-prone region.

2. Materials and methods

2.1. The study region

We selected our study region in north-eastern Madagascar (Fig. 1) because it is home to some of the last remaining humid primary forests containing the extraordinary biodiversity for which Madagascar is known (Ganzhorn, Lowry, Schatz, & Sommer, 2001; Myers et al. 2000). Therefore it features a number of protected areas which have the aim to halt deforestation and forest resource exploitation. We chose the administrative region of Analanjirofo as the extent of the analysis, as this is the level at which decision making for regional development takes place. However, the northernmost tip of the Analanjiorofo region is not included as the available land cover data did not extend this far. Instead, the Masoala peninsula, of which part belongs to the Sava administrative region, is included, as it represents a biodiversity hotspot of great interest to many conservation actors.

This region receives about 3,600 mm of annual precipitation and has an average annual temperature of 24 °C (Jury, 2003). Makira Natural Park, established in 2005, encloses one of the largest continuous rainforests in the country and provides a habitat for more than 18 species of lemurs (Golden, Fernald, Brashares, Rasolofoniaina, & Kremen, 2011). Other large forest conservation sites include Masoala National Park (established in 1997), Ambatovaky Special Reserve (established in 1958), and Mananara Nord National Park (established in 1989). Together these protected areas cover 23% of our study region (International Union for Conservation of Nature & UNEP, 2014). Access to these forests by local land users is restricted, but due to their limited accessibility and limited funding, enforcement is rather weak.

Apart from these forests, the region is characterized by small plots with diverse land uses. Rice is the main staple crop in Madagascar. Both rain-fed upland and irrigated lowland paddy rice are produced for subsistence by the local land users, ethnically dominated by the Betsimisaraka people. Also important are commercial crops such as clove, vanilla, coffee, and lychee (Locatelli, 2000). The volatility in prices for these crops creates uncertainty for local farmers (Food and Agriculture Organization, 2014).

Traditional shifting cultivation is used to produce rain-fed upland rice on moderate to steep slopes. Most commonly land users clear and burn small plots, which they plant with rice (often in combination with maize) for a single year. Subsequently, tuber crops such as cassava or sweet potatoes are often cultivated for another one to two years. Thereafter the fields lie fallow for several years (Messerli, 2004). For permanent rice cultivation, land users need access to paddies at the valley bottoms and to irrigation water. Ploughing and weeding the irrigated rice fields is labour-intensive, and external inputs such as fertilizers are rare (Locatelli, 2000). Clove trees, coffee bushes and vanilla lianas are often grown in agroforests together with a diverse mix of fruit trees and tuber crops for home consumption. Monocultures of clove trees are also common. Zebu cattle are used for ploughing and in ancestral ceremonies. They mostly graze in irrigated rice paddies after harvest and along footpaths, as relatively few land users have sufficient land for pastures. Small forest fragments, often family owned, are dispersed throughout the region and provide construction materials, wild food, space for burial grounds and other benefits (Urech, Rabenilalana, Sorg, & Felber, 2011).

Property rights for agricultural land are very complex in this region. Within shifting cultivation systems, all descendants of the person who first clears a forest plot have the right to use it for rice cultivation. From year to year, elders consider the land needs of households within their lineage and then allocate the plots (Urech et al., 2011). The conversion of forest into agricultural land is one of the few ways to assure food security for future descendants (Keller, 2008). The increasing scarcity of natural forests and expansion of protected areas might therefore incite land users to accelerate deforestation. For the cultivation of permanent agricultural land, such as irrigated rice paddies and agroforests, individual or family-based land rights usually prevail. Descendants mostly inherit these

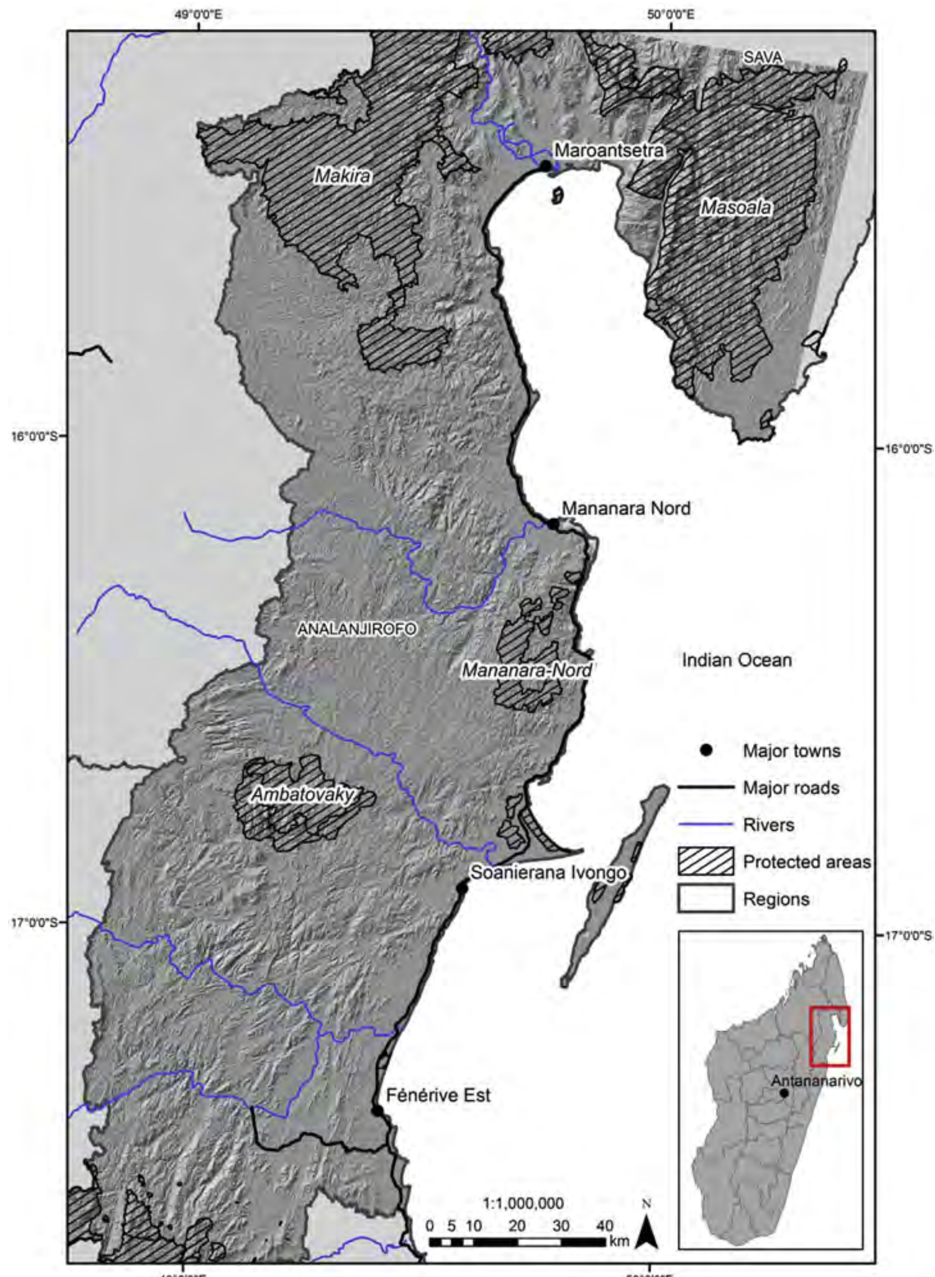

Fig. 1. Study region in north-eastern Madagascar (adapted from Zaehringer et al., 2015).

plots from their parents, while immigrants can sometimes purchase them (Messerli, 2004).

2.2. Remote sensing data and analysis

The land cover data used for this study were published by Zaehringer et al. (2015); only the most important methodological steps are described here. Landsat imagery was used to create land cover maps for 1995 and 2011, applying a maximum likelihood supervised classification. Both high-resolution images and field sampling data were used to verify the classification of the 2011 imagery. Accuracy assessment taking into account different map area proportions—as recommended by Olofsson, Foody, Stehman, and Woodcock (2013)—yielded an overall accuracy of 87% for the 2011 map. For the 1995 classification, no independent reference data such as aerial photos exist. However, the accuracy was estimated to be similar to that of the 2011 classification, as the same classification algorithm was applied.

The land cover classes of further interest for this article include *forest* (primary and degraded continuous forest and forest fragments), *flooded vegetation* (flooded low-growth and non-woody vegetation), *burnt plots* (recently cleared and burnt plots with little or no vegetation cover), *low-height vegetation* (mostly non-woody vegetation such as grasses, herbaceous plants and ferns) and *medium-height vegetation* (primarily trees, often mixed with shrubs and large herbaceous plants). In terms of land use, flooded vegetation consists mainly of irrigated lowland paddies, while burnt plots are fields prepared for upland rice in the shifting cultivation cycle. Other minor land cover classes include bare land, grassland and water.

2.3. Describing the landscape mosaic

While it is possible to distinguish different land cover classes from pixel-based remote sensing images, these cannot be directly linked to land uses. To address this problem, Messerli, Heinimann, and Epprecht (2009) proposed a landscape mosaic approach that interprets land cover pixels by taking into account human–environment interactions and the condition of neighbouring pixels. For example, a patch of low-height vegetation, viewed in isolation, could represent several land uses, such as forest regrowth after a disturbance, a young fallow in the shifting cultivation cycle or even a pasture. But if it is surrounded by burnt plots and forest, it is probably a young fallow in a shifting cultivation system. Thus, two steps are needed to derive landscape types from land cover data: identification of land cover patterns, or mosaics, and their contextual interpretation.

Hett, Castella, Heinimann, Messerli, and Pfund (2012), studying shifting cultivation in northern Laos, further developed this approach in two ways: using a hierarchical decision tree to classify landscape types, and analysing change by comparing landscape mosaic maps of two points in time. This addressed a problem associated with studying shifting cultivation landscapes. These landscapes, consisting of cultivated plots in a matrix of fallows at different regrowth stages, with the location of each plot changing every year, are difficult to delineate with pixel-based approaches. The following sections show how we applied the landscape mosaic approach developed in Laos to the context of north-eastern Madagascar to describe and quantify landscape types.

For the first step, we used a moving window technique in ArcGIS to provide every pixel in the land cover map with information about the composition of neighbouring pixels, with the size of the neighbourhood (and moving window) set to reflect the average area influenced by an individual land user. Based on interview data, we assessed the range of influence of land users at a maximum of about 2.5 km from the home village. We therefore set the size of the moving window to 5×5 km. The proportion of each land cover class on the total 25 km^2 neighbourhood area was attributed to the pixel (equivalent to 30×30 m of land) at the window centre.

In the second step, the land cover mosaics were interpreted in order to extract information on land use (Messerli et al., 2009) at a larger scale. This interpretation took into account the socio-ecological context (as established in extensive field studies by the authors) and was guided by two land use issues that are important for conservation and development in the region:

1. *Intensity of staple crop cultivation:* Land users in the study region rely heavily on the cultivation of subsistence rice, as the income from cash crops is highly variable and market accessibility low. Therefore, the presence or absence of rice fields is a reliable indicator of agricultural land use in this region. We use the term *intensification* to describe a change in land use from shifting cultivation to irrigated rice production and the term *extensification* for the opposite process. Intensification and extensification can also occur within a single land use system—for example, by changing fallow duration in shifting cultivation systems or the number of times irrigated rice is cultivated per year—but these are not detected through our approach.
2. *Proportion of tree cover:* While at the global level the forests of north-eastern Madagascar are highly valued for the benefits of carbon sequestration and biodiversity maintenance (Holmes et al., 2008; Kremen et al., 2000), local land users value the forests primarily as potential future agricultural land (Keller, 2008) and as a source of goods necessary for their well-being (Golden, Bonds, Brashares, Rasolofoniaina, & Kremen, 2014; Urech et al., 2011). The high international demand for precious woods and their illegal exploitation (Schuurman & Lowry, 2009) adds another challenge to forest maintenance. Tree cover exists not only in forests but also on smallholders' cultivated land. Clove trees (*Syzygium aromaticum*) provide the main cash crop, and many other tree species such as lychee (*Litchi chinensis*), breadfruit (*Artocarpus altilis*) and jackfruit (*Artocarpus heterophyllus*) deliver important food supplements (Pfund et al., 2011).

A matrix of landscape types, based on these two land use issues, was developed (Fig. 2). The criteria describing each of the landscape types were translated into conditional statements executed in ArcGIS. Two maps were generated, with every pixel in the land cover map assigned, first, to one of five classes of staple crop cultivation, and second, to one of three classes of tree cover, depending on the composition of land cover classes in its neighbourhood. Finally, the two maps were intersected to produce one map with all 15 landscape types.

Along the gradient of staple crop intensity, we classified pixels as follows:

- Those without either burnt plots or flooded vegetation in their neighbourhoods were classified as *no staple crop.* This landscape type contains only forest and medium- and low-height vegetation.
- A strong domination of burnt plots over flooded vegetation was classified as *shifting cultivation.* A threshold of 95:5 was chosen to allow for the presence of single pixels resulting from wrongly classified flooded vegetation in the land cover map.
- A strong domination of flooded vegetation over burnt plots was classified as *paddy cultivation*, with the same threshold.
- The remaining area, which contained both shifting and paddy cultivation, was classified as *mixed shifting* or *mixed paddy* depending on whether burnt plots or flooded vegetation, respectively, predominated.

Along the tree cover gradient, we classified pixels as follows:

- Those for which forest covered more of their neighbourhoods than either medium- or low-height vegetation were classified as *forest dominated.*
- The remaining pixels were classified as *high-intensity tree crop* if their neighbourhoods' share of medium-height vegetation was higher than the average for the entire analysed area, and otherwise as *low-intensity tree crop.* These two labels were deemed adequate because the medium-height vegetation in the area consists mainly of clove and fruit trees (Zaehringer et al., 2015).

The resulting landscape mosaic maps represent aggregated land use information at the landscape level. Pixels featuring a similar composition of land cover categories in their neighbourhood are classified as the same landscape type. For landscape-level assessments in general, an error assessment is not possible. However, single pixel classification errors in the land cover maps used as an input do not weigh.

The land cover maps contained substantial areas for which no data were available due to cloud cover. Thus, if a pixel's 5×5 km neighbourhood contained more than 70% "no data" pixels, the pixel was classified as "no data" in the landscape mosaic map as well. The no-data area in the landscape mosaic map covered about 15% of the total study region. The remaining area amounted to 20,507 km^2 and is referred to in this article as the analysed area.

2.4. Analysing landscape change

The landscape mosaic approach enables the detection of changes affecting entire land use systems instead of single land cover pixels. This is particularly useful when investigating changes

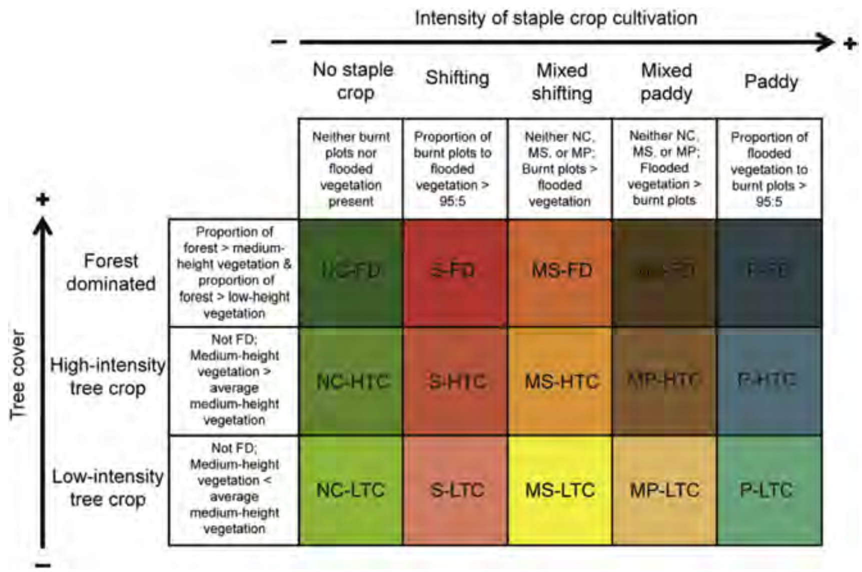

Fig. 2. Landscape types categorized by staple crop intensity and tree cover. (FD = forest dominated, HTC = high-intensity tree crop, LTC = low-intensity tree crop, NC = no staple crop, S = shifting, MS = mixed shifting, MP = mixed paddy, P = paddy).

in shifting cultivation systems, characterized by annual rotations of crop fields and fallows. In a land cover change map, such dynamics would appear on single pixels as year-to-year deforestation and regrowth. In contrast, using the landscape mosaic approach, such changes inherent to the character of a shifting cultivation land use system will not appear. This allows for the monitoring of overall changes between shifting cultivation and other land use systems over time. To analyse landscape change, we classified transitions from one landscape type to another according to changes in staple crop intensity and tree cover (Fig. 3). Change processes were then quantified by overlaying the landscape mosaic maps from 1995 to 2011 in ArcGIS.

A change towards more irrigated rice cultivation was termed *land use intensification*, whereas the opposite process was termed *land use extensification*. Changes from areas without staple crop cultivation to any intensity of staple crop cultivation were termed *new staple crop cultivation*. *Abandonment of staple crop cultivation* was considered to have occurred when areas formerly cultivated with staple crops no longer showed signs of cultivation. Whenever *low-intensity tree crop* changed to *high-intensity tree crop* or *forest dominated,* we considered this an *increase in tree cover,* and *loss of tree cover* occurred if the opposite was the case.

3. Results

3.1. Current landscapes in the study region

While the pixel-level differentiation between land cover classes makes it hard to visually apprehend different agricultural categories on the land cover map, the landscape mosaic map makes it easy to distinguish them (Fig. 4).

While in 2011, about half of the analysed area had forest-dominated tree cover, all but about 7% showed signs of at least some agricultural use, e.g. single shifting-cultivation plots (Fig. 5). Although forest cover was still widespread in 2011 (see Fig. 4, left), much of it existed in fragments smaller than 5 × 5 km, dispersed throughout the study region. Large continuous forest areas without any sign of agricultural use were limited to the core zones of Masoala and Makira protected areas in the north of the study region. The other two tree cover categories, high- and low-intensity tree crops, only existed in combination with staple crop production and covered 35% and 13% of the analysed area, respectively.

Landscapes where rice was produced only through shifting cultivation covered only 3% of the analysed area in 2011. These landscapes were almost exclusively forest dominated and encircled the forest-dominated landscapes without staple crop production, mainly in the Makira Natural Park and along the eastern border of Masoala National Park. Mixed agricultural landscapes dominated by shifting cultivation were common and covered the interior of the study region towards the highlands. They were mostly forest dominated, especially in the northern part of the study region. Almost half of the study region was covered with mixed agricultural landscapes dominated by paddy rice production. In terms of vegetation cover, these landscapes were about equally dominated by forest and high-intensity tree crops. While the mixed paddy landscapes dominated by forest were common surrounding the protected areas, the ones dominated by high-intensity tree crops occurred all along the coast between the cities of Maroantsetra and Fénérive Est. Landscapes entirely based on paddy rice production were only present in 8% of the analysed area and limited to the plains around Maroantsetra and Mananara Nord and along the western border of Masoala National Park. While in the plains they were associated with high-intensity tree crops, along the protected area boundary they were forest dominated.

3.2. Landscape change from 1995 to 2011

In 1995, forest-dominated landscapes without any sign of staple crop cultivation were still quite widespread in the northern part of the study region. By 2011 they had decreased considerably, especially in the southern part of what today is the Makira Natural Park. The edges of the Masoala National Park were dominated by shifting cultivation in 1995, which had intensified into mixed paddy cultivation by 2011. In 1995, the middle part of the study region was covered with forest-dominated, mixed shifting cultivation landscapes. In this area from 1995 to 2011 the main change was a degradation of tree cover, which also occurred in mixed paddy cultivation landscapes in the southern part of the region (Fig. 6).

In general, between 1995 and 2011, landscapes with no staple crop production and landscapes based entirely on shifting

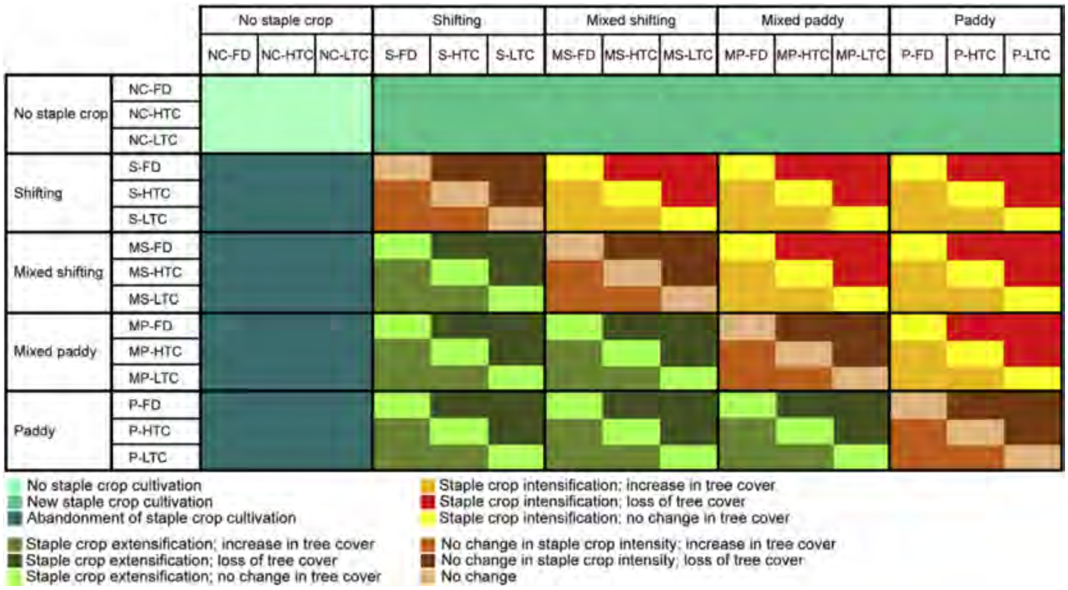

Fig. 3. Classification of landscape change processes based on the matrix of landscape types. (FD = forest dominated, HTC = high-intensity tree crop, LTC = low-intensity tree crop, NC = no staple crop, S = shifting, MS = mixed shifting, MP = mixed paddy, P = paddy).

cultivation decreased, while the mixed and paddy-based landscapes increased (Fig. 6). Mixed landscapes had already covered by far the largest share of the study region in 1995. Forest-dominated landscapes decreased for all levels of staple crop intensity.

Mixed shifting cultivation landscapes with a high intensity of tree crops experienced the greatest net increase. Mixed paddy landscapes with a low intensity of tree crops experienced the second largest net increase, followed by mixed shifting cultivation landscapes with a low intensity of tree crops. Large net decreases were experienced by forest-dominated landscapes, mainly those based on shifting and mixed shifting cultivation. The least human-influenced landscape type, forest-dominated landscapes without staple crop production, decreased. The small gain of forest-dominated landscapes without staple crop production that occurred elsewhere can be explained by single shifting cultivation rice fields established in the interior of the Masoala and Makira National Parks before 1995, which had disappeared by 2011. Some landscape mosaics that experienced small net changes, such as the mixed agricultural landscapes, experienced large "swaps" (simultaneous gains and losses occurring in different areas—Pontius, Shusas, & McEachern, 2004). The most stable landscape type in terms of both net change and swap was the mixed paddy landscape dominated by high-intensity tree crops.

The forest-dominated landscapes without staple crop cultivation were transformed mainly into mixed shifting cultivation landscapes (Fig. 7). Shifting cultivation and mixed shifting cultivation landscapes were both changed into mixed paddy landscapes, while forest remained the dominant tree cover. The opposite change, from mixed paddy to mixed shifting cultivation, was also common and occurred mainly in forest-dominated landscapes. Forest-dominated paddy-based landscapes mainly experienced a change into mixed paddy landscapes. Within mixed shifting cultivation and mixed paddy landscapes, degradation of tree cover from forest to high- or low-intensity tree crop or from high-to low-intensity tree crop was very common. The change from mixed shifting cultivation to mixed paddy landscapes was often associated with an increase in tree cover from low-to high-intensity tree crop. The same was true within mixed shifting cultivation landscapes where the change from low-to high-intensity tree crop was widespread.

3.3. *Intensification and extensification*

To better understand the importance of different landscape change trajectories, we aggregated the transitions between single landscape types (Fig. 7) according to the schema presented in Fig. 3. About one-third of the analysed area did not undergo any landscape change from 1995 to 2011 (Fig. 8). By far the most common change was staple crop intensification (more irrigated rice paddies or fewer shifting cultivation plots) without any change in tree cover. This occurred primarily around the Masoala National Park in the north of the study region as well as in the coastal area around Soanierana Ivongo. No change in staple crop intensity but a loss of tree cover was the second most common change trajectory, mainly observed towards the western border of the study region. Staple crop extensification (more shifting cultivation plots or fewer irrigated paddies) was also observed in the interior of the region towards the highlands as well as along the southern edge of Makira Natural Park, with and without loss of tree cover. Most new staple crop cultivation occurred in forest-dominated areas in the south-western part of Makira Natural Park. Other landscape change trajectories were less common.

4. Discussion

4.1. *Delineating shifting and permanent cultivation systems*

Landscapes in which rice is produced only through shifting cultivation were rare in 2011 and limited to forested areas, mainly in Makira Natural Park. These areas are hotspots of pioneering shifting cultivation (Castella et al., 2012), where people acquire agricultural land by establishing rice fields in forests. For many land users in our study region, this is still the only way to secure land for their families and descendants (Keller, 2008). While in 1995 the borders of the Masoala forest were dominated by pioneering shifting cultivation, these areas had transformed into mixed paddy landscapes by 2011. However, shifting cultivation is still present in 85% of the study region (see Fig. 5).

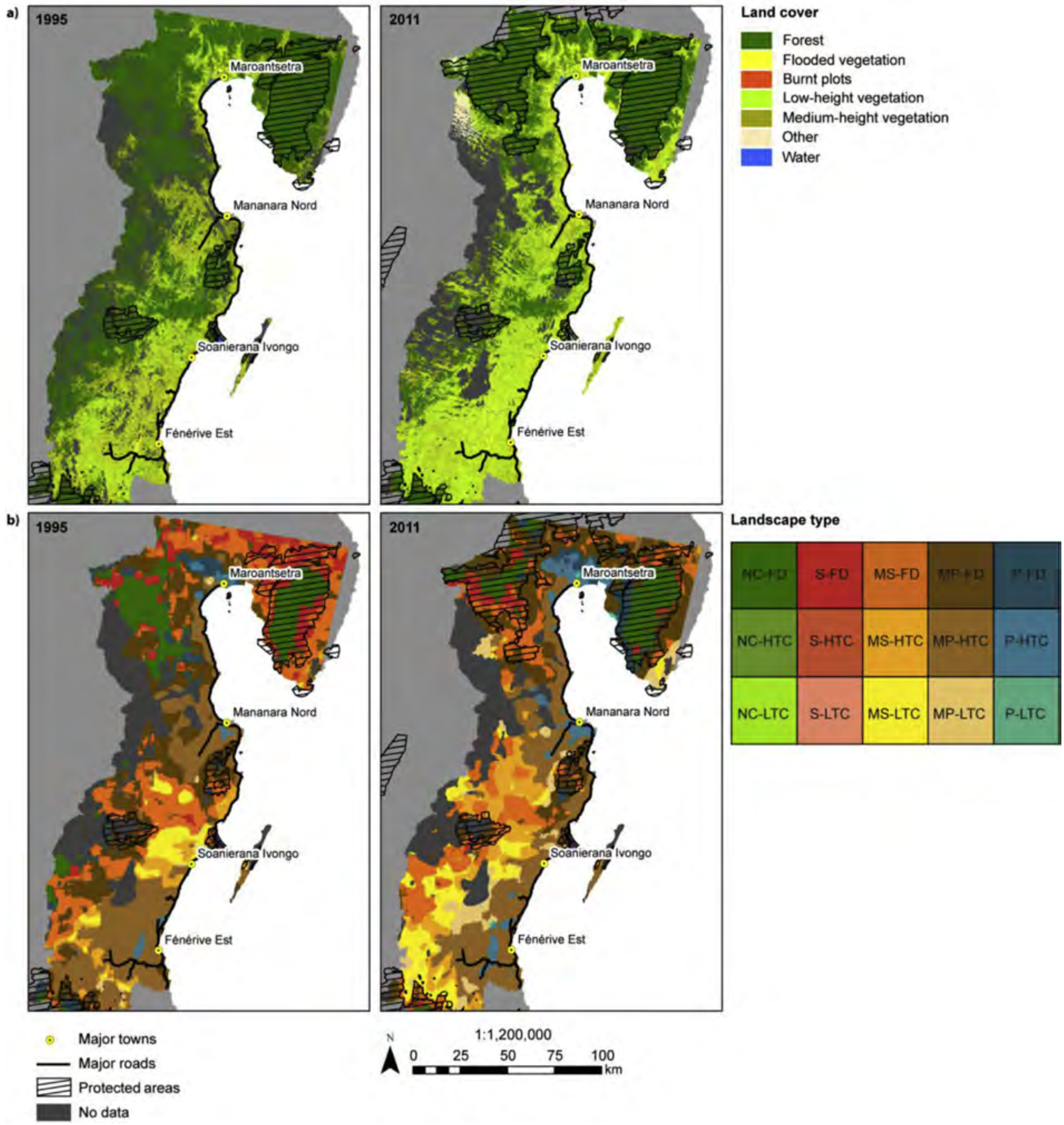

Fig. 4. a) Land cover maps (adapted from Zaehringer et al., 2015) and b) landscape mosaic maps for 1995 and 2011. (FD = forest dominated, HTC = high-intensity tree crop, LTC = low-intensity tree crop, NC = no staple crop, S = shifting, MS = mixed shifting, MP = mixed paddy, P = paddy).

Mixed land use, in which rice is produced through both shifting and paddy cultivation, predominates in north-eastern Madagascar. More than 80% of the region is still characterized by a high tree cover that includes both forests and planted fruit trees. This reflects the diverse local strategies to use available labour and land resources to produce as much rice for subsistence as possible as well as cash crops such as clove and vanilla (Brimont et al., 2015; Cullman, 2015; Locatelli, 2000; Urech et al., 2011). Diversification reduces vulnerability to crop loss during cyclones, which are common in this region (Birkinshaw & Randrianjanahary, 2007; Harvey et al., 2014). Towards the coast, these mixed systems are dominated more by irrigated rice production than by shifting cultivation. This is probably a result of both flatter topography, which facilitates the establishment of irrigated paddies, and better access to major towns. The transformation from forests to agricultural land began in the coastal areas. From there, the deforestation frontier, dominated by shifting cultivation, has gradually advanced towards the interior. Coastal mixed paddy landscapes are characterized by a dense cover of tree crops, primarily clove, coffee and lychee. Pure paddy cultivation has increased since 1995 and now covers the plains around the district capitals of Maroantsetra and Mananara Nord.

An area without urban centres and large floodplains where paddy rice cultivation nonetheless flourishes is the western boundary of Masoala National Park in the Ambanizana River valley; in 2011 only paddy rice was produced in this area. This might be due to greater law enforcement by park wardens due to the area's relative ease of access from Maroantsetra compared to other parts of the Masoala peninsula. Land users in Ambanizana are aware of the heavy fines for slashing and burning vegetation inside the

Intensity of staple crop cultivation (– → +); Tree cover (– → +)

	No staple crop	Shifting	Mixed shifting	Mixed paddy	Paddy	Total
Forest dominated	7	3	17	21	4	52
High-intensity tree crop	0	0	9	22	4	35
Low-intensity tree crop	0	0	8	5	0	13
Total	7	3	34	48	8	

Fig. 5. Landscape types as percentage of total analysed area in 2011.

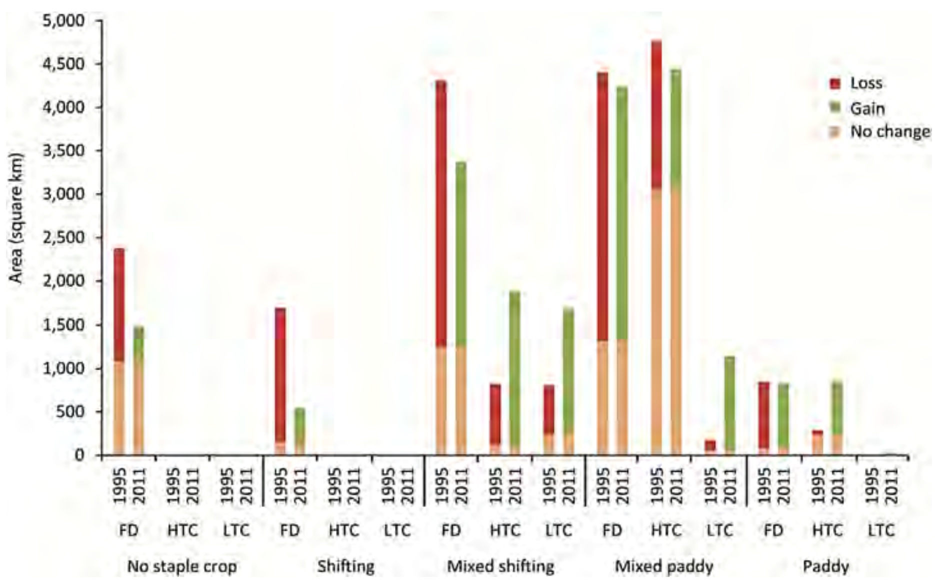

Fig. 6. Stable areas, losses and gains in area for each landscape type, 1995 to 2011. The difference between the heights of the bars within each landscape type represents net change whereas overlapping losses and gains represent swap change. Where there is no value, the landscape type did not exist in the respective year. (FD = forest dominated, HTC = high-intensity tree crop, LTC = low-intensity tree crop).

protected area (Keller, 2008) and might therefore abstain from shifting cultivation. Although from the point of view of the national park management this might present a favourable outcome, it should not be regarded as a sustainable solution to curb deforestation, as in moments of reduced law enforcement land users are likely to continue clearing land. Further, the prohibition for land users to produce rice through shifting cultivation on their ancestral land, now included in the national park, has reportedly driven affected families deeper into poverty (Keller, 2015). In other locations in the cores of the protected areas of Makira and Masoala, staple crop cultivation has been abandoned altogether. However, these forests face other considerable threats as well, such as the illegal harvest of rosewood for the international market (Caramel, 2015; Randriamalala & Liu, 2010; Schuurman & Lowry, 2009).

4.2. Evidence of intensification

Staple crop intensification (a move from shifting to paddy cultivation) without a change in tree cover was the most common change in the study region between 1995 and 2011. This took place mainly in the surroundings of the Masoala National Park. We therefore hypothesize that intensification was induced by the restricted access to new land for shifting cultivation. This could be considered a desired outcome of the protected-area strategy (Phalan, Onial, Balmford, & Green, 2011). The second most common change, which occurred throughout the interior and more remote part of the region, was the loss of tree cover while staple crop production remained stable. As the two change processes of staple crop intensification and loss of tree cover hardly occurred together, this indicates that trade-offs between more intensive staple crop production and the maintenance of tree cover at the landscape level were limited. An exception was observed on the southern tip of the Masoala peninsula though, where intensification occurred with simultaneous vegetation degradation from forest to low-intensity tree crops. Such a change process at landscape level away from shifting cultivation towards more irrigated rice production might have various consequences for ecosystem service provision, for example with respect to carbon sequestration, as long-fallow shifting cultivation could raise carbon stocks at the landscape level (Mertz et al., 2009). While tree cover remains high

			2011														
			No staple crop			Shifting			Mixed shifting			Mixed paddy			Paddy		
			FD	HTC	LTC	FD	HTC	LTC	FD	HTC	LTC	FD	HTC	LTC	FD	HTC	LTC
1995	No staple crop	FD	1,087	0	0	279	0	0	531	0	3	394	0	2	81	0	0
		HTC	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		LTC	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Shifting	FD	289	0	0	149	[illegible]	[illegible]	356	4	1	687	24	16	175	0	0
		HTC	0	0	0	0	0	[illegible]	0	1	0	0	2	0	0	0	0
		LTC	0	0	0	0	0	0	0	3	0	0	1	0	0	0	0
	Mixed shifting	FD	22	0	0	30	0	[illegible]	1,245	[illegible]	[illegible]	1,537	139	131	265	1	0
		HTC	0	0	0	0	0	[illegible]	0	120	[illegible]	0	429	87	0	0	0
		LTC	0	0	0	0	0	0	0	332	244	4	157	72	0	0	0
	Mixed paddy	FD	16	0	0	47	0	1	1,017	[illegible]	[illegible]	1,318	[illegible]	[illegible]	223	32	10
		HTC	0	0	0	0	0	[illegible]	0	381	[illegible]	13	3,062	[illegible]	4	468	7
		LTC	0	0	0	0	0	0	0	26	24	0	60	58	0	4	2
	Paddy	FD	70	0	0	37	0	[illegible]	222	[illegible]	1	282	[illegible]	[illegible]	83	[illegible]	[illegible]
		HTC	0	0	0	0	0	[illegible]	0	0	[illegible]	0	39	[illegible]	0	238	[illegible]
		LTC	0	0	0	0	0	0	0	0	0	0	0	0	0	2	1

FD = forest dominated; HTC = high-intensity tree crop; LTC = low-intensity tree crop.

Fig. 7. Landscape type transitions in the analysed area (km^2), 1995 to 2011.

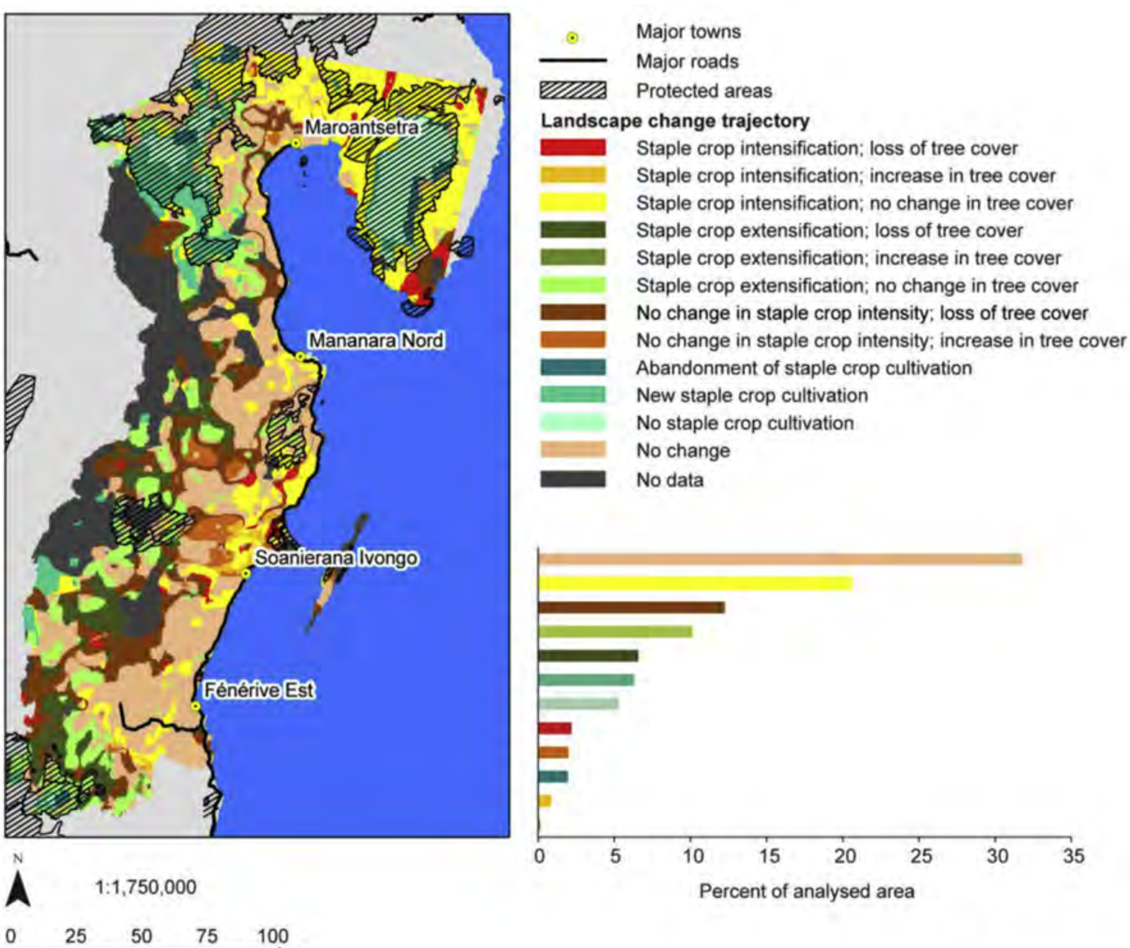

Fig. 8. Detailed landscape change trajectories in the study region and in percent of total analysed area, 1995 to 2011.

in most of the region and landscapes still contain many semi-natural features such as forest fragments and agroforests, a reduction of tree cover might be the next step following the intensification of staple crop cultivation.

At least at the regional level, the observed intensification at landscape level seems to contradict the common narrative (Kull, 2000) that population growth and increased poverty lead to increased shifting cultivation and thus deforestation. While population in the Analanjirofo region increased by about 54% from 1995 to 2011 (Institut National de la Statistique de Madagascar, 2011), the share of the poor rural population in Madagascar (based on the national poverty line) increased from 70.8% to 75.3% between 2001 and 2010 (World Bank, 2015). Our findings rather support the observations by Kull (1998) in the Malagasy highlands and Laney (2002) in the Andapa Valley that when access to resources is constrained, population increase can lead to intensification rather than degradation of agricultural land.

4.3. Potential of the landscape mosaic approach for land use planning in Madagascar

The landscape mosaic approach allowed us to delineate shifting cultivation and permanent land use systems using basic land cover information. With this approach, although the precise land cover at the location of each single pixel is lost, knowledge is gained about land use by interpreting the spatial combination of different land cover pixels within a defined neighbourhood. Land use patterns delineated in this way are also easier to see than those in a standard land cover map (see Fig. 4).

North-eastern Madagascar is one of the key priorities for conservation in the country and hosts the first REDD + project in Africa, which generates revenues from government-owned carbon credits (Brimont et al., 2015). In this context, it will be crucial to monitor changes in land use and to understand the effects of these interventions on both agricultural intensification and reforestation. The landscape mosaic approach enables identification of hotspots of land use change and thus provides evidence on which land use planning and forest conservation can build.

5. Conclusion

Using the landscape mosaic approach, we revealed hotspots of shifting cultivation and a trend towards staple crop intensification in north-eastern Madagascar. Shifting cultivation is still an important livelihood strategy, present to some degree in about 85% of the region. This regional-level evidence adds to the scarce existing knowledge on the trajectories of shifting cultivation from local-level case studies in this biodiversity hotspot. From our analysis we can conclude that (1) in north-eastern Madagascar today, mixed shifting and permanent paddy rice cultivation predominate, with a relatively high cover of tree crops, (2) areas where rice was produced only through shifting cultivation have almost disappeared since 1995 and (3) intensification from shifting to paddy cultivation has been the most common change since 1995 and has occurred mainly in the vicinity of protected areas. Landscapes without any obvious agricultural activities and with continuous forest cover are limited to the core zones of the two largest protected areas, Masoala and Makira. To protect the forests while simultaneously increasing local land users' well-being, it is necessary to better understand the socio-ecological systems that shape these landscapes. In particular, factors influencing land users' access to and ability to cultivate irrigable land need to be recognized and considered in planning. Although we saw that mixed agricultural landscapes prevail, we do not know how great a proportion of land users are pursuing mixed rice cultivation and how many continue to depend fully on shifting cultivation. This knowledge will be crucial to developing conservation and development interventions that benefit all land users equally and thus help prevent the further conversion of forest to agricultural land.

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Paper IV: Navigating conservation–development trade-offs in biodiversity hotspots: landscape types, ecosystem services, and livelihoods in north-eastern Madagascar

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Navigating conservation–development trade-offs in biodiversity hotspots: landscape types, ecosystem services, and livelihoods in north-eastern Madagascar

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Abstract

Through ongoing deforestation in the tropics, forest-related ecosystem services are in decline, while ecosystem services provided by agricultural land uses are on the increase. Land system science provides a framework for analysing the links between land use change and the resulting socio-environmental trade-offs. However, the evidence base to support the navigation of such trade-offs is often lacking, as information on land use cannot directly be obtained through remote sensing and census data is often unavailable at sufficient spatial resolution. The global biodiversity hotspot of north-eastern Madagascar exemplifies these challenges. Integrating land use data obtained through remote sensing with socioecological data from a regional level household survey, we attempt to make the links between land use and ecosystem service benefits explicit. Our study confirmed that remotely sensed information on landscapes reflects households' involvement in shifting cultivation and irrigated rice production. We further characterized landscapes in terms of ecosystem service bundles linked to specific land uses as well as in terms of key ecosystem service benefits to households. Such spatially explicit evidence is required to support the navigation of conservation–development trade-offs in this global biodiversity hotspot.

1 Introduction

Despite decades of international conservation efforts, tropical forests are still shrinking to make way for agricultural land (Hansen et al., 2013; Malhi, Gardner, Goldsmith, Silman, & Zelazowski, 2014). The loss of these important reservoirs of biodiversity and biomass has numerous repercussions for the provision of ecosystem services (ES) to both local and distant human populations (Costanza et al., 2014; Foley et al., 2005). Adopting a sustainability perspective, land system science seeks to understand the links between human activities, land use change, and the resulting socio-environmental trade-offs (Reenberg, 2009; Turner II, Lambin, & Reenberg, 2007; Verburg et al., 2015). Environmental and agricultural policy and decision-making takes place at different administrative scales beyond the local context. Therefore, knowledge on human-environmental interactions needs to be generalizable to serve specific planning needs at those scales, without oversimplifying highly complex and context-specific socioecological dynamics (Magliocca et al., 2014). A major challenge of land system science, however, pertains to the difficulty of using remotely sensed land cover information to infer land use and its links to actors' well-being (Verburg, van de Steeg, Veldkamp, & Willemen, 2009). While in spatial analysis new approaches for generalization and upscaling exist that allow a better representation of land use (e.g. Hett, Castella, Heinimann, Messerli, & Pfund, 2012; Messerli, Heinimann, & Epprecht, 2009; Zaehringer, Eckert, & Messerli, 2015), they reveal only one side of the larger picture regarding the linkages between land use and human well-being. The integration of spatially explicit land use data with social science information at regional to national level is crucial for the advancement of land system science (Rindfuss et al., 2007). So far, few examples exist from developing countries: the unavailability of census data at sufficient spatial resolution usually presents a major obstacle to such an endeavour. To tackle this challenge for the biodiversity hotspot of north-eastern Madagascar (Ganzhorn, Lowry, Schatz, & Sommer, 2001; Myers, Mittermeier, Mittermeier, da Fonseca, & Kent, 2000), we collected primary data through a regional level household survey to make explicit the links between land use and ES benefits.

The ES concept was proposed almost two decades ago to frame the connections between land use and human well-being (Costanza et al., 1997; Daily, 1997). Despite its holistic focus and widespread application since the Millennium Ecosystem Assessment (MEA, 2005), the concept has shown several weaknesses in terms of understanding the linkages between natural resources and human well-being (e.g. Dawson & Martin, 2015; Villamagna & Giesecke, 2014). Especially in a developing-country context, where poverty alleviation is a major objective of sustainable development planning, we see the following as the most important weaknesses in ES research: 1) Often, only single ES are selected for assessment based on researchers' main interest and data availability. In tropical forest regions, where ES research is often steered by land managers concentrating on biodiversity conservation, many studies focus on forests as a single land use type (for Madagascar e.g. Brown et al., 2013; Kari & Korhonen-Kurki, 2013; Kramer, Richter, Pattanayak, & Sharma, 1997; Wendland et al., 2010). However, especially in multifunctional tropical landscapes, human well-being depends on a range of land use activities and ES, and the interactions between them. To generate meaningful knowledge for the negotiation of trade-offs between conservation and human well-being, we should therefore try to embrace the whole set of land uses and ES linked to them. 2) A single ES can have various different values to different land users based on its contribution to their well-being (Daw, Brown, Rosendo, & Pomeroy, 2011; Jax et al., 2013). This means that a single focus on monetary valuation in ES assessments limits our understanding of the multiple demands that influence local land users' decision-making in terms of land use and management (Turnhout, Waterton, Neves, & Buizer, 2013).

3) Aggregating land users, their socio-economic characteristics, and demands for ES over landscape or regional scales impedes the development of strategies directed at lifting people out of poverty (Dawson & Martin, 2015; Daw et al., 2011; Fisher et al., 2013). People value ES differently, and their ability to benefit from a specific service – and thus its potential contribution to poverty alleviation – depends on their endowments and entitlements (Leach M., Mearns R., & Scoones I., 1999).

While in many regions the drivers of deforestation have changed from local smallholders' subsistence needs to globalized demands for food and energy crops (DeFries, Rudel, Uriarte, & Hansen, 2010; Gibbs et al., 2010; Lambin & Meyfroidt, 2011; van Vliet et al., 2012), the eastern coast of Madagascar presents a clear exception to this trend (Laney & Turner, 2015; Urech, Zaehringer, Rickenbach, Sorg, & Felber, 2015; Zaehringer et al., 2015). As global awareness of the importance of biodiversity conservation and carbon sequestration rose, so did attention of international conservation actors to Madagascar's tropical forests (Kull, 2014; Kull, Ibrahim, & Meredith, 2007). Although its assumptions have been questioned (Vandermeer & Perfecto, 2007), the most common approach to slowing the conversion of forests into agricultural lands aims at intensifying smallholders' irrigated rice production. However, these landscapes feature highly diverse production systems, and thus the complex links between land use and smallholders' well-being must be understood, for any external interventions to be successful (Brimont, Ezzine-de-Blas, Karsenty, & Toulon, 2015; Messerli, 2004; Pollini, 2009; Poudyal et al., 2016).

The overall goal of this study is to establish a spatially explicit and comprehensive evidence base regarding land use and ES benefits for the biodiversity hotspot of north-eastern Madagascar. To achieve this goal we use a regional-level approach integrating information on landscape types, obtained through remote sensing and spatial analysis, with household survey data on ES perceptions. More specifically, we aim to answer the following three research questions:

(1) do different landscape types, classified through remote sensing, reflect households' involvement in shifting cultivation and irrigated rice production?

(2) do the bundles of ES linked to specific land uses vary across different landscape types?

(3) do different landscape types correlate with household types in terms of key ES benefits they obtain?

To conclude, we discuss the potential ES trade-offs related to the expected landscape change trajectories in the region.

2 Methods

2.1 Study region

Our study region in north-eastern Madagascar (Figure 2) features one of the world's most unique ecoregions in terms of endemic species of plants and animals. The humid forests, representing some of the last remaining continuous surfaces of this vegetation type in Madagascar, are still under threat due to agricultural expansion and the international rosewood trade (Ganzhorn et al., 2001; Myers et al., 2000; Schuurman & Lowry, 2009). Several protected areas have been established to promote biodiversity protection, the two largest and most recent of which are the Masoala National Park (est. 1997) and Makira Natural Park (est. 2005). For our analysis we chose the administrative region of Analanjirofo, as this represents the level at which decisions on agricultural and infrastructural development are taken. However, we also added the part of the Masoala peninsula belonging to the

Sava administrative region, due to the pronounced global interest in the conservation of this biodiversity hotspot.

North-eastern Madagascar is characterized by a hot and humid climate with an average temperature of 24°C and about 3,600 mm of rainfall per year (Jury, 2003). Population in Analanjirofo increased by about 54% from 1995 to 2011 and was estimated at nearly 1 million people in 2011 (INSTAT, 2011). Mean annual income from agriculture was about US$ 292 per household and the share of poor people (based on the national poverty line) was estimated at 63.5% in 2013 (INSTAT, 2014).

Rice production is at the very centre of life in the culture of the local Betsimisaraka population. Similar to the Tsimihety ethnic group in the Andapa valley studied by Laney et al. (2015), the Betsimisaraka apply a diverse production system. They produce hill rice through shifting cultivation and permanent irrigated paddy rice for subsistence; in addition, they grow a number of commercial cash crops. However, while land users in the Andapa valley mainly rely on vanilla and coffee for income generation, in our study region clove is the main cash crop. Prices paid for these cash crops show high inter-annual variability and thus create a lot of uncertainty for local land users (FAO, 2014). Zebu cattle are an important asset needed for the ploughing of irrigated rice and are of important spiritual value. While large contiguous forests today are restricted to the core zones of protected areas, smaller forest fragments are dispersed throughout the agricultural matrix.

Agricultural land is managed through a complex system of mixed family- and individual-based rights. Land for rice production through shifting cultivation is managed at the extended family level, with plots allocated to individual households by family elders (Urech, Rabenilalana, Sorg, & Felber, 2011). Converting forest into agricultural fields is one of the few ways for family elders to bring additional land into production and thus assure food security for their descendants (Keller, 2008). Irrigated rice paddies and plots for cash crop cultivation are usually managed at the household level and passed on from parents to their children. New arrivals can rent or purchase such lands upon the approval of village authorities (Messerli, 2004).

2.2 Conceptual framework

To frame the link between land use and benefits to households we used the cascading ES model as proposed by Haines-Young and Potschin (2010) and adapted by de Groot et al. (2010). As we aimed at a comprehensive assessment of ES at landscape level, ES linked to agricultural land uses played a major role. We conceptualized the ES actively used by households as ES benefits (Figure 1). As highlighted by Zhang et al. (2007), in our study some ES provided by a certain land use can be important for the functioning of another land use (Figure 1). For example, the ES of water regulation provided by forests was also an important ES to irrigated paddy rice production. We assessed the perception of those ES by asking land users about the constraints related to a certain land use and conceptualized them as indicating an unfulfilled demand for ES.

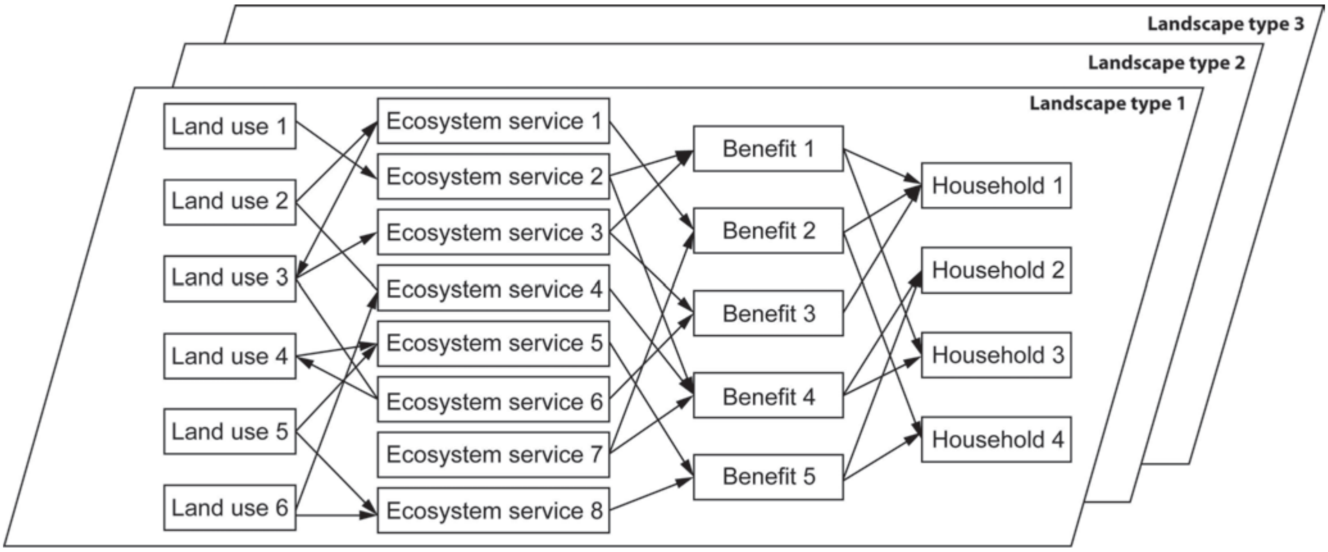

Figure 1. Conceptual framework to link land use with ES, ES benefits, and households. Different land uses provide ES while at the same time requiring ES provided by other land uses. One land use can provide several ES; one ES can have several benefits; and different households can obtain different benefits from the same ES.

2.3 Remotely sensed information on land use

We used a landscape mosaic approach to address the challenge that land cover information at the level of single pixels, obtained from satellite imagery, cannot be directly linked to peoples' land use activities at a larger scale (Hett et al., 2012; Messerli et al., 2009; Zaehringer, Hett, Ramamonjisoa, & Messerli, 2016). To circumvent this problem, pixel-based land cover information must be interpreted taking into account the local context – i.e. the land cover information of surrounding pixels. If viewed in isolation, we cannot determine whether a pixel of low-height vegetation in a land cover map represents a shifting cultivation fallow, or forest regrowth after a disturbance. Only if we know that the pixel has burnt plots (fields prepared for hill rice cultivation) in its vicinity, we can assume that it represents a young fallow in a shifting cultivation system. The landscape mosaic approach first analyses the composition of neighbouring pixels for each pixel in a land cover map using a moving window approach in Arc-GIS, and then classifies the different compositions into landscape types.

To spatially represent land use at the scale of our 20,507 km^2-large study region, we used a landscape mosaic map of 2011, developed by Zaehringer et al. (2016). The landscape mosaic map describes the entire region in terms of five different landscape types, based on their degree of staple crop intensity, which was determined as follows:

- Pixels without either burnt plots or flooded vegetation (representing irrigated rice production) in their neighbourhoods were classified as no staple crop.
- A strong domination of burnt plots over flooded vegetation was classified as shifting cultivation while the opposite was termed paddy cultivation.
- The rest of the region, which contained both shifting and paddy cultivation, was classified as mixed shifting or mixed paddy depending on whether burnt plots or flooded vegetation, respectively, predominated.

2.4 Socioecological data from household surveys

We collected socioecological data through a stratified sampling of 45 villages distributed among the three most common landscape types (based on staple crop intensity) in the study region: mixed shifting cultivation (MS), mixed paddy cultivation (MP), and paddy (P) landscapes (Figure 2). These three landscape types present a gradient of intensification from less to more intensive agricultural landscapes. Study villages were selected from an official administrative GIS layer (FTM, 1998) and distributed throughout the region, taking into consideration the challenge of extremely limited accessibility (villages were only accessible on foot). This is a semi-random sample, as no prior knowledge about these villages was available.

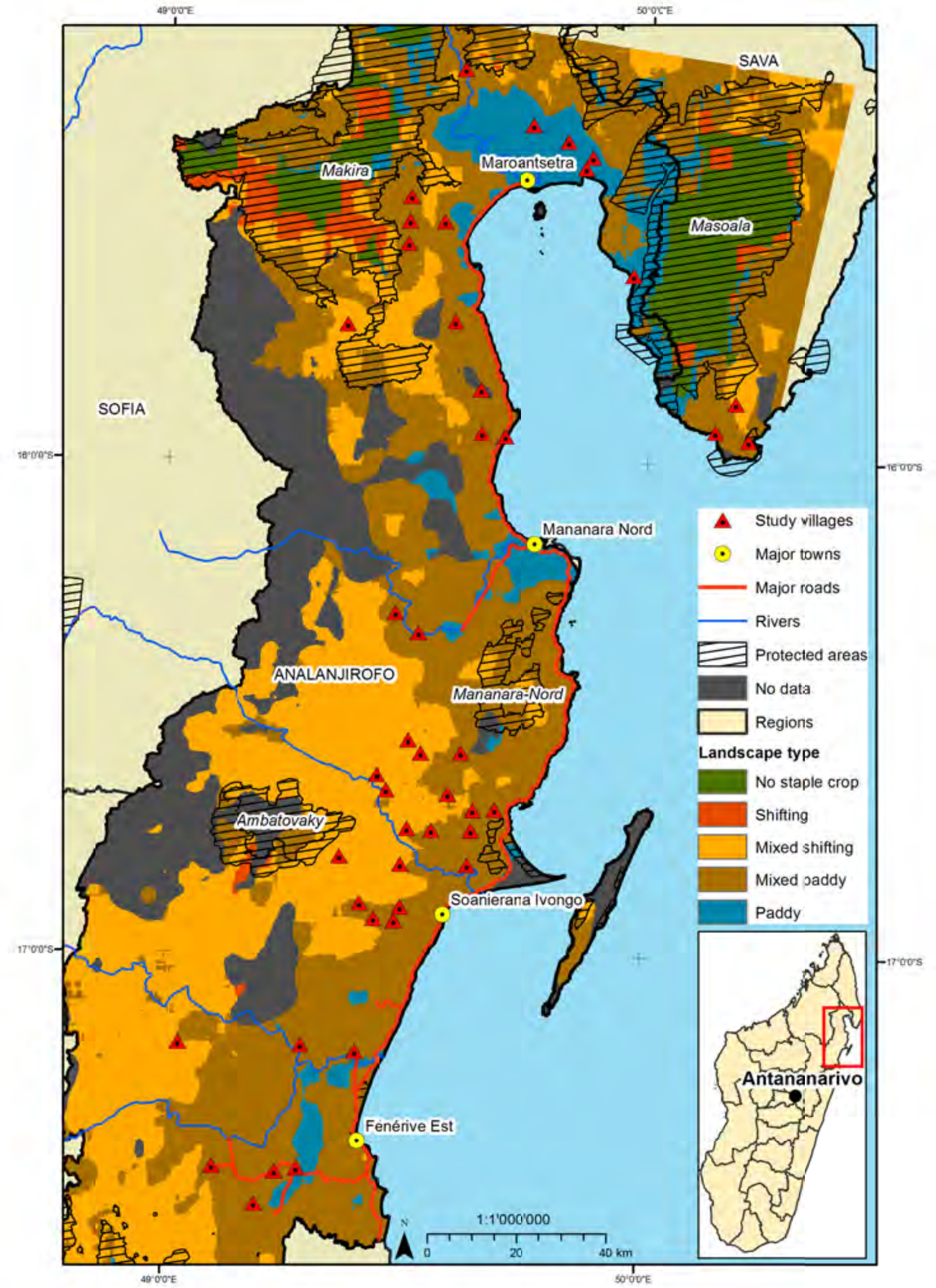

Figure 2. Distribution of study villages along the three main landscape types of mixed shifting, mixed paddy, and paddy-based landscapes in north-eastern Madagascar (adapted from [Zaehringer et al., 2016]).

Field research was conducted between November 2013 and March 2015 by the first author of this paper and a team of six research assistants. In each village we conducted face-to-face interviews with land users at household level, administering a standardized survey questionnaire. To develop the questionnaire, we conducted a first field mission to two villages excluded from the final sample, where we conducted semi-structured interviews with land users and village authorities to obtain a broad understanding of land use in the study region. The final questionnaire was structured according to the six distinct land uses present in the region: irrigated paddy rice fields; rain-fed hill rice plots and fallows (both of which are integral parts of shifting cultivation); agroforests; pasture; and forest. It further contained three general sections about socio-demographic characteristics, households' well-being, and development aspirations. The questionnaire included open questions to allow respondents to explain what benefits and challenges they associated with each land use activity, and why they did not engage in certain land use activities. Questions about quantifiable household resources (e.g. kg of rice harvested, number of zebus, and revenue from cash crops) were included to indicate differences in the socio-economic status of households. However, our survey did not represent a standardized socio-economic survey (e.g. The World Bank, 2016). We refrained from asking land users directly about ES, as we view the ES concept as a specific lens to examine the links between land use and human well-being, rather than a concept depicting land users' reality. Instead, our aim was to obtain a comprehensive understanding of households' land use activities and the associated benefits and challenges, and then frame the results according to the ES framework.

In each village, we interviewed on average 32% (but at least 10%) of households, resulting in a total of 1,187 interviews. As the village authorities had no comprehensive list of households, we proceeded with a semi-random selection of households. Along every row of houses in a village we sampled every second household, if people were present and willing to participate in the interview. The household member who stated having the most comprehensive understanding of the households' different land use activities was interviewed. Interviews lasted between 30 minutes and 3 hours, depending on the number of different land activities a household was involved in and the willingness of respondents to discuss. Interviews were held in the local Betsimisaraka dialect of Malagasy; respondents' answers were directly translated to French and recorded in writing. Interviews were later coded and transferred to an Excel database for statistical analysis.

2.5 Integration of spatially explicit land use information with socioecological data

Each sampled village was assigned to one of the three landscape types, depending on its spatially explicit location. For a characterization of the three landscape types we applied descriptive statistics on quantitative and qualitative coded information related to land use and ES in the R statistical software (R Core Team, 2015). More specifically, we tested for differences between the three landscape types using Wilcoxon-Mann-Whitney and Fisher's exact tests for numerical and categorical variables, respectively. For all variables we first controlled for differences at the level of villages before testing for differences between landscape types.

Table 1. Proportion of landscape types on total map area, villages, and households sampled

	Landscape type			Total
	Mixed shifting	Mixed paddy	Paddy	
Proportion of landscape type [%]	38	53	9	
Proportion of villages [%] (total no.)	25 (11)	64 (29)	11 (5)	100 (45)
Proportion of households [%] (total no.)	25 (297)	62 (727)	14 (163)	100 (1,187)

To develop a household typology in terms of key ES benefits, we considered the following quantitative variables, available for 1,184 of the 1,187 households: 1) duration of rice sufficiency in months, 2) rice production through shifting cultivation, 3) rice production through irrigated cultivation, 4) income from cash crops, 5) number of zebu cattle, and 6) number of forest products collected. Additionally, we included the variables of household size and the number of different land use activities which are pertinent to the characterization of households. We then conducted a hierarchical agglomerative cluster analysis using Ward's method and the Manhattan distance algorithm in R (R Core Team, 2015).

3 Results

3.1 Verification of remotely sensed landscape types with socioecological survey data

The three landscape types obtained through remote sensing are based on the different proportions of hill rice fields and irrigated paddy rice fields present in the landscape. Next, we will verify if the landscape types based on the analysis of satellite imagery correlate with information on rice production systems used by local households. In all landscape types over 95% of the interviewed households produce rice. In mixed shifting and mixed paddy landscapes, over 50% of households used both permanent irrigated and shifting cultivation to produce rice (Table 2). However, while in mixed shifting landscapes more than a third of households relied uniquely on shifting cultivation, in mixed paddy landscapes the opposite was true. In paddy landscapes almost all households obtained rice from irrigated fields only. While very few households also practiced shifting cultivation, no household relied uniquely on shifting cultivation. Rice sufficiency was significantly higher in paddy landscapes than in mixed paddy landscapes. On average households consumed their own rice during between 7.4 months in mixed paddy and 8.6 months in paddy landscapes. In all landscapes only about 40% of all households commercialized all or part of their rice production. The percentage of households always selling part of their rice was highest in paddy landscapes.

Table 2. Differences between landscape types regarding rice production systems

		Landscape type			Significance
		MS	MP	P	
Households producing rice [% HH]		96	98	99	ns
		(n=285)	(n=713)	(n=160)	
Rice production mode [% HH]	Shifting cultivation only	**35**	14	0	***
	Irrigated only	14	**31**	**96**	
	Shifting and irrigated	51	55	4	
Households are rice sufficient all year long [% HH]		22[ac]	18[a]	**26**[bc]	*
Mean duration of rice sufficiency [months] (SD)		(n=284) 8.5 (2.8)	(n=693) 7.4 (3.3)	(n=159) 8.6 (3.1)	ns
		(n=285)[ac]	(n=713)[b]	(n=160)[bc]	
Commercializing rice [% HH]	Always	21	16	**24**	*
	Sometimes	18	25	19	
	Never	61	59	57	
Mean quantity of rice produced per year and household [kg] (SD)		(n=285) 644 (403)	(n=700) 538 (433)	(n=154) 705 (505)	ns

Level of significance: ns p>0.05, *≤0.05, **≤0.01, ***≤0.001. Different superscript letters indicate pairwise significance. Values highlighted in the accompanying text are highlighted in bold. (MS=Mixed shifting, MP=Mixed paddy, P=Paddy, HH=Households, SD=Standard Deviation).

3.2 Characterization of landscape types in terms of ES bundles linked to land use

In this section we will go through each of the six land uses present in our region (see section 2.4) and compare the ES bundles linked to them in each of the three landscape types. For each land use we will consider the benefits households obtain from provisioning ES as well as their unfulfilled demand for regulating ES. As land users were asked about the benefits they associated with each land use through open questions, cultural ES were only mentioned in relation to forests.

ES bundles linked to irrigated paddy rice fields

The surface area of paddy rice fields per household seemed to be higher in paddy-based landscapes than in the other two landscape types, but the difference was not significant (Table 3). Irrigated paddy rice production was significantly more intensive in paddy landscapes, where 83% of households cultivated paddy rice twice per year, than in mixed shifting landscapes with only 58% of households doing so. In terms of benefits, the two provisioning ES of rice and fodder for zebu cattle were mentioned by the interviewed households. The quantity of rice produced in irrigated paddy fields was higher in paddy landscapes than in mixed shifting and mixed paddy landscapes. Irrigated rice paddies provided the main source of fodder for zebu cattle to 32% of zebu-owning households in mixed shifting landscapes (not shown in table). This was significantly lower in mixed paddy and paddy landscapes. From the perspective of households using irrigated rice fields, less than 10% used those fields as the main source of fodder for their zebu cattle.

The perception that soil fertility had declined since the start of cultivation was strongest in paddy landscapes (see Table 3). Water shortage was the main constraint to irrigated rice production in all landscape types and mentioned by a significantly higher percentage of households in paddy than in mixed paddy and mixed shifting landscapes. Animal pests (rats, birds, insects, and worms) were the second most important constraint in mixed shifting and paddy landscapes but significantly less important in mixed paddy landscapes. Weeds were a constraint in all landscape types, but perceived by a significantly higher proportion of households in mixed shifting than in mixed paddy landscapes. The lack of zebu cattle, which are important as draught animals for ploughing, was of similar importance in all landscape types. Floods were mentioned as a constraint primarily in paddy landscapes.

Table 3. Differences between irrigated paddy rice fields in three different landscape types in terms of their use, reported benefits from provisioning ES, and constraints indicating unfulfilled demand for ES

			Landscape type			
			MS	**MP**	**P**	**Significance**
Use of irrigated rice fields	Mean total surface area of irrigated rice fields per HH [ha] (SD)		(n=103) 0.7 (0.7)	(n=186) 0.9 (0.6)	(n=30) **1.4** (0.9)	ns
	Number of times irrigated rice cultivated per year [% HH]		(n=184)	(n=613)	(n=162)	***
		1	42	34	17	
		2	**58**	66	**83**	
ES benefits	Mean quantity of rice produced per year and HH [kg] (SD)		(n=184) 360 (228)	(n=581) 397 (311)	(n=153) **694** (512)	
	Irrigated rice fields are used for zebu cattle grazing [% HH]		(n=233) 3	(n=611) 5	(n=119) 8	ns
Constraints reported (indicating unfulfilled demand for ES) [% HH]	Reduced soil fertility		(n=166)	(n=585)	(n=140)	***
		Strong	38	53	**64**	
		Medium	23	20	24	
		None	39	27	12	
			(n=187)	(n=616)	(n=160)	
	Water shortage		42[a]	35[a]	**55[b]**	**
	Animal pests		30[a]	**14[b]**	33[a]	***
	Weeds		**29[a]**	19[b]	26[ab]	**
	No zebu cattle for ploughing		23	29	27	ns
	Floods		6[a]	6[a]	**14[b]**	**

Level of significance: ns p>0.05, *≤0.05, **≤0.01, ***≤0.001. Where no significance level is indicated village level had a significant effect. Different superscript letters indicate pairwise significance. Values mentioned in the accompanying text are highlighted in bold. (MS=Mixed shifting, MP=Mixed paddy, P=Paddy, HH=Households, SD=Standard Deviation).

ES bundles linked to rain-fed hill rice fields in shifting cultivation

In this section we only compare indicators between mixed shifting and mixed paddy landscapes, as not enough households in paddy landscapes use shifting cultivation to allow for comparison. The total surface area of hill rice fields cultivated per household in one year is about 1 ha in both landscape types (Table 4). In terms of benefits from hill rice fields, only the provisioning ES of rice was mentioned. Households in mixed shifting cultivation landscapes produce more hill rice per year than households in mixed paddy landscapes.

In mixed shifting landscapes significantly more households than in mixed paddy landscapes perceived that soil fertility in hill rice fields had strongly declined. Weeds were by far the main constraint to hill rice production in both landscape types, but perceived by a significantly higher proportion of households in mixed shifting than in mixed paddy landscapes. Both the decreased availability of land for shifting cultivation and the destruction of hill rice fields through cyclones were mentioned by a significantly higher percentage of households in mixed shifting than in mixed paddy landscapes.

Animal pests, drought, and a shift in seasonal rainfall patterns were constraints of similar importance in both landscape types.

Table 4. Differences between hill rice fields in two different landscape types in terms of their use, reported benefits from provisioning ES, and constraints indicating unfulfilled demand for ES

			Landscape Type		Significance
			MS	MP	
Use of hill rice fields	Mean total surface area of hill rice fields cultivated per HH [ha] (SD)		(n=234) 1.2 (0.9)	(n=321) 1.0 (0.7)	ns
ES benefit	Mean rice production from hill rice fields per HH and year [kg] (SD)		(n=245) **476 (336)**	(n=468) 306 (318)	
Constraints reported (indicating unfulfilled demand for ES) [% HH]			(n=242)	(n=471)	
	Reduced soil fertility	Strong	**38**	28	**
		Medium	33	31	
		None	29	41	
			(n=246)	(n=494)	
	Weeds		**82**	73	*
	Animal pests		23	17	ns
	Decreased land availability		**16**	4	***
	Crop damage through cyclones		**15**	9	*
	Water shortages		10	9	ns
	Shift in rainfall patterns		7	12	ns

Level of significance: ns p>0.05, *≤0.05, **≤0.01, ***≤0.001. Where no significance level is indicated village level had a significant effect. Values mentioned in the accompanying text are highlighted in bold. (MS=Mixed shifting, MP=Mixed paddy, P=Paddy, HH=Households, SD=Standard Deviation).

ES bundles linked to fallows from shifting cultivation

Fallows are an integral part of shifting cultivation systems and ensure the replenishment of soil fertility. In paddy landscapes fallows are scarce as very few households use shifting cultivation to produce rice. Therefore, we only compared ES from fallows in mixed shifting and mixed paddy landscapes (Table 5). In both landscapes a little more than 75% of all interviewed households owned fallows. Of the remaining households, more than 80% had access to other households' fallows. The intensity of the fallow–crop rotation cycle was similar in mixed shifting and mixed paddy landscapes, with a mean fallow duration of 5 and 4 years, respectively.

In both landscape types, the five most important ES obtained from fallows were: firewood, staple crops (mainly cassava), timber, the maintenance of soil fertility, and fodder for zebu cattle. Apart from the regulating ES of soil fertility maintenance, all other ES reported were provisioning ES. Firewood, staple crops, and the maintenance of soil fertility were mentioned by a significantly higher proportion of households in mixed shifting than in mixed paddy landscapes. Conversely, weaving materials were used by a significantly higher number of households in mixed paddy than in mixed shifting landscapes. Wild foods, medicinal plants, and gems were mentioned only by a small percentage of households in both landscape types.

Table 5. Differences between fallows in two different landscape types in terms of their use and reported benefits from provisioning and regulating ES

		Landscape type		Significance
		MS	**MP**	
Mean fallow length [years](SD)		(n=221) 4.8 (1.9)	(n=408) 4.0 (2.7)	
		(n=267)	(n=519)	
Reported ES benefits [% HH]	Firewood	**95**	84	***
	Staple crops	**56**	42	***
	Timber	42	37	ns
	Maintenance of soil fertility	**32**	21	**
	Fodder for zebu cattle	5	8	ns
	Wild foods	2	1	ns
	Weaving materials	1	**7**	***
	Medicinal plants	1	0	ns
	Gems	0	1	ns

Level of significance: ns p>0.05, *≤0.05, **≤0.01, ***≤0.001. Where no significance level is indicated village level had a significant effect. Values mentioned in the accompanying text are highlighted in bold. (MS=Mixed shifting, MP=Mixed paddy, P=Paddy, HH=Households, SD=Standard Deviation).

ES bundles linked to agroforestry plots

The large majority of interviewed households used at least one agroforestry plot to cultivate cash crops (Table 6). In mixed shifting landscapes the percentage of households doing so was significantly lower than in the other two landscape types. Only provisioning ES were mentioned as benefits from agroforestry plots including cash crops, subsistence crops, timber, and firewood. Households cultivated between one and five cash crops. In mixed shifting landscapes, significantly more households only cultivated one cash crop than in mixed paddy and in paddy landscapes. The percentage of households cultivating two cash crops was significantly higher in paddy landscapes than in the other two landscapes. Around one-quarter of households cultivated three or more cash crops in all landscape types. The three main cash crops were clove, vanilla, and coffee. Other cash crops cultivated by a few of the interviewed households included lychee, sugarcane, orange, banana, sweet potato, taro, cucumber, African aubergine, cola nut, and several edible leaves. Clove was the most common cash crop in all landscape types. Vanilla cultivation was significantly more common in paddy than in mixed paddy and in mixed shifting. Coffee was cultivated for commercialization only by about one-quarter of households in all landscape types. Mean annual revenue from cash crops did not differ between the three landscape types and was on average around US$ 350 per household.

In paddy landscapes significantly more households also cultivated fruit trees, tubers (mainly cassava, yam, and sweet potato), and sugarcane for home consumption than in mixed paddy and mixed shifting landscapes. Coffee for subsistence use was more commonly cultivated in mixed paddy than in shifting cultivation landscapes. Furthermore, the benefit of timber from agroforests played an important role in paddy landscapes, but less so in the other two landscape types. The same was true for firewood.

Table 6. Differences between agroforestry plots in three different landscape types in terms of their use, reported benefits from provisioning ES, and constraints indicating unfulfilled demand for ES

			Landscape type			
			MS	**MP**	**P**	**Significance**
Use of agroforestry plots [% HH]			(n= 297)	(n=727)	(n=163)	
	Cultivating agroforestry plots		**84**^{a}	93^{b}	93^{b}	**
	Cultivating cash crops		**80**^{a}	92^{b}	92^{b}	***
ES benefits	Number of cash crops cultivated per HH [% HH]		(n=237)	(n=667)	(n=150)	
		1	**46**^{a}	32^{b}	19^{c}	***
		2	30^{a}	40^{b}	**54**^{c}	***(a/c),**(a/b,b/c)
		≥ 3	24	28	27	ns
	Cash crops cultivated [% HH]	Clove	94	95	97	ns
		Vanilla	23^{a}	50^{b}	**81**^{c}	***
		Coffee	24	32	29	ns
	Earning revenues from sale of cash crops [% HH]		(n=159) 50	(n=580) 67	(n=163) **76**	ns
	Mean annual revenue from cash crops [US$] (SD)		(n=87) 364 (408)	(n=386) 321 (455)	(n=124) 354 (510)	ns
	Subsistence crop cultivation [% HH]		(n=238)	(n=648)	(n=153)	
		Fruits	60^{a}	76^{b}	**94**^{c}	***
		Tubers	46^{a}	62^{b}	**88**^{c}	***
		Coffee	34^{a}	**46**^{b}	35^{ab}	***
		Sugarcane	34^{a}	40^{b}	**47**^{c}	***(a/c),*(a/b,b/c)
			(n=225)	(n=523)	(n=65)	
	Timber [% HH]		10^{a}	11^{a}	**29**^{b}	***
	Firewood [% HH]		1	14	**80**	
Constraints reported (indicating unfulfilled demand for ES) [% HH]			(n=249)	(n=676)	(n=152)	
	Plant illness		17^{a}	16^{a}	**41**^{b}	***
	Animal pests		14^{a}	12^{a}	**24**^{b}	*
	Crop damage through cyclones		8^{a}	5^{a}	**25**^{b}	***
	Lack of cash crop seedlings		5	3	4	ns
	Water shortage		2	3	5	ns
	Reduced soil fertility		2	2	5	ns
	Cattle trampling		2	3	2	ns
	Land conflicts		0	2	2	ns
	Weeds		0^{a}	3^{b}	0^{a}	*

Level of significance: ns p>0.05, *≤0.05, **≤0.01, ***≤0.001. Where no significance level is indicated village level had a significant effect. Different superscript letters indicate pairwise significance. Values mentioned in the accompanying text are highlighted in bold. (MS=Mixed shifting, MP=Mixed paddy, P=Paddy, HH=Households, SD=Standard Deviation).

Illness of clove and vanilla plants was the main constraint in all landscapes and perceived by a significantly higher proportion of households in paddy than in the other two landscape types (Table 6). The same was the case for animal pests (insects, rats, and worms) damaging cash crops. The destruction of cash crops through cyclones was another constraint significantly more important in paddy than in the other two landscapes. Other constraints were mentioned only by a low percentage of households.

ES bundles from pastures

Only in paddy landscapes did all households who have zebus also own pastures for grazing (Table 7). In the other two landscape types, only about half of the zebu-owning households use pastures to graze them. There, zebus mainly graze in irrigated rice fields after harvest (Table 3) and on fallows (Table 5). In paddy landscapes more than half of all households raise zebu cattle. This is significantly higher than in mixed paddy and in mixed shifting landscapes. The main reason why households did not own zebus was the lack of financial means, especially in mixed shifting landscapes. A significantly higher percentage of households in paddy landscapes than in the other two landscape types gave the following reasons for not owning zebus: the loss or sale of zebus, and zebu ownership by other family members.

Table 7. Differences between pastures for zebu cattle raising in three different landscape types in terms of their use, reported benefits from provisioning ES, and constraints indicating unfulfilled demand for ES

			Landscape type			
			MS	**MP**	**P**	**Significance**
Use of pastures for zebu cattle raising [%HH]			(n=297)	(n=767)	(n=163)	
	Use of pastures		10^{a}	16^{b}	**52^{c}**	*** (a/c,b/c) * (a/b)
	Zebu cattle raising		22^{a}	29^{b}	**50^{c}**	*** (a/c,b/c) * (a/b)
			(n=230)	(n=480)	(n=56)	
	Why no zebus	No financial means	**90^{a}**	80^{b}	61^{c}	***(a/b,a/c) **(b/c)
		No pasture	3	7	9	ns
		No time	3	7	7	ns
		No need	1	2	2	ns
		Loss / sale of zebus	0^{a}	2^{a}	**14^{b}**	***
		Family owns	0^{a}	1^{a}	7^{b}	**
		Other	3	1	0	ns
ES benefits	Mean number of zebus (SD)		(n=65) 3.6 (2.8)	(n=210) 3.2 (2.4)	(n=82) 2.8 (1.8)	ns
	Use of trees [% HH]	Overall	(n=24) **71^{a}**	(n=65) 54^{b}	(n=82) 63^{a}	*
			(n=18)	(n=37)	(n=52)	
		Fruit trees	72	68	62	ns
		Cash crop	72	62	63	ns
		Timber	28	19	21	ns
		Firewood	0	0	4	ns
Constraints reported (indicating unfulfilled demand for ESs) [% HH]			(n=30)	(n=114)	(n=84)	
	Shortage of herb s		**20^{ac}**	4^{b}	**26^{c}**	***(b/c) *(ac/b)
	Weeds (spiny plants)		**18^{ac}**	2^{b}	**18^{c}**	***(b/c) **(ac/b)
	Water shortage		**10**	5	5	ns
	Water pollution		**7**	2	0	ns
	Cattle diseases		3	1	**5**	ns
	Flooding of pasture		0	3	**5**	ns

Level of significance: ns p>0.05, *≤0.05, **≤0.01, ***≤0.001. Where no significance level is indicated village level had a significant effect. Different superscript letters indicate pairwise significance. Values mentioned in the accompanying text are highlighted in bold. (MS=Mixed shifting, MP=Mixed paddy, P=Paddy, HH=Households, SD=Standard Deviation).

In terms of ES benefits from pastures, households mentioned zebus as well as a number of tree products. Households owning zebus have on average between three and four zebus in all three landscape types. In mixed shifting and paddy landscapes a significantly higher proportion of households using pastures maintained and planted trees on them than in mixed paddy landscapes. Trees on pastures mainly provide edible fruits, cash crops (mainly clove), and timber (e.g. *Eucalyptus* sp., Bamboo, and *Intsia* sp.). In paddy landscapes a few households grow *Grevillea* sp. as firewood. The main constraints to pastures were the low production of herbs and the presence of spiny unpalatable plants, mainly in paddy and mixed shifting landscapes. The shortage and low quality of drinking water for zebus was a constraint mentioned mainly in mixed shifting landscapes while cattle diseases and flooding of pastures were constraints mainly in paddy landscapes.

ES bundles from forest

About half of the interviewed households use forests in all landscape types (Table 8). The reasons for not using forests differed significantly between paddy landscapes and the other two landscape types. While in mixed shifting and mixed paddy landscapes distance was the main reason for non-use of forests, in paddy landscapes the main reason was restricted access. Having no need for forests was another reason mentioned by a significantly higher proportion of households in paddy than in the other landscape types. The mean number of forest products collected did not differ significantly between households in the different landscape types.

In terms of benefits from forests, land users reported about equal numbers of provisioning and regulating ES, as well as few cultural ES. For households collecting forest products, timber was by far the most important in all landscapes types. In mixed shifting landscapes significantly more households collected pandanus (*Pandanus sp.*), honey, ravenala (*Ravenala madagascariensis*), dypsis (*Dypsis sp.*), and medicinal plants than in the other two landscape types. Pandanus, ravenala, and dypsis are different types of palms with various functions in the construction of local huts and the manufacturing of household items. Wild edible plant materials, such as palm hearts, wild yams, and wild bananas were of similar importance in mixed shifting and mixed paddy landscapes and significantly more important than in mixed shifting landscapes. Lianas, used to produce string, were significantly more important in mixed shifting and paddy landscapes than in mixed paddy landscapes. Firewood was the only provisioning ES from forests that was more important in mixed paddy and paddy landscapes than in mixed shifting landscapes.

Table 8. Differences between forest in three different landscape types in terms of its use and reported benefits from provisioning, regulating, habitat and supporting, and cultural ES

			Landscape type			
			MS	**MP**	**P**	**Significance**
Forest use	Using forests [% HH]		(n=297)	(n=727)	(n=163)	
			52	44	48	ns
	Reasons for non-use of forests [% HH]		(n=143)	(n=410)	(n=84)	
		Distance	**76**^{a}	**76**^{a}	27^{b}	***
		Restricted access	16^{a}	17^{a}	**42**^{b}	***
		No need	7^{a}	4^{ab}	20^{c}	**(a/c),***(ab/c)
		Other	1^{a}	4^{ab}	11^{c}	** (a/c),*(ab/c)
ES benefits [reported by % HH]	Mean number of forest products collected (SD)		(n=147)	(n=298)	(n=75)	
			3.4 (1.9)	2.3 (1.9)	1.9 (1.1)	ns
	Provisioning ES		(n=147)	(n=298)	(n=75)	
		Timber	87	77	77	ns
		Pandanus (weaving)	**49**^{a}	26^{b}	21^{b}	***
		Honey	**49**^{a}	18^{b}	3^{c}	***
		Ravenala (huts)	**32**^{a}	15^{b}	19^{bc}	***(a/b),*(a/bc)
		Dypsis (roofs)	**31**^{a}	9^{b}	7^{b}	***
		Wild plant food	**25**^{a}	**23**^{ab}	5^{c}	**(a/c),*(ab/c)
		Lianas for string	**21**^{a}	12^{b}	**27**^{ac}	*(a/b),**(b/ac)
		Medicinal plants	**15**^{a}	6^{b}	1^{bc}	**(a/b),***(a/bc)
		Firewood	10^{ac}	**21**^{b}	**20**^{bc}	**
		Other wood	11	6	4	ns
		Gems	3	7	1	ns
		Bushmeat	0	2	1	ns
	Regulating ES		(n=194)	(n=456)	(n=162)	
		Water regulation	**72**^{a}	52^{b}	64^{ac}	***(a/b),*(b/ac)
		Climate regulation[1]	**18**^{a}	6^{b}	10^{bc}	***(a/b),*(a/bc)
		Cyclone protection	**18**^{a}	4^{b}	1^{b}	***
		Erosion protection	**14**^{a}	6^{b}	8^{ab}	**(a/b)
		Environmental quality	7	6	10	ns
		Soil humidity	4	6	2	ns
		Human health	2	0	0	ns
		Air quality regulation	1	2	1	ns
		Clean water	1	1	0	ns
		Animal health	1	0	0	ns
		Soil fertility	0	1	0	ns
	Habitat and supporting ES	Habitat for animals	10	**11**	**16**	ns
	Cultural ES	Land reserve for descendants	**5**	4	5	ns
		Aesthetics	**5**	3	1	ns
		Recreation	4	**7**	**8**	ns
		Tourism	0	**2**	0	ns

Level of significance: ns p>0.05, *≤0.05, **≤0.01, ***≤0.001. Where no significance level is indicated village level had a significant effect. Different superscript letters indicate pairwise significance. Values mentioned in the accompanying text are highlighted in bold. (MS=Mixed shifting, MP=Mixed paddy, P=Paddy, HH=Households, SD=Standard Deviation).

[1] When asked about the benefits from forests, respondents mentioned the forest's ability to slow temperature rise, which we translated into "climate regulation" for the purpose of the analysis. It was not clear though whether the respondents meant at the global or at the local level.

The contribution of forest to the maintenance of the hydrological cycle and thus sufficient water for irrigation was the most important regulating ES perceived in all landscape types, and significantly more important in mixed shifting and in paddy than in mixed paddy landscapes. In mixed shifting landscapes this was followed by climate change mitigation as well as protection from cyclones. These ES were mentioned significantly more often in mixed shifting than in the other two landscape types. Protection from soil erosion was also significantly more important in mixed shifting than in mixed paddy landscapes. Other regulating ES were mentioned only by a low proportion of households in all landscape types. In both mixed paddy and paddy landscapes the habitat function of forests (from the category of habitat and supporting ES) was perceived as more important than other ES from the category of regulating ES. In terms of cultural ES, in mixed shifting landscapes forest was mainly perceived as a land reserve for descendants to be used in future, and as a beautiful landscape element. In both mixed paddy and paddy landscapes, recreation was perceived as the most important cultural ES from forest. Tourism was mentioned by few households in mixed paddy landscapes only.

3.3 Characterization of landscape types in terms of socio-demographic characteristics and ES benefits to households

While in the previous section we characterized landscape types in terms of different land use activities and the ES bundles linked to those, in the following we will concentrate on the households populating those landscapes, their socio-demographic characteristics, and key benefits obtained from ES.

Socio-demographic characteristics of households in different landscapes

Mean age of the interviewed persons ranged from 39 years in mixed paddy to 45 years in paddy landscapes (Table 9). Illiteracy of respondents varied significantly between the three landscape types; it was highest in mixed shifting landscapes. The main income source in all landscapes was agriculture followed by trade. Significantly more households employed agricultural wage labour in mixed paddy than in mixed shifting and in paddy landscapes. In paddy landscapes significantly more households were members of an association than in the other two landscape types. Significantly more households had received support from extension services in paddy landscapes than in mixed paddy and mixed shifting landscapes.

Table 9. Socio-demographic characteristics of households in different landscape types

	Landscape type			Significance
	MS	MP	P	
Mean age of respondent [years] (SD)	(n=297) 40 (15)	(n=713) 39 (15)	(n=158) 45 (15)	ns
Respondent was illiterate [% HH]	(n=294) **38**[a]	(n=714) 22[b]	(n=163) 10[c]	***
Main income source reported [% HH]	(n=297)[a]	(n=727)[b]	(n=163)[ac]	***(a/b) **(b/c)
Agriculture	75	67	72	
Trade	9	14	13	
Wage labour	2	8	1	
Own business	5	6	9	
Professional	5	4	2	
Other	4	1	3	
Employing wage labour [% HH]	(n=296) 51[a]	(n=723) **62**[b]	(n=162) 43[c]	*** (a/c),(b/c) ** (a/b)
Member of association [% HH]	(n=297) 48[a]	(n=721) 48[a]	(n=162) **73**[b]	***
Support from extension services [% HH]	(n=295) 9[a]	(n=715) 19[b]	(n=162) **30**[c]	*** (a/b),(a/c) ** (b/c)

Level of significance: ns p>0.05, *≤0.05, **≤0.01, ***≤0.001. Different superscript letters indicate pairwise significance. Values highlighted in the accompanying text are highlighted in bold. (MS=Mixed shifting, MP=Mixed paddy, P=Paddy, HH=Households, SD=Standard Deviation).

Aggregating our data at the level of different landscape types served to characterize the three landscape types in terms of their socio-demographic characteristics as well as ES bundles linked to different land uses. However, we were also interested to know if there are different types of households in terms of the key benefits they obtain from ES. For this we conducted a hierarchical cluster analysis to come up with five distinct household types (Table 10). The most common household type in mixed shifting and mixed paddy landscapes (Figure 3) was termed "Diverse Subsistence". It is characterized by a relatively high rice sufficiency of nine months, equally important rice production from shifting and irrigated cultivation, and a high diversity of land use activities. The second most common household type in mixed shifting landscapes was the "Shifting and Forest" type, characterized by a medium rice sufficiency, high production of rice through shifting cultivation, almost no irrigated rice production, and the collection of forest products. This household type was also present in mixed paddy landscape, although to a much lower extent, and (with the exception of one single household) absent from paddy landscapes. In mixed paddy landscapes the second most common household type of "Low Irrigated Subsistence" has a very low rice sufficiency of only five months, little rice produced (only in irrigated fields), little income from cash crops, and a low land use diversity. This household type was also present in paddy landscapes among a similar proportion of households.

Table 10. Typology of households (n=1,184) based on key ES benefits in north-eastern Madagascar and obtained through hierarchical cluster analysis. Values represent means (standard deviations) for each variable.

		Household type				
		Shifting and Forest (18%; n=207)	Diverse Subsistence (31%; n=368)	Low Irrigated Subsistence (22%; n=263)	Irrigated Commercial (18%; n=214)	Commercial Livestock (11%; n=132)
Key ES benefits	Rice sufficiency [months]	8 (3)	9 (3)	5 (3)	8 (4)	8 (4)
	Rice from shifting cultivation [kg]	488 (483)	360 (199)	34 (55)	30 (195)	90 (180)
	Irrigated paddy rice [kg]	19 (52)	350 (197)	136 (119)	722 (447)	599 (428)
	Cash crop income [US$]	56 (104)	85 (163)	67 (97)	69 (109)	940 (640)
	No. of zebus	1 (2)	1 (2)	1 (1)	1 (2)	2 (2)
	No. of forest products	2 (2)	1 (2)	1 (1)	1 (2)	1 (2)
Other HH character-istcis	Household size [no. of people]	5 (2)	5 (2)	4 (2)	5 (2)	6 (2)
	No. of land use activities	4 (1)	5 (1)	3 (1)	3 (1)	4 (1)

(HH=Households)

Paddy landscapes were dominated by the household type named “Irrigated Commercial”, which produced the largest quantity of rice (entirely in irrigated fields) and some income from cash crops despite its relatively low diversity of land use activities. The second most common household type in paddy landscapes was the “Commercial Livestock” type of household, characterized by high income from cash crops, high irrigated rice production, and higher numbers of zebus owned. This type was also present in mixed paddy and mixed shifting landscapes, but with a much lower proportion of households.

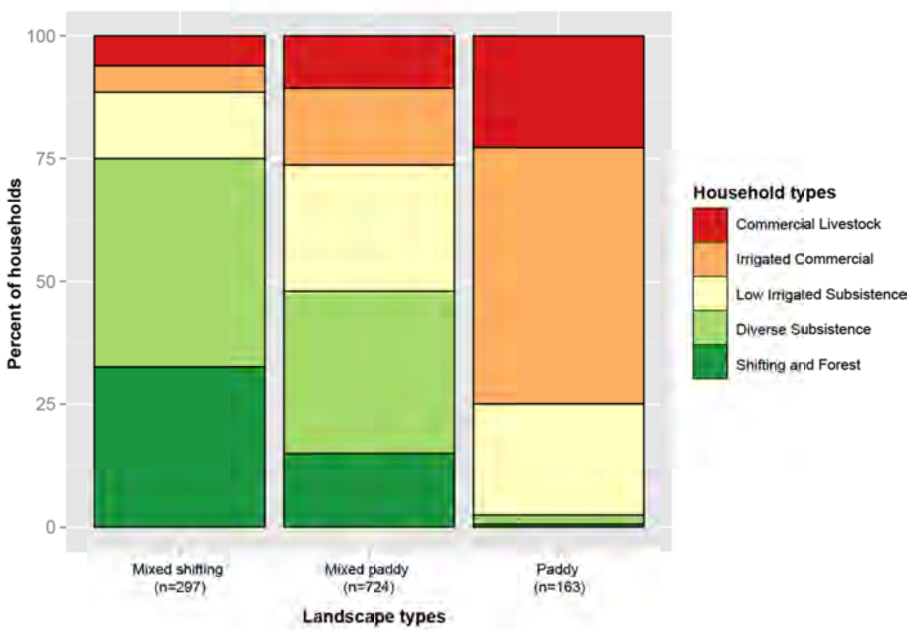

Figure 3. Characterization of landscape types in terms of ES benefits to households in north-eastern Madagascar

4 Discussion

4.1 A promising approach for monitoring landscape intensification

The information on households' rice production modes in north-eastern Madagascar, obtained from our interviews, confirms the categorization of landscape types through remote sensing methods and spatial analysis. In mixed shifting landscapes, more than 85% of households produced rice through shifting cultivation, with about one-third of all interviewed households relying entirely on this mode of rice production. Both rice production systems were employed in parallel by about the same proportion of households in mixed paddy landscapes as in mixed shifting landscapes, with almost one-third entirely relying on irrigated rice production. Thus, even in mixed paddy landscapes, still almost 70% of households use shifting cultivation, and it is only in paddy landscapes where almost all households rely entirely on irrigated rice production. This shows that despite two decades of intensive conservation efforts, at the regional level the biodiversity hotspot of north-eastern Madagascar is still very much under the influence of shifting cultivation. Furthermore, although the differences were not significant, mixed paddy landscapes seem to have a lower proportion of fully rice-sufficient households, lower average duration of rice sufficiency, as well as lower total rice production than the other two landscape types. This suggests that food security in mixed paddy landscapes was lower than in mixed shifting landscapes, despite a higher overall degree of staple crop intensity at landscape level (i.e. a larger area under irrigated rice than under hill rice production). In this context, spatially explicit information on land use is crucial for directing conservation and development efforts to the areas where they are most needed. As we have shown that in this region land use can be inferred from satellite imagery analysed with the landscape mosaic approach (Zaehringer et al., 2016), this approach holds strong potential for the future monitoring of landscape intensification.

4.2 Landscapes characterized by land use and ES bundles

Our second research question asked if landscape types could be characterized by different bundles of ES linked to land use. Our analysis shows that although the overall composition of different ES linked to each land use is similar in all landscape types, the importance of different ES in the perception of households differs widely.

In mixed shifting landscapes, there is a trend towards more rice being produced through shifting cultivation than in mixed paddy landscapes. By far the most important constraints to hill rice production mentioned by land users were weeds, animal pests, crop damage through cyclones, and water shortage, which all indicate an unfulfilled demand for regulating ES. Shifting cultivation is perceived as less prone to crop damage from cyclones than irrigated rice production, which was often mentioned as a reason why this land use system is likely to persist in the region (Brimont et al., 2015; Kistler, Messerli, & Wohlhauser, 2001; Messerli & Pfund, 1999; Urech et al., 2015). However, in our case, cyclones were mentioned as a constraint mainly for shifting cultivation and to a lesser extent also for agroforestry. The decrease in land available for shifting cultivation was another important constraint mentioned by a much higher proportion of land users in mixed shifting than in mixed paddy landscapes. Land users in our study region obtain the customary rights to use new land by slashing a plot of forest (Keller, 2008; Urech et al., 2015). The shrinking of large continuous forest areas and the expansion of protected areas leads to an unfulfilled demand for this ES formerly provided by forests. The decreasing fertility of hill rice fields was another important constraint, which was higher than in mixed paddy landscapes. Also in relation to ES benefits from fallows, a higher proportion of households reported the regulating ES of soil fertility maintenance than in mixed paddy landscapes. Although in both landscapes fallow length is on average between 4-5 years (which is in line with the few available estimates from earlier studies), in mixed shifting landscapes a larger proportion of households depends on shifting cultivation. Thus a fertility decline might be perceived as a larger threat to food security than in mixed paddy landscapes. Fallows were also more important in providing firewood and staple crops in mixed shifting landscapes, while in mixed paddy landscapes a higher proportion of households collected plant materials used for weaving. By contrast, weaving materials in mixed shifting landscapes were obtained from forest. If these products are no longer easily obtained from forests, households might replace them with products from fallows, which are however, often of lesser quality (Urech, Felber, & Sorg, 2012). Nonetheless, this shows that shifting cultivation, through the presence of fallows, delivers a range of important ES benefits.

The intensity of irrigated rice production increases from mixed shifting to mixed paddy to paddy landscapes (i.e. increasingly more households cultivate irrigated rice fields twice a year). The lower intensity in mixed shifting landscapes is probably due to the time and labour constraints of households using both types of rice production. Paddy landscapes feature the highest degree of fully rice-sufficient households, although the mean duration of rice sufficiency is similar to the other landscape types and the total quantity of rice produced per year is not much higher than in mixed shifting landscapes. Also, about the same proportion of households in paddy landscapes is selling part of the rice production as in the other landscape types, which indicates that even in these flat landscapes, offering optimal terrain for irrigated rice cultivation, the current production conditions in terms of water availability, labour, and external inputs do not allow households to produce more. The second ES benefit from irrigated rice fields is the provision of fodder for zebu cattle after harvest, which was most important in paddy landscapes. In terms of constraints, almost 65% of households in paddy landscapes stressed that soil fertility had strongly declined since they started cultivating their fields, which was much higher than in the other landscape types. In the absence of job opportunities outside the agricultural sector, irrigated rice plots are becoming smaller in size with every generation inheriting these lands from their parents. In terms of constraints for irrigated rice production, water shortage was the main issue in all landscape types, but perceived by a higher proportion of households in paddy landscapes. The same was true for the constraint of floods. Water shortage and floods reflect land users' unfulfilled demand for regulating ES provided by the interactions between the climatic system and land uses in the watershed. However, in this case it is the absence of appropriate technical infrastructure such as canals and watergates, as well as of a functioning management system, which reduces households' access to this important ES. Animal pests and weeds were perceived as more of a constraint to irrigated rice production in mixed shifting than in mixed paddy landscapes.

The use of agroforests and cash crop cultivation were lowest in mixed shifting landscapes and the majority of households only cultivated one cash crop: clove. The percentage of households cultivating vanilla as a second cash crop increases from mixed shifting to mixed paddy to paddy landscapes. This is likely related to shorter distances to district capitals in mixed paddy and paddy landscapes, as most land users rely on collectors coming to their villages to buy their products and take them to the main traders' shops in district capitals. However, average income from the sale of cash crops was about the same in all landscapes. This indicates that it might not be sufficient to rely on diversification alone to increase land users' income from cash crops, which is one of the strategies pursued by conservation organizations in view of decreasing dependency on shifting cultivation (Brimont et al., 2015; Pollini, 2009). In addition, it is vital to address the manifold production constraints especially in terms of plant illnesses (e.g. bacteria and viruses), animal pests (insects, birds), and crop damage through cyclones, which were all perceived as more important in paddy than in the other landscapes. Although cyclones are perceived as a major risk which can deter land users from investing more into cash crop production, this does not explain the relatively low income reported in paddy landscapes, as no major cyclones hit the area in the year before the interviews were conducted. The importance of agroforests in delivering ES benefits in terms of subsistence crops (mainly different fruits and tubers) also increases from mixed shifting to mixed paddy to paddy landscapes. In mixed shifting landscapes households rely more on forests to collect wild foods than households in paddy landscapes. Another peculiarity of paddy landscapes is that the majority of households collect firewood and even timber from agroforests; this is probably because there are no fallows, which deliver these ES benefits in the other two landscape types.

The use of pastures for zebu cattle raising also correlates with increasing landscape intensity from mixed shifting to paddy landscapes. This can be explained by an increasing focus on irrigated rice production, which requires zebu cattle for ploughing. Pastures are a rather uncommon land use in mixed shifting landscapes. However, of the few households owning pastures in mixed shifting landscapes the majority combine them with fruit trees, cash crops (mainly clove), or even with trees providing timber.

While the percentage of households using forests was similar in all landscape types, the reasons for those households not using them differed in paddy landscapes. In mixed shifting and mixed paddy landscapes the distance to forests was by far the most important reason for households not using forests, whereas in paddy landscapes it was the existing access restrictions. This is because the paddy landscapes in our study region were found mainly bordering the protected areas of Masoala and Makira. However, another 20% of households not using forest in paddy landscapes said they did not need anything from forests; this is probably due to the fact that the majority of these villages are comparatively close to the main market of Maroantsetra, where alternatives to forest products can be obtained. The observation that of those households using forests, a much lower percentage collects honey, wild foods, and medicinal plants than in the other two landscape types, supports this hypothesis. In mixed shifting landscapes households seem to collect a greater variety of forest products than in the other two landscapes. In addition, a larger proportion of households obtains ES benefits from plants (such as *Pandanus sp*., *Ravenala madagascariensis,* and *Dypsis sp.*) used for handicrafts or for the construction of traditional houses. It might be that some of these products are less common in the study villages located in mixed paddy and paddy landscapes where (accessible) forest persists in small fragments only. Firewood was the only forest product collected by a higher proportion of households in mixed paddy and paddy than in mixed shifting landscapes. The reason for this may be that fallows in mixed paddy landscapes contain fewer woody plants (and thus less firewood) due to the trend towards shorter fallow duration; in addition, in paddy landscapes firewood can only be obtained from agroforests. Bushmeat was mentioned only by a very low percentage of land users in mixed paddy and paddy landscapes. This may not represent the true picture, but may instead reflect households' reluctance to share such sensitive information with outsiders. Golden et al. (2009; 2013) have shown the importance of bushmeat in the diet of households in the vicinities of the Makira and Masoala protected areas. Regulating ES from forests in terms of water and climate regulation as well as protection from cyclones and erosion were perceived to be important by a higher proportion of households in mixed shifting than in the other two landscape types. On the other hand, the habitat and supporting ES of forests providing a habitat for animals was mentioned by a higher proportion of households in mixed paddy and paddy than in mixed shifting landscapes. It is likely that with households being less dependent on exploitable forest products and on forest as a source of land for future agricultural expansion, their awareness of the value of intact forests rises. Similar observations were made by Urech et al. (2012) in the Manompana forest corridor to the south of our study region. Four cultural ES were mentioned in our study region, although only by a small percentage of households in each landscape type. Forest was perceived as a reserve of land for future descendants by households in all landscapes. The low percentage of households reporting this ES might indicate, however, that many land users are already aware that with the presence of protected areas and also with the increasing distance of forests from villages, this will not be the case for much longer. The decreasing availability of land mentioned as a constraint for shifting cultivation also points in that direction.

4.3 The need for disaggregating data on ES benefits

Apart from land use activities and the ES bundles linked to them, the three landscape types dominating our study region also differ in terms of several socio-demographic household characteristics. Mixed shifting landscapes are characterized by a high proportion of illiterate respondents. This is likely related to the generally low accessibility of these landscapes, which are located mostly in the interior of the study region far from the main road and the district capitals (see Figure 2). This probably also explains why only a very low proportion of interviewed households had previously received support from extension services as compared to the other two landscape types. Mixed paddy landscapes differed from the two other landscape types in that agricultural wage labour was more widespread, both in terms of households employing workers as well as households earning income from agricultural wage labour. Paddy landscapes, which represent the most intensive of the three landscape types in terms of staple crop cultivation, differed from the other two landscape types by having a lower degree of illiteracy among respondents, fewer households employing wage labour, more households being members of an association, and more households having received support from extension services. Villages sampled in paddy landscapes are located in the large plain surrounding the district capital of Maroantsetra as well as on the western border of the Masoala protected area. These landscapes have therefore experienced more external influences from the state and from non-governmental organizations. The reason that fewer people employ wage labour might be related to the fact that in paddy landscapes almost all households focus entirely on irrigated rice production. This might reduce the labour needs, which can be very high especially in the case of households cultivating hill rice and irrigated rice during the summer months.

Although these generalizations at landscape level give useful hints for tailoring future conservation and development interventions to specific areas, the cluster analysis showed that we should still consider the heterogeneity of households populating different landscapes. In mixed shifting landscapes the two more subsistence-based household types, of which one relies on both types of rice production and the other on shifting cultivation only, accounted for three-quarters of all households. This suggests that conservation actors, whose aim is to steer land users away from shifting cultivation, will need to develop different strategies depending on the household type. Approaches based on increasing production in irrigated fields would only benefit some of the households and thus presumably have very little effect on the extent of shifting cultivation. Mixed paddy landscapes, which dominate the study region in terms of area, also feature the highest diversity of household types. In these landscapes special attention should be given to the household type exhibiting low land use diversity with rice only produced in irrigated fields, but with a very low average rice production and duration of rice sufficiency. These households could either be very destitute or on the contrary have lucrative alternative sources of income, which in the context of our study region, often means involvement in the illegal rosewood trade (Randriamalala & Liu, 2010;

Schuurman & Lowry, 2009). Paddy landscapes show less diversification in terms of household types as most households can be assigned to the "Irrigated Commercial" type, which has comparatively high production of irrigated rice but rather low income from cash crops and a few zebus. In paddy landscapes development interventions could therefore focus on cash crop production as well as improving households' access to zebus for cattle raising.

4.4 An evidence base to negotiate trade-offs related to land use change

Our results highlight the importance of considering the whole range of land use activities and the bundles of ES connected to these, when planning for sustainable development in north-eastern Madagascar. Households in this biodiversity hotspot perceive a wide range of ES: on the one hand in terms of ES benefits provided by a certain land use, and on the other in terms of ES provided by surrounding land uses, which are indispensable in supporting a specific land use. The lack of the latter, which are mostly regulating ES, leads to major constraints for the production of both subsistence rice as well as cash crops for monetary income. In terms of regulating and maintenance ES from forest, land users reported as many as 11 different services. As only a few land users in a small fraction of the villages sampled had previously had any interaction with staff from non-governmental organizations or extension services, we can assume that these are the land users' own perceptions. This suggests that there is no need for environmental education approaches aimed at increasing land users' knowledge about the importance of forests to maintain their own well-being. Land users are well aware of the indirect benefits forests provide to food security as well as to income from agriculture. However, in this context of low rice sufficiency and highly variable income from cash crops, there is a difficult trade-off between maintaining forests for the provision of ES and the conversion into agricultural lands. Cultural ES are known to be difficult to elicit through open-ended questions in standardized surveys, something our study confirms. Land users only mentioned few cultural ES linked to forests and none of them could be assigned to the spiritual or religious theme. We would like to stress though that among the Betsimisaraka people in north-eastern Madagascar it is not primarily the pristine forest but rather the various agricultural land uses which are deeply interwoven with the spiritual world (Osterhoudt, 2010).

A previous study has shown that the main landscape change trajectories during the past 20 years have gone towards intensification from mixed shifting to mixed paddy and then into paddy landscapes (Zaehringer et al., 2016). As we can assume that restrictions regarding the further expansion of the agricultural frontier will remain or even increase in future – and thus the current trend of landscape intensification will continue – our results shed some light on the potential trade-offs between different land uses in the region. With the decline of shifting cultivation, and especially the transformation of fallows into agroforests or pastures, a range of provisioning ES currently important to the local land users would disappear. While firewood and timber can also be obtained from agroforests, other provisioning ES such as weaving materials would likely not be available anymore. Furthermore, fallows are important carbon sinks and can thus contribute to the mitigation of global warming (Bruun, Neergaard, Lawrence, & Ziegler, 2009). Households would also obtain fewer benefits from forest products, which could have implications on land users' diet and health. In terms of ES benefits from rice production, crucial to satisfying the subsistence needs for almost all households interviewed, landscape intensification towards a stronger reliance on irrigated rice will not necessarily coincide with higher food security. Although along this landscape change trajectory households tend to cultivate their irrigated rice fields more intensively, planting twice per year instead of only once, this has so far not led to higher total rice availability per household than in the less intensive mixed shifting landscapes. Although the households we interviewed did not specifically mention the risk of cyclones for irrigated rice production, the focus on irrigated rice as a single rice production system is more risky, especially also to crop damage from water shortages and floods. The disaggregation of household types has further revealed that with increasing intensification from mixed shifting to paddy landscapes a larger proportion of households obtains increased benefits from irrigated rice production and agroforestry. However, at the same time there is also an increase in the proportion of households which profit very little from key ES benefits. This indicates that the change away from more subsistence-based shifting cultivation livelihoods towards livelihoods based on irrigated rice and cash crop production can take very different directions, something which has to be addressed in planning for more sustainable regional development.

5 Conclusion

Integrating land use data obtained through remote sensing with socioecological data from a regional level household survey in north-eastern Madagascar, we characterized current landscapes in terms of ES bundles and key ES benefits to households. Our results add to the small body of scientific evidence in this biodiversity hotspot on the links between land use and benefits to humans.

Returning to the research questions we asked at the start of this article, we can conclude the following: (1) the map of landscape types obtained through remote sensing and spatial analysis adequately reflects households' involvement in shifting cultivation and irrigated rice production; (2) the bundles of ES linked to specific land uses differ between landscape types; (3) each landscape type can be characterized by a certain composition of household types based on the key benefits they obtain from land use.

Such evidence is needed to support the negotiation of trade-offs between conservation of the biodiversity-rich forests and the provision of other ES benefits to land users. Many challenges are linked to the current trend of landscape intensification in the region. Increased reliance on irrigated rice production does not automatically lead to higher food security and cash crop diversification does not necessarily result in higher income. Furthermore, the differences between households in terms of key ES benefits obtained need to be considered in devising development interventions that benefit all households equally. We propose that the map of landscape types and the knowledge about ES and household types linked to it could serve as a basis for directing future conservation and development efforts to those places where and people for whom they have the highest potential for success.

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Paper V: Understanding deforestation and forest fragmentation from a livelihood perspective

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Understanding deforestation and forest fragmentation from a livelihood perspective

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ABSTRACT

Worldwide, forests provide a wide variety of resources to rural inhabitants, and especially to the poor. In Madagascar, forest resources make important contributions to the livelihoods of the rural population living at the edges of these forests. Although people benefit from forest resources, forests are continuously cleared and converted into arable land. Despite long-term efforts on the part of researchers, development cooperation projects and government, Madagascar has not been able to achieve a fundamental decrease in deforestation. The question of why deforestation continues in spite of such efforts remains. To answer this question, we aimed at understanding deforestation and forest fragmentation from the perspective of rural households in the Manompana corridor on the east coast. Applying a sustainable livelihood approach, we explored local social-ecological systems to understand: (i) how livelihood strategies leading to deforestation evolve and (ii) how the decrease of forest impacts on households' strategies. Results highlight the complexity of the environmental, cultural and political context in which households' decision-making takes place. Further, we found crucial impacts of deforestation and forest fragmentation on livelihood systems, but also recognized that people have been able to adapt to the changing landscapes without major impacts on their welfare.

RÉSUMÉ

Partout dans le monde les forêts fournissent une grande variété de ressources aux habitants des régions rurales, particulièrement aux plus pauvres. À Madagascar, les ressources forestières contribuent dans une grande mesure aux moyens d'existence des populations riveraines des forêts. Cependant, bien que les populations tirent parti des ressources de la forêt, les défrichements ne cessent pas et la conversion des zones boisées en terres cultivables se poursuit. Malgré les efforts entrepris depuis des années par les milieux de la recherche et du développement ainsi que par le gouvernement, Madagascar n'a pas encore connu d'inversion du rythme de la déforestation. Pourquoi les défrichements se poursuivent-ils en dépit des efforts entrepris ? C'est à cette question que nous souhaitons apporter une réponse en essayant de comprendre la déforestation et la fragmentation des forêts en prenant en compte les moyens d'existence des ménages ruraux dans le corridor de Manompana, côte Est de Madagascar. En tirant parti de la méthodologie SLA (*sustainable livelihood approach*), nous avons analysé les systèmes d'existence des populations locales dans le but de comprendre (i) comment évoluent les stratégies de vie impliquant la déforestation et (ii) quel est l'impact de la diminution des surfaces forestières sur les stratégies de vie des ménages. Les résultats mettent en évidence la complexité du contexte environnemental, culturel et politique dans lequel les ménages sont amenés à prendre leurs décisions. La déforestation et la fragmentation des forêts exercent des impacts cruciaux sur les moyens d'existence des ménages. Cependant, il apparait également que les populations sont en mesure de s'adapter à des modifications des paysages sans que cela n'entraîne d'effets majeurs sur leur bien-être. Notre recherche s'est déroulée dans quatre villages, dont deux proches de grands massifs forestiers, les deux autres éloignés des massifs et voisins de fragments de forêts. D'intéressantes différences ont été mises en évidence entre les deux catégories de villages en ce qui concerne l'interface homme-forêt et la perception du rôle joué par la forêt aujourd'hui et à long terme.

INTRODUCTION

Deforestation of tropical forests around the globe has been happening for tens of thousands of years (Malhi et al. 2014). The underlying drivers have shown to be manifold and interacting with each other (Geist and Lambin 2002). While in many countries the main drivers today are the expansion of large scale agribusiness and a rising demand for forest products by urban populations (Lambin and Meyfroidt 2011), the deforestation frontier of eastern Madagascar is still characterized by smallholders' agricultural expansion for subsistence needs (Zaehringer et al. 2015).

Madagascar's tropical rainforests contain a unique biodiversity (Myers et al. 2000) and provide a broad variety of products and environmental services to local populations and their livelihoods (Kremen et al. 1998). Yet, despite their importance, forests have been used since the first human settlement in Madagascar around 2000 B.C. (Dewar et al. 2013); existing evidence documents a general trend of forest loss (McConnell and Kull 2014) and forest

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fragmentation (Harper et al. 2007). The most recent nation-wide deforestation analyses report a decrease from 0.9% deforestation per year from 1990–2000 (ibid), to 0.5% from 2000 to 2005 (MEFT et al. 2007) to 0.4% from 2005–2010 (ONE et al. 2013). However, local scale forest change studies from the east coast have reported overall increases of forest change and deforestation rates above 1% (Eckert et al. 2011, Allnutt et al. 2013).

Along the eastern escarpment of Madagascar, currently the main direct cause of deforestation and forest fragmentation is the land use practice of slash-and-burn to cultivate rain-fed hill rice, a system known as *tavy* in the Malagasy language (Gorenflo et al. 2011). Once the forest is burned, rain-fed hill rice is usually cultivated for only one season, followed by manioc or sweet potato the next (Messerli 2002, Aubert 2008). As a result of the tavy system, soils are heavily washed out and their fertility decreases with every rotation (Pfund 1997, Brand and Pfund 1998). Longer fallow periods maintain better soil fertility. Thus, farmers pursue agricultural expansion as long as forest is available and until enough arable land for long fallow periods is assured (Pollini et al. 2014). At the same time, forest products and resources of remaining forests are used, sold or exchanged. Eventually, however, forests are cleared and converted into complex mosaic landscapes consisting of forest fragments and other mainly agricultural land use types (Pfund 2000, Bennett et al. 2006, Eckert et al. 2011). As described in Urech et al. (2011) forest fragmentation is a dynamic process that reduces larger contiguous forests (called forest massif in this article) into smaller forest patches which become more isolated and increasingly affected by edge effects.

As a consequence, people lose access to forest resources. The reasons why farmers continue to slash-and-burn forested land to grow rain-fed rice, reducing other important forest services and thus undermining part of their own security net, are known to be complex. Multilateral donors and researchers have been engaged for decades in the issue of deforestation in Madagascar, trying to find solutions to stop slash-and-burn agriculture (Messerli 2002, McConnell and Sweeney 2005, Pollini 2009, Freudenberger 2010). Three different approaches have been pursued by these actors as well as the state: (i) attention has been given to testing alternative agricultural practices and finding mechanisms and incentives that would enable land users to adopt those practices (Messerli 2002, Moser and Barrett 2003, Pollini 2009, Freudenberger 2010); (ii) areas reserved for strict nature conservation have been defined (Randrianandianina et al. 2003, Corson 2011); and (iii) a framework for community-based forest management has been implemented by the state with strong support from international donors (Pollini and Lassoie 2011, Bertrand et al. 2014, Corson 2014, Cullman 2015, Rasolofoson et al. 2015).

But deforestation continues nonetheless (ONE et al. 2013) with rural farmers perceived to be the main responsible actors (The World Bank 2013). Behind the direct reason of forest clearance for agricultural use, however, lie a variety of intricately linked indirect economic, political, ecological and social factors influencing farmers' actions (Jarosz 1993, Aubert et al. 2003, Casse et al. 2004, Muttenzer 2010). Meanwhile, it remains poorly understood what role local farmers' socio-cultural realm of attitudes, motivations and behavior plays within this network of driving forces and how deforestation affects their livelihood systems.

The aim of our research was to fill this gap by investigating deforestation and forest fragmentation on the eastern escarpment of Madagascar from a livelihood perspective. The objectives were (i) to identify core and context factors of livelihood systems that lead to agricultural expansion at the expense of natural forests and (ii) to analyze how farmers' livelihood systems are affected by deforestation. In order to understand the evolvement of livelihood systems and strategies, we worked in a transect covering different forest landscapes with different deforestation rates over the past decades. With the aim of obtaining a broad understanding we put our own empirical data in a wider context and complemented it with information from other scientific research articles.

METHODOLOGY

STUDY SITE. Geographical situation: The Manompana corridor study site (cf. Urech et al. 2012) is located on the east coast of Madagascar in the region of Analanjirofo, district Soanierana-Ivongo, and comprises the three municipalities of Manompana, Ambahoabe and Antenina. The Manompana corridor comprises a forested area of around 30,000 ha. From 2007 to 2012 a forest project called KoloAla Manompana was implemented in the corridor, aimed at transferring the management rights of the forest resources to the local communities in order to allow local communities to benefit from sustainable timber harvesting and trade (Urech et al. 2013). The nearest town with a bigger market and connected to the town Manompana with a tarred street is Soanierana-Ivongo. This market is accessible in about 1–2 days walking time from the villages within the Manompana corridor. Only small local markets selling staple foods exist along the tarred street in the Manompana corridor, following the coast. From remote villages, the road is reachable in 7–8 hours walking time, across swampy and hilly landscapes. Annually, Manompana experiences several tropical cyclones (Jury et al. 1999), causing serious damage to agriculture and infrastructure.

Population: All households within the study site are involved in a mixed-production system combining subsistence rice and staple crop cultivation, with market-crop production in some cases. Staple crops (rain-fed rice, manioc, sweet potato) are mainly cultivated with slash-and-burn systems on slopes; if households have access to suitable land, they also cultivate irrigated rice in paddies on valley bottoms. Terraces on slopes for crop cultivation are nonexistent in this zone. For income generation, households sell rice surplus and market crops such as cloves, vanilla, coffee or litchi. Most households cultivate 1–3 land slots in an agroforestry system, combining annual crops (manioc, sweet potato, sugar cane, etc.) and trees (clove, papaya, jackfruit and other fruit and non-fruit trees or bushes). The large majority of the study site's population belongs to the Betsimisaraka ethnic group and around 89% of households in the Manompana corridor are living below the national poverty line (INSTAT 2011).

SUSTAINABLE LIVELIHOOD APPROACH. In order to gain a holistic understanding of households' livelihood systems and decision-making processes with respect to deforestation, the Sustainable Livelihood Approach (SLA), as described in Högger and Baumgartner (2004) and Eyhorn (2007), was chosen as the conceptual framework. Compared to other livelihood frameworks, the SLA also takes further dimensions into account, such as the personality characteristics of individuals, their perceptions, emotions, attachments and traditions (Eyhorn 2007). It integrates the analyses of (i) livelihood context factors, (ii) the livelihood core factors and strategy development and (iii) the livelihood outcomes.

Decisions which lead to deforestation in our study site are taken on the individual level, but can be influenced by factors connected to an ethnical group, the village or even the national level. The SLA is the most adequate approach for the analytical distinction of the broad variety of factors that influence households in our study site.

CONTEXT FACTORS. Context factors are the dynamic external conditions influencing the strategy development process of a household. The SLA divides these factors into opportunities, risks and vulnerabilities; policies, institutions and organizations; and processes and services. We analyzed the 'opportunities' that forests provide that could pose incentives to households to decrease deforestation and forest fragmentation; thus, opportunities that could positively influence households' decision-making process towards a more sustainable forest management.

As 'risks and vulnerabilities' we assessed possible events or realities that can negatively impact livelihoods and drive people to clear forests. Risks are in our case mainly biophysical events (e.g., climatic variability, cyclones, disease). Such risks can lead to vulnerability, depending on the household's ability to cope with them. Similarly, we explored 'policies, institutions, organizations and processes' as well as existent and non-existent farmer support 'services' that could influence households' decisions with respect to deforestation.

CORE FACTORS AND STRATEGY DEVELOPMENT. Personal, emotional and spiritual aspects and orientations are considered the core factors of rural livelihood systems which directly influence the decision-making process of a household (Eyhorn 2007). Core factors and the resulting decision-making process are analyzed with the help of the nine-square mandala (Högger 2004). It can be depicted as a house (Supplementary Material 2) with the three floors representing (i) the orientations at the individual, family and community level in the roof layer, (ii) the interactions of socioeconomic aspects as well as family and individual dimensions and (iii) the household's material resources, its knowledge, skills and emotional values as the household's foundation. Livelihood strategies reflect the range of activities and choices that people make based on the given context and core factors (Eyhorn 2007).

LIVELIHOOD OUTCOMES. Livelihood outcomes are the achievements of livelihood strategies (Chambers 1995, NADEL 2007). The outcomes then feedback into the livelihood system and influence all its dimensions (context factors, core factors and strategy development). In this study, we aimed to analyze what outcomes result directly from deforestation and forest fragmentation. We worked in villages along a landscape transect covering different forest landscapes; from scarcely forested areas up to densely forested areas.

Based on satellite image interpretation (Rabenilalana 2011) we know that the villages with scarce forested areas lost a large amount of forest resources in the past few decades, due to deforestation. Working along a landscape transect allowed us to understand how the decrease of forest resources influences livelihood systems.

DATA COLLECTION. Research was conducted in four villages situated at differing distances to the forest massif and with varying forest resource availability (Table 1). We understand the term 'forest massif' as the entire contiguous forest area of the Manompana corridor as well as forest patches with a surface of more than 500 ha and a distance of less than 100 m to the contiguous forest area. In two villages, Ambofampana and Maromitety, forest still covers 75% and 86% of the total village territory, respectively, and villages are situated near the large contiguous forest massif (≤0.5 hours walking time). Thus, deforestation and forest fragmentation are assumed to not yet have had an immediate, measurable impact on local livelihoods. The other two villages, Bevalaina and Antsahabe, are situated far from the forest (>1 hour walking time) and have highly fragmented and degraded forest covers of 20% and 43%, respectively. We know that those villages were also situated near to the forest massif in the past (Green and Sussmann 1990). Thus, deforestation and forest fragmentation are assumed to have already exerted a measurable outcome on local livelihoods. The selection of the two villages near the forest massif and the two villages far from the forest massif allowed us to analyze the direct outcomes of deforestation and forest fragmentation.

Table 1. Characteristics of the four studied villages.

Characteristics	Ambofampana	Maromitety	Bevalaina	Antsahabe
Distance to forest massif (walking time in h)	0.25	0.5	2	3
Category of distance to forest massif	near	near	far	far
Forest cover (% of total village territory)	86	75	43	21
Forest fragments (% of forest cover in village territory)	5	20	100	100
Number of households living in village	27	26	110	65
Market proximity (walking time in h)	6	8	2	1
Primary school is available	no	no	yes	yes
Age of village: (foundation year)	around 1980	around 1998	around 1910	around 1950

In order to limit our investigations to factors and strategies relevant to our research question, we first had to obtain an overall understanding of the local situation. Therefore, open discussions with randomly selected households (total N=20) were conducted in the four villages. The discussions covered were related to major problems and key livelihood strategies, the relatedness between people and natural resources and general core and context factors.

Specific details with regard to forest use, deforestation and agricultural expansion were explored using household surveys (N=110) and focus group discussions (N=24) with five participants each, disaggregated by gender and wealth. Furthermore, we used participatory and direct observation techniques (Marshall and Rossman 2011). Additional semi-structured interviews with resource persons (e.g., village authorities, village elders) allowed for the triangulation of results (Denzin 1970).

QUALITATIVE AND QUANTITATIVE DATA INTERPRETATION. Most data have been qualitatively analyzed and interpreted. We grouped and categorized frequent statements from households and focus groups and took different factors such as gender and wealth into account. This allowed us to identify driving forces of current livelihood strategies of local households. In the analysis, we focused mainly on those household strategies that were common for a larger part of the population or the collective, rather than on single exceptional strategies. However, strategies representing either a potential benefit or a hazard to the collective (e.g., if an individual household does not respect the common community rules) have also been considered. Since our aim was to provide a comprehensive understanding of farmers' complex realities we complemented our own empirical data with the existing scientific knowledge in this region (Jarosz 1993, Brand and Pfund 1998, Styger et al. 1999, Pfund 2000, Kistler and Messerli 2002, Messerli 2002, Aubert et al. 2003, Kull 2004, Hume 2006, Keller 2008, Pollini 2009, Rakotoarison 2009, Muttenzer 2010, Gorenflo et al. 2011).

To test the correlation of quantitative non-parametrical data in relation to the distance of the four studied villages to the forest massif, the Spearman's rank correlation coefficient was used. To test the difference between the two categories near and far from the forest massif for significance, the Pearson's X2-test was applied.

RESULTS AND DISCUSSIONS

CONTEXT FACTORS. Opportunities provided by forests: We found several situations in which forest resources could potentially provide opportunities for simultaneously improving local livelihoods and preserving the forests. Forests provide diverse products that are used for personal consumption and income generation. All interviewed households depend on timber for house and tool construction, and 79% of households use edible non-timber forest products (NTFPs) such as tuber, roots, fruits and palm hearts to complement cultivated crops or to enhance cash income (Table 2). This is especially important during the lean season, when households have consumed all rice from the last harvest and not yet harvested again. However, the quantity of edible NTPFs is very small and insufficient to feed a whole household (mean of five persons). Other products used for household consumption are fuel wood, plants for braiding activities and medicinal plants.

Cash income from NTFPs or timber is generated by 47% (N=49) of all households. However, the annual income per household generated from forest products is only 0.7% (1.6 Euro) to 9.3% (19.7 Euro) of the total annual cash income per household (Urech et al. 2012). This is very low compared to the income generation through forest products in other regions of Madagascar (Shyamsundar and Kramer 1996). In the Manompana corridor, NTFPs as well as timber products are sold at prices that do not match the amount of time and effort people spend for harvest and transport. However, the potential of forest products to increase monetary benefit is exploited only to a limited extent. According to Rabenilalana (2011) the high potential of precious woods, mainly of the genus Dalbergia, in the Manompana corridor could, at least for households in the two remote study villages Maromitety and Ambofampana, provide a maximum annual gross income of up to 40 Euro per household, if harvested sustainably. This corresponds to 19% of the mean annual income per household in the region (Rakotoarison 2009). Thus, the potential is considerably higher than the current earnings from timber trade and NTFPs combined. Nevertheless, limited market access in the two remotest villages hampers the harvest of precious woods for trade. In contrast, in the two villages enjoying better market access, the potential of precious woods is already fully exploited (Rabenilalana 2011). People coming from other territories log the remaining precious woods illegally. For instance, over a ten-day observation period in an accessible forest near one of the study villages, we observed 82 loggers. They transported timber by foot, carrying one timber board on their shoulder. Of the 82 observed loggers, 78 came from neighboring territories. Thus, the benefits from the village's precious wood are lost to households in other territories. Since the management rights for forest resources have not yet been transferred to the villages, they have no legal basis to defend their forest territories.

Table 2. Number and percentage of households (out of 110) collecting different categories of forest products for personal consumption.

Categories of products provided by forests	Household harvesting	
	Number	%
Timber for house construction	110	100
Food (tuber, roots, fruits, palm heart)	87	79
Timber for fuel wood	81	74
Plant leaves for braiding	81	74
Medicinal plants	23	21

Risks and Vulnerabilities: Risks in the Manompana corridor are represented by the highly variable environmental (e.g., natural hazards) and economic context (high price fluctuations) as well as by diseases or death of a family member. Due to extreme poverty, households in the study site are particularly vulnerable to these risks, as they are unable to cope with such changes. Examples would be that they cannot hire additional labor to cope with labor shortages or spend money and time to rebuild irrigation systems if a cyclone has destroyed those.

Despite planting rice and other staple crops for subsistence, 60% of all households have to buy additional food during the lean season because they do not produce enough crops to feed all household members. The majority of households are therefore engaged in casual day labor to generate additional cash. Moser and Barrett (2006) identified dependency on day wages and thus reduced labor availability for the households' own fields as one of the most important factors hindering farmers from improving agricultural practices. In our study site, households do not have enough time, money and flexibility to experiment with risky new technologies and thus prefer to maintain their low-input tavy system. Unfortunately, the main potentiality to escape poverty depends on increasing the productivity of one's one own field (ibid). Thus, households are caught in a poverty trap (Rakodi 2002, Sachs et al. 2004).

Diseases, such as malaria, which is highly prevalent in the region (WHO 2014), constitute another permanent risk as they can fatally reduce labor availability for agricultural activities.

According to the interviewed households, decreasing soil fertility in the whole region further constrains already low yields, and through this increases their vulnerability to natural hazards. Where possible, households thus extend their land under fallow. Cyclones do not only periodically devastate or damage annual rice crops but also destroy irrigation systems and perennial market crops on agroforestry parcels. This deters households from experimenting with permanent agricultural systems and undermines their nutritional and economic security.

With regards to important market crops (e.g., clove trees and vanilla), price fluctuations are another factor reducing motivation to invest household resources into agricultural diversification. Some agroforestry plots were even cleared for this reason. A stable market system that could guarantee a minimum annual income from specific market crops could significantly assist the diversification of households' production and agricultural systems.

Policies, institutions, organizations and processes: According to the policies of the state government, forests are state property and any forest clearance is strictly forbidden. This ban seems to have little effect on local practices. Currently, local customary rights determine forest management and forest clearance in these remote areas. Most commonly, the process of deforestation around our study villages occurs in two steps: (i) forest fragmentation and (ii) forest clearance. By segregating a forest fragment from the large forest massif, households are subsequently considered the rightful owners of the newly created forest fragments next to their arable land, following the local customary right. Consequently, the right to clear the forest fragment is restricted to them (Aubert 2008, Muttenzer 2010, Urech et al. 2011).

As the state forest service has failed to control and assure forest conservation through a centralized forest management policy (Kull 2004), a framework for community-based forest management was established in 1996 (Bertrand et al. 1999). Based on this framework, a local conservation and development project, aimed to establish the necessary local institutions for sustainable and economically beneficial forest management, has been set up in the Manompana corridor. Hence, management rights were transferred to local communities. Local inhabitants should have control of timber logging in allocated areas and can thus benefit directly from the timber trade. The general aim of placing value on existing precious woods, enabling the local population to benefit from them and assuring sustainable forest management through community-based management, is a fundamental opportunity for local inhabitants. However, a recent study by Rasolofoson et al. (2015) showed that commercial community-based forest management can only contribute to reducing deforestation in Madagascar if institutional shortcomings are solved and local participation is guaranteed.

While decentralized community-based forest management could present an opportunity for local people, it is also highly challenging. If the *tavy* practice continues as it has until today, sustainable forest management cannot be realized. For households to be able to reduce their dependence on *tavy*, alternative, productive and sustainable agricultural techniques are needed. Our research shows that officially accepted land tenure rights are also an important barrier preventing households from investing time and labor in the improvement of their agricultural systems. According to the state law very few individuals are recognized landowners. In the two villages near the forest massif, official land ownership does not even exist. Agricultural land for *tavy* is traditionally distributed among children by their parents. As long as parents have not officially distributed their land, descendants have to cultivate another slot of land every year, allocated by the parents. Thus, many young households have little motivation to invest more time and labor in their cultivation systems, than absolutely necessary, as they cannot be sure to reap the long-term benefits of their investments. Additionally, many households have to lease a slot of land from another owner because they do not own land in their family or because they have immigrated. Several households of the same lineage also cultivate some land areas jointly, in which case no one feels responsible for improving production. This complex situation of land tenure combined with the fact that many farmers do not own land hinders the planting of trees for market crops (stated by 40% of the farmers), because households can only plant trees if they traditionally own the land. Thus, households need to own their land to improve yields and to diversify their systems with trees. This, however, can often only be achieved by clearing the forest.

Farmer support services: Manompana's farmers cultivate their hill rice in the same fashion as their ancestors have for centuries. The villages in our study site do not receive support from the government or from NGOs for improving production systems or introducing new agricultural techniques. In regions with better access to roads or rivers, only one organization financed by foreign donors tries to implement a system of intensified rice cultivation (SRI) on irrigated fields. Although experimental studies have shown that, in Madagascar, SRI could increase yields (Barison 2002, Uphoff and Randriamiharisoa 2002), these systems are poorly adopted by local households in ours as well as in other regions (Moser and Barrett 2003). Furthermore, results from interviews and literature review (Hume 2006) show that improved crop yields on irrigated rice fields do not replace the system of *tavy* on slopes; among other reasons, some of the farmers do simply not have access to irrigated rice fields. To improve current agricultural production and to change the current *tavy* system, low-investment technologies that can be applied to steep slopes and small plots are necessary. Such innovative technologies were developed by research institutions in Madagascar, e.g., direct seeding on permanent vegetal cover (O. Husson pers. comm.). However, pest and disease control in the absence of chemical inputs is often a major constraint for the success of those technologies (Messerli 2002). Furthermore, households' flexibility to experiment is strongly restricted by the availability of money (Uphoff and Langholz 1998), time and the fear of cyclones. In any case, replacing traditional systems of *tavy* with a permanent and sustainable cultivation system will require the constant and long-term support of professional technicians (O. Husson pers. comm.).

With regard to forest management, the state forest service is nearly nonexistent in rural areas. The state forest service has one person responsible for the control and monitoring of the whole Analanjirofo region, which includes 1.2 million ha of forests. Considering the remoteness and inaccessibility of most of the region, we can conclude that the control of these forests by a single person is impossible. Community-based forest management might be a step in the right direction, but the local population needs stronger support from the forest service in order to develop the necessary skills to manage forest resources on their own and to resolve possible conflicts among stakeholders.

CORE FACTORS AND STRATEGY DEVELOPMENT. Enhance food security through risk minimization: Producing enough crops to feed all household members is the main aim of households in the study site. The current strategy to maintain soil fertility is to keep long fallow periods. As a result, forests are cleared to make new agricultural land available. In villages close to the forest, fallow periods are up to 10 years, while in villages far from the forest fallow periods have decreased to about five years. Compared to the crop yield of *tavy* systems, traditional irrigated rice cultivation can produce twice as much (Brand 1998). But, as stated by farmers, the latter requires higher time investment to prepare the terrain, to transplant the seedlings and build irrigation systems, and to rebuild them after the damages caused by annual cyclones. Furthermore, farmers explained during interviews that even if irrigated fields produced more than enough rice for personal consumption, they would still continue with *tavy*, in order to diversify their systems and to reduce the risk of crop failure due to cyclones. *Tavy* is known to be a flexible, low-intensive and cyclone adapted system in other regions (ibid). Households stated that they prefer to grow food in slash-and-burn systems in order to enhance food security in the short-term. Moreover, due to the rugged topography, 34% of households in the remote villages do not have access to suitable land to cultivate irrigated rice.

Attain customary land ownership through deforestation: As described above, according to customary law, households can become traditional owners of forest fragments and land through clearing forests. Especially for poorer households or immigrants this is often the only possibility to attain land ownership. Thus, many landless people move to very remote regions where they can find a contiguous forest massif not yet owned by other families. When more land is needed for future descendants or if soil fertility in the tavy system is decreasing, households begin to clear their own forest fragments to bring the forest soil into production.

Attachment to ancestors: The system of *tavy*, as we observed in the Manompana corridor, is an integral part of the culture pertaining to the region's dominant ethnic group of the Betsimisaraka. This is the case also for other regions of eastern Madagascar (Bertrand and Lemalade 2008). Keller (2008) observed on the Masoala peninsula that the conversion of forest into arable land is considered essential for ensuring a connection between the ancestors and future generations. Descendants should be rooted in the land of the ancestors by cultivating their land (ibid), and forests are ancestral land. According to long tradition, deforestation and subsequent cultivation are a means of guaranteeing this connection.

Another important element of the Betsimisaraka's culture, which could be observed in our study site as well as in other regions of the eastern escarpment (Kistler and Messerli 2002), is the duty to honor the ancestral way of life and continue with the same systems of cultivation as were used in the past. Thus, these traditions hinder households from experimenting with new technologies, as they provoke social pressure from other villagers. Many taboos are linked to cultivation systems, especially *tavy*, and village chiefs and other village members control the application of taboos. Village chiefs in our study site noted that if households renege on particular taboos, village authorities must sanction them. This was the case if farmers applied new technologies or if they did not respect the two to three days (according to the individual village) per week during which farmers are not allowed to work in their agricultural fields.

Individual, family and community orientation towards forest conservation: 62 households (N=110) claimed to be very motivated to conserve their remaining forest fragments and to stop forest clearance by *tavy*. These were mainly wealthier households who already own large areas of land and are aware of the finiteness of natural resources (Urech et al. 2012). To enhance sustainable forest management, such individual interests preserving forest fragments must become collective concerns; otherwise communal interventions and regulations will fail (Ostrom 1999).

However, according to Cole (2001), the mobilization of the Betsimisaraka into acting as a community has always been difficult, which is in line with Berkes (2004) who showed that the concept of a 'community' is very heterogeneous. Families are more strongly attached to their lineages than to spatial organizations or administrative structures imposed by the state. Although we could identify communal regulations that predict a sustainable use for some NTFPs (e.g., Pandanaceae) we did not observe any community-based approaches with regard to sustainable forest management as a whole. Forests are ancestral land and accordingly managed by lineage and clans, as observed in other regions of Madagascar (Kull 2004, Muttenzer 2006). Thus, while bans on the clearance of certain forest fragments or restrictions on the use of forest products exist, they are based on clan or lineage-specific taboos. We found several such remaining forests near the two villages close to the forest massif. In the two other villages, however, most of these so called 'sacred forests' have already been cleared by lineages that do not have to respect the specific taboo. Therefore, lineage-specific taboos are no guarantee for forest protection. Moreover, taboos can change within a family as resources become scarce (Fedele et al. 2011, Urech et al. 2011). This shows that orientations which could enhance forest conservation differ between lineages but can be adapted to changing circumstances over time.

Awareness of forest depletion: While exploring households' decision-making processes, we questioned people about the consequences of a landscape without forests on their livelihood systems. Most households living close to the forest massif are unable to envision a landscape without forests and are thus not aware of forest resource's finiteness. Households living far from the forest massif are significantly more aware of the exhaustibility of forest resources. They have witnessed the large-scale disappearance of forest resources and the consequent scarcity of resources. The further households were living from the forest massif, the more able they were to name forest products existing in the past from the village territory (Spearman's correlation, r=0.305, N=88, p=0.004). We also asked households if they would agree to a prohibition of the expansion of *tavy* practice on natural forest in their village territory. The further away the village is from the forest massif, the higher the agreement is to prohibit such extensions in order to preserve remaining forests (Spearman's correlation, r=0.557, N=96, p<0.001).

LIVELIHOOD OUTCOMES AND THEIR INFLUENCE ON LIVELI HOOD SYSTEMS. The number of households collecting timber and NTFPs for personal use does not differ significantly between households living near or far from the forest massif (Table 3). However, there is a significantly higher proportion of households living far from the massif who gain cash with timber (Pearson's $X2 = 7.08$, df=1, p=0.008). This can be explained by market accessibility, rather than by proximity to the forest massif. Near the forest massif, people have better access to precious woods but cannot exploit it because of market inaccessibility. In contrast, the number of households selling NTFPs is significantly higher close to the massif (Pearson's $X2 = 15.07$, df=1, p<0.001). This is due to the proximity to the forests where NTFPs are still available in high quantities and are of good quality. Moreover, NTFPs are easier to carry over long distances to markets than timber.

Table 3. Number of households (out of 110) collecting timber and NTFPs for personal use or trade, separated by the distance to the forest massif (near and far).

	Near forest massif		Far from forest massif	
Answers from questioned households (N=110)	Number	%	Number	%
Timber harvest for personal use	48	100	62	100
NTFP harvest for personal use	47	98	52	84
Timber harvest for trade	7	15	24	38
NTFP harvest for trade	27	59	9	14

Households collect a decreasing number of different NTFPs for personal use or trade the further they live from the forest massif (Spearman's correlation, r=-0.777, N=102, p<0.001) (Figure 1). One reason for this decrease is obvious: the less forest area that exists in the village territory, the less people can collect NTFPs. Another reason is that people living near the forest massif must invest less time in searching for NTFPs that exist only in the massif (e.g., wild pigs, lemurs). A third reason is the decreasing quality of products, as is the case with tsiriky (*Pandanus guillaumetii*), for example. This plant is still well-represented in fragments surrounding villages far from the massif, but due to human population pressure plants of suitable quality for mat weaving are becoming rare. As a result, people do not collect *tsiriky* anymore and replace it with *Lepironia mucronata*, a Cyperaceae growing in marshlands (Fedele et al. 2011).

Close to the forest massif all households still have access to forest products and there is a collective orientation of all households to apply the customary rights of open access to all forest products. In the villages far from the forest massif we could observe growing dissatisfaction with regard to open access to forest products. Fragment owners fear that forest resources will not satisfy their future needs, especially for fuel and timber. Some farmers also began to ask for money from outsiders who want to cut timber in their fragments. Their dissatisfaction may influence the social cohesion of the community and has already resulted in social conflicts among villagers.

Households living far from the forest massif have found ways to adapt their livelihood strategies to the new context of degraded and limited remaining forest resources. Some forest products are replaced with alternative products growing in land use types other than forests. However, the use of alternative products often results in a forfeit of quality. For instance, the leaves of *ravintsira* (*Dypsis* sp.) a palm species growing in forests (Byg and Balslev 2001), are used to build house roofs, but can be replaced by the leaves of *ravinala* (*Ravenala* sp.), growing in secondary vegetation. *Ravinala* is less resistible to rain and lasts only a few years. Other forest products such as high quality timber, certain edible roots or meat (e.g., from lemurs) must be bought at local markets because they are no longer available in the vicinity of the study villages. This adaptation of livelihood strategies has a significant outcome on livelihood systems: if products have to be bought, households become more dependent on cash availability through income generation activities. In turn, this has a negative influence on the social cohesion between villagers. Many households noted that in the past, families helped each other to cultivate their fields. Nowadays, people want to be paid for their work. Forest products such as tubers or fruits are replaced by products growing in crop and agroforestry systems. As a consequence, with decreasing availability of forest products, the increasing diversification of crop and agroforestry systems can be observed. Products from agroforestry systems can also be sold and allow households to increase their cash income. However, as described above, major obstacles for the expansion of agroforestry systems include the risk of cyclone damage, limited market access to sell fruits, and the high price fluctuations of the market crops.

Research results show that households living close to the forest massif depend more on forest resources than households living far from the massif. To explore households' own perception about their dependency on forests, we asked them "What are the consequences of deforestation on your personal well-being?"; 59% of all answering families see negative consequences (details described in Urech et al. 2013). The most frequent negative consequences cited are that families will need more time to find necessary products, that income generation through timber and NTFP will decrease and that forest products will be of lower quality. However, our concluding question after the analysis of the specific consequences was: "Could you survive without forests?", and 79% (N=19) of the households living closest to the forest massif confirmed that they could survive without forests (Figure 2). Considering only the three villages within 0.2 to 2 hours walking distance of the forest massif, the percentage of people answering with "no" increased significantly and correlated inversely with distance (Spearman's correlation, r=-0.324, n=67, p=0.008) to the massif. Surprisingly, in the fourth village furthest from the massif, 85% (N= 23) answered again with yes, they could survive without forests.

We associate the predominant perception close to the forest massif of not being dependent on forest resources with a low awareness of forest scarcity. Moreover, the strategy of households living close to the massif is still to clear forests to gain more arable land. This shows that for the decision-making process, forests are not perceived as very important in terms of their products, but rather as a future land resource for agriculture. However, in the village furthest from the forest massif, people are aware of the consequences of deforestation but have learned that they are able to survive with very limited forest resources.

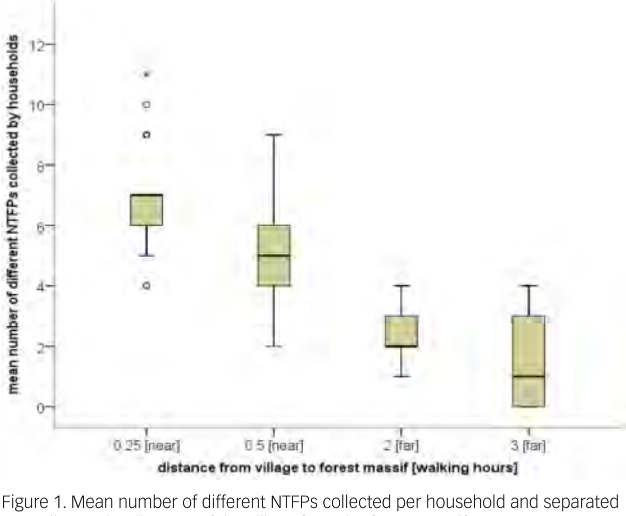

Figure 1. Mean number of different NTFPs collected per household and separated according to the distance of the village from the forest massif.

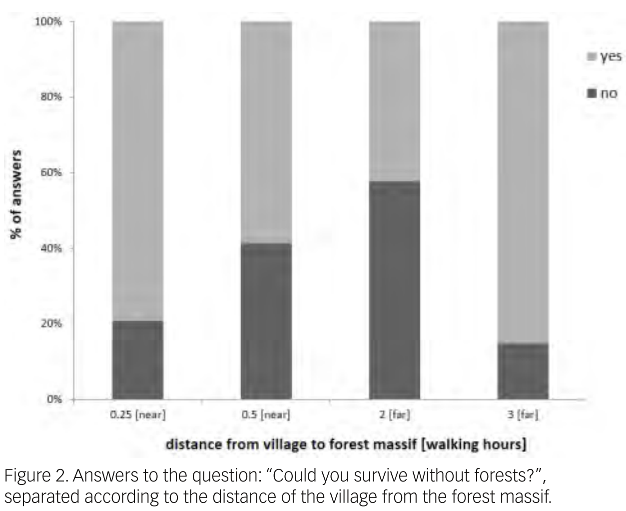

Figure 2. Answers to the question: "Could you survive without forests?", separated according to the distance of the village from the forest massif.

CONCLUSION

The current livelihood strategies of local households are based on the traditional tavy rice cultivation practice, which leads to deforestation and forest fragmentation. The opportunities arising from exploitable forest resources do not seem beneficial enough to make households change their livelihood strategies to preserve those resources for the future. Although there is an existing potential for the commercialization of precious woods and NTFPs, currently it cannot be exploited due to nonexistent infrastructure, limited market access, a lack of an institutional framework and the absence of regulations that would allow a legal, sustainable and profitable trade in forest resources. In addition, the very slow growth of *Dalbergia* species as well as the currently intensive illegal logging (Randriamalala and Liu 2010) considerably reduce the potential for an ecologically sustainable exploitation.

Forest products are used as long as they are available. Once forest resources become scarce, people demonstrate the flexibility to adapt. Products are substituted and cultural values and rules are adapted accordingly. Nevertheless, it must be noted that all of our studied villages still have forest resources left. The *tavy* rotation cycle in these villages is 5–10 years, whereas it has decreased to three years in other regions of Madagascar (Styger et al. 1999, Hume 2006). Households in our study villages have not yet experienced the consequences of the high soil erosion and degradation that have occurred elsewhere on the island. If deforestation continues, the environmental consequences are likely to negatively impact agricultural production systems in the Manompana corridor in the future.

In order to improve the overall sustainability of livelihood systems and wellbeing of households, current agricultural practices should be transformed into permanent cultivation systems that (i) do not undermine soil fertility, (ii) produce enough crops to feed the growing local population and (iii) can co-exist with the remaining forests. Such improved production systems have to be designed and tested in close collaboration with the concerned households and farmer communities, so that the new practices are in line with livelihood strategies and the common obstacles to adoption are considered. Those obstacles are manifold: Households' current livelihood strategies are based on experience and risk management, and may be wise with regard to their biophysical environment.

The *tavy* practice is flexible and less vulnerable to damages caused by cyclones than are irrigated rice fields (Brand 1998, Laney 2002). The fact that tavy is deeply anchored in Betsimisaraka culture and that innovation often is hampered by social pressure, adds an additional hurdle to the implementation of innovative technologies. Unsecured tenure rights are another obstacle for local households to diversify their traditional agricultural systems. Moreover, the high vulnerability of local households severely limits their motivation to experiment with and to invest time and resources in new agricultural practices. Therefore, any new technologies that are proposed should be low-input and adaptable to local conditions, and not too susceptible to cyclones. Households need access to additional and alternative income sources in order to allow them a minimal flexibility to experiment with innovative technologies. Moreover, a long-lasting collaboration between local traditional authorities, extension workers and agronomists is needed to adapt new technologies to given cultural factors and social circumstances and to involve local authorities in a common decision-making process.

In order to guarantee forest conservation, it is recommendable to harness the existing potential of forest resources in such a way that preserving forests becomes a more attractive option to households than clearing them. An institutional framework encouraging the sustainable use of these opportunities is vital. The community-based forest management project which was implemented in the Manompana corridor was a significant first step in the direction of beneficial and sustainable forest management and the support of local institutions created in the course of the project should be maintained to ensure their continuity. Income generation from forest products would also allow households to have an alternative source of cash income, which in turn would give them more flexibility to invest in agricultural improvement. It would thus be possible to ensure the future availability of forest resources and environmental services to a greater extent. However, community-based forest management can only be realized if livelihood systems as a whole are considered. Innovative approaches that address the current problems of rural livelihood systems and that can cope with the complexity of rural peoples' realities are needed. The forestry sector should develop a more integrative landscape planning approach, widening the scope to include agricultural land use.

Our research shows that to counter the strategies leading to deforestation, changing one context factor or simply improving one sector of peoples' realities will not be sufficient. National and international organizations are confronted with considerable challenges. They need a broad understanding of the different factors that influence people's decision-making process, including socioeconomic, ecological, and cultural aspects. However, the local population must also contribute to the betterment of its current situation. While the ability of local households to change their livelihood strategies is limited by their given context, their willingness to change some of their habits, customs and traditions is indispensable for a successful collaboration between different institutions and the local population. A holistic understanding is the necessary starting point for further investigations and future interventions. However, particularly in regard to understanding, aspects of cultural attachments, and the dilemma between collective orientation and individual innovation, will require further research by anthropologists or even psychologists.

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SUPPLEMENTARY MATERIAL.

Available online only.

Figure S1. The Sustainable Livelihood Approach, adapted from NADEL (2007).

Figure S2. The nine-square mandala adapted from Högger (2004).

S3. Questionnaires and guidelines for discussions.

Paper VI: People, protected areas and ecosystem services: a qualitative and quantitative analysis of local people's perception and preferences in Côte d'Ivoire

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People, protected areas and ecosystem services: a qualitative and quantitative analysis of local people's perception and preferences in Côte d'Ivoire

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Abstract

The long-term integrity of protected areas (PAs), and hence the maintenance of related ecosystem services (ES), are dependent on the support of local people. In the present study, local people's perceptions of ecosystem services from PAs and factors that govern local preferences for PAs are assessed. Fourteen study villages were randomly selected from three different protected forest areas and one control site along the southern coast of Côte d'Ivoire. Data was collected through a mixed-method approach, including qualitative semi-structured interviews and a household survey based on hypothetical choice scenarios. Local people's perceptions of ecosystem service provision was decrypted through qualitative content analysis, while the relation between people's preferences and potential factors that affect preferences were analyzed through multinomial models. This study shows that rural villagers do perceive a number of different ecosystem services as benefits from PAs in Côte d'Ivoire. The results based on quantitative data also suggest that local preferences for PAs and related ecosystem services are driven by PAs' management rules, age, and people's dependence on natural resources.

Keywords: Biodiversity; conservation; ecosystem services; perceptions; preferences; choice models; West Africa.

1. Introduction

The world's most biodiverse forest ecosystems are found in developing countries of the southern hemisphere, where they are surrounded by poor, rural farming populations (Fisher and Christopher, 2007; Naughton-Treves *et al*., 2005). To date, the main instrument in securing this exceptional biodiversity remains the designation of protected areas (PAs) (Deke, 2008; Dudley, 2008), whose impact on local people is still poorly understood. Although it has been shown that areas rich in biodiversity have a high potential to generate benefits for local people (Turner *et al*., 2012), to reconcile conservation goals with local needs has always been a challenge (Tallis *et al*., 2008). The demand to protect tropical forests and ecosystem services through PAs, is often generated at the global level, as are some of the benefits of the resulting conservation efforts (e.g. carbon sequestration). Furthermore, global decisions affecting the local provision of ecosystem services from PAs are made using an approach that is overly standardized and oblivious to local realities (Kaul *et al*., 2003). In some cases, however, local populations do perceive PAs as beneficial for ecosystem service provision (Abbot *et al*., 2001; Allendorf and Yang, 2013; Hartter and Goldman, 2011; Sodhi *et al*., 2010). At the same time, they feel the burden of PA establishment, mainly through reduced access to provisioning ecosystem services (Guerbois *et al*., 2012; Robertson and Lawes, 2005), displacement, and the curtailment of property rights (Brockington and Schmidt-Soltau, 2004; Colchester, 2004; Ghimire *et al*., 1997; Muhumuza and Balkwill, 2013).

Many studies have reported that the long-term integrity of African PAs, which often coincide with immense pressure exerted by human population (Balmford *et al*., 2001), depends on the support of local people (Ferraro, 2002; Kremen *et al*., 1999; Vodouhê *et al*., 2010). A meta-study on African protected forest areas found that a positive attitude towards the PA by the surrounding communities was the strongest correlate of PA success (Struhsaker *et al*., 2005). In any developing country context, key questions are what it really means for local people to live near a land devoted to conservation, and which key factors determine

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people's attitudes towards PAs and their support for conservation. The importance of local people's perspectives is further reinforced by the principle of subsidiarity, which suggests, in a simplified form, that those affected by a good should have a say in its provision (Breton, 1965; Oates, 1972; Olson, 1971). Moreover, improved knowledge regarding the importance of PAs and related ecosystem services for local people is important for conservation policy efficiency. This will help policymakers orient further conservation project development towards fulfilling local demands for ecosystem services and enhance local people's awareness about conservation. The question of local perception of and preferences for PAs is therefore of great relevance for scholars and practitioners in conservation. In recent years, studies examining perceptions or preferences of people living in the vicinity of PAs in developing countries, and more precisely in Sub-Saharan Africa (SSA), have greatly increased. However, the majority of studies have been conducted in savannah ecosystems in areas of low or moderate human population density (Hartter and Goldman, 2011). Preferences were found to be mixed, with negative perceptions often linked to crop raiding damage by wild animals (Anthony, 2007; Guerbois *et al*., 2012) or restriction of access to forest products (Guerbois *et al*., 2012; Robertson and Lawes, 2005), and positive perceptions related mainly to financial benefits (Anthony, 2007) and development programmes (Infield and Namara, 2001). In SSA, preferences were also found to be linked with socioeconomic factors (Brännlund *et al*., 2009; Coulibaly-Lingani *et al*., 2011; Ezebilo, 2011, 2012; Kaltenborn *et al*., 2006; Kideghesho *et al*., 2007; Shibia, 2010; Tessema *et al*., 2010; Vodouhê *et al*., 2010).

This paper seeks to add to this literature by presenting an example from the West African country of Côte d'Ivoire, from where, so far, no published studies of local perceptions of and preferences for PAs are available. We examined different facets of local perceptions of ecosystem service provision from protected forest areas and conservation preferences, using methods from ecological economics as well as social sciences. The paper proceeds as follows: in section 2 we describe the four local research sites, the survey design, and the data analysis; in section 3 we analyze and discuss people's perceptions of ecosystem service provision from PAs, as well as the determinants of PA preferences; and in section 4 we conclude with a number of policy recommendations.

2. Methods

2.1. Research sites

Three different protected forest areas were selected along the southern coast of Côte d'Ivoire (see Figure 1). The PAs differ with regard to their governance types and their protection status according to IUCN categories (see Table 1). Around each PA, four study villages were randomly selected, located on either side of the PA. Two villages located in the same agro-ecological zone, but with no protected forest areas in their vicinity, were included as control sites. All sites belong to the humid Guinean forest region and experience a subequatorial climate. Rainfall occurs mainly between February and November and the monthly mean temperature is between 24.5° and 26.7°C (Eldin, 1971). Vegetation in all sites is dominated by a range of coastal and lagoon ecosystems, including lowland evergreen forest, swamps and mangroves.

A mixed-method approach was applied, including (1) semi-structured, open-ended interviews and (2) a household survey using face-to-face interviews. In total, 27 semi-structured interviews were conducted with key informants and 303 households were surveyed in 14 villages from the four study sites (details on survey design are available under Supplementary Materials). Fieldwork was conducted in October 2012 by two researchers at the doctoral level (one of whom is a national of Côte d'Ivoire) and five local research assistants, all at the master's or doctoral level.

2.2. Semi-structured, open-ended interviews with key informants

Semi-structured, open-ended interviews were conducted in each of the four study sites and lasted between 30 minutes and 2 hours. Key informants included village chiefs, leaders of community associations (such as for nature conservation or fisheries' management), and representatives from women's and youth groups. In each study site, at least one woman among the key informants was interviewed. Interviews were conducted in French, and a local research assistant helped to translate into the respective local language when necessary. An interview guide was developed to gather information about the perception of ecosystem service provision from PAs and the surrounding land uses. The guide was divided into four parts. In the first part, general information about the respondent was collected. The second part concentrated on the different land uses surrounding the PA, and the associated stakeholders, as well as the constraints faced by the local population regarding land use. In the third part, changes for each of the aforementioned land uses, including changes regarding the extent of each land use along with changes in use/production mode, were discussed. Part four focused on the perception of ecosystem services from each of the land uses, including the PA and changes associated with these services over the past ten years. For part four, a list of ecosystem services, based on the Common International Classification of Ecosystem Services (CICES) of the European Environment Agency (Haines-Young and Potschin, 2010), was developed. The main difference between this classification and the one proposed by the Millennium Ecosystem Assessment (MEA) (Hassan *et al*., 2005) is that the MEA's categories of supporting services

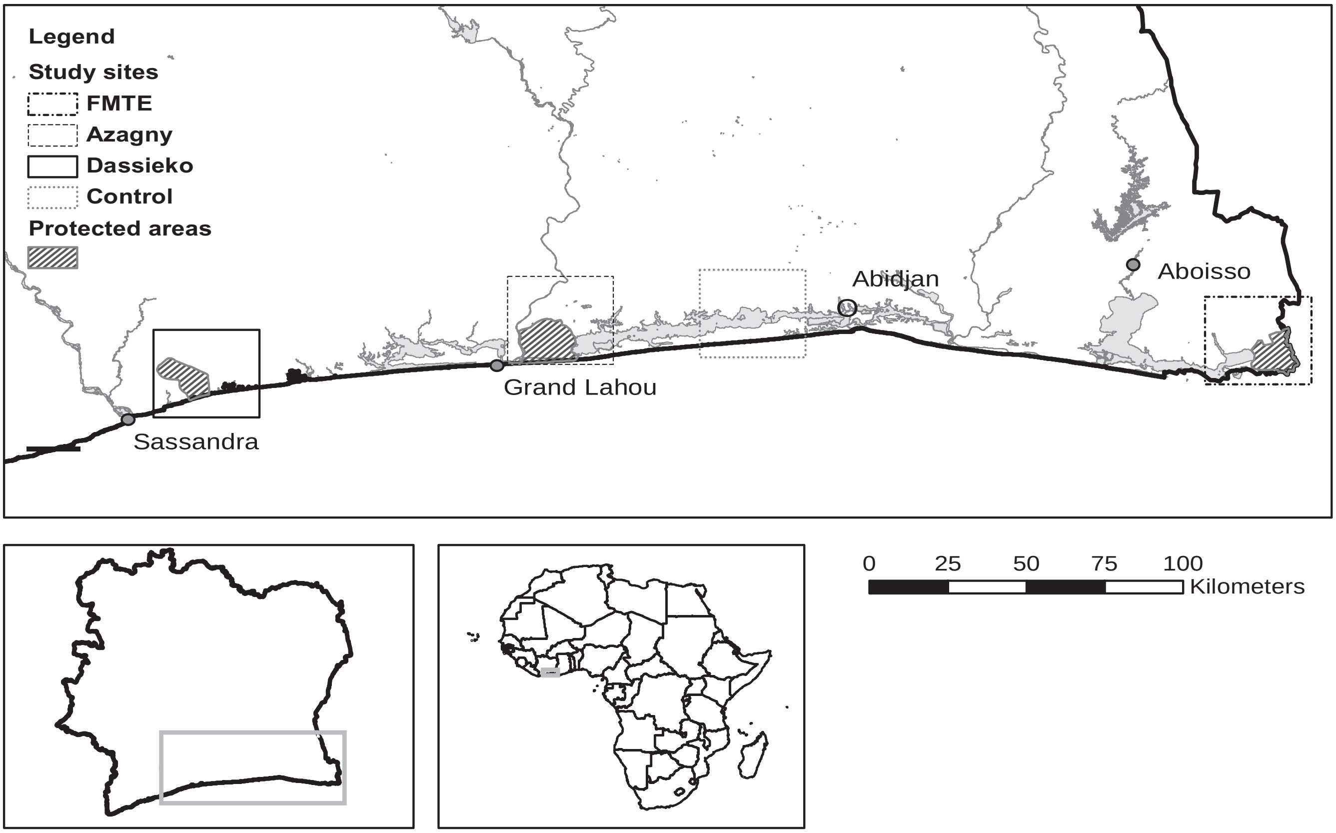

Figure 1. Map of southern Côte d'Ivoire showing the location of the four study sites around the PAs of Forêt marécageuse de Tanoe-Ehy (FMTE), National Park of Azagny, Classified forest of Dassioko, and the control site.

Table 1. Characteristics of PAs and background information for the four study sites

Name of PA	IUCN category	Governance types	Surface (ha)	Year of creation	Location (latitude/longitude)
Community based Forêt Marécageuse de Tanoe-Ehy (FMTE)	IUCN category VI Species (primates) management area, core area with buffer zone	Type B: Shared governance (local communities, national agency, private actors in charge)	12,000	2006	Lat: between 5°05′ and 5°15′ N Long: between 2°45′ and 2°53′ W
National Park of Azagny	IUCN category II Wilderness area, core area with buffer zone	Type A: Governance by government (national agency in charge)	19,400	1981	Lat: between 5°09′ and 5°16′ N Long: between 4°48′ and 4°58′ W
Classified forest of Dassioko	IUCN category VI Buffer zone	Type A: Governance by government (state enterprise in charge)	12,540	N/A	Lat: between 5°00′ and 5°07′ N Long: 5°49′ and 5°56′ W
Control site without forest cover	Unprotected status	Open access			

Notes: IUCN categories and governance types are from IUCN guidelines for applying protected area management categories (Dudley, 2008). Information on FMTE are from Zadou *et al*., (2011). Information on the National Park of Azagny and the Classified forest of Dassioko are from the World Database on Protected Areas (IUCN and UNEP, 2014).

and regulating services are combined into one category called "regulation and maintenance." Further, this classification categorizes ecosystem services into themes, classes, groups, and types. To facilitate comprehension by local interview partners, the list was simplified and adapted to the local context, drawing on a study conducted by local colleagues around the PA of FMTE (Zadou *et al*., 2011). Prior to implementation, the list was validated by a small group of local natural resource management specialists during a workshop on land use mapping at the Centre Suisse de Recherche Scientifique in Abidjan. The full list of ecosystem services and their classification used in interviews is available under Supplementary Materials. Participants were asked about their perceptions regarding the importance of each of the 20 ecosystem service groups (instead of the more detailed ecosystem service types) from the PA. For example, they were asked if the PA provided them with natural materials (ecosystem service group), but not if those natural materials consisted of glue, weaving materials, paint, sand, rubber, spices, or strings, which represent different ecosystem service types within this group. For each of the ecosystem service groups that the respondent agreed on as being important with respect to the PA, we further asked which ecosystem service type was provided, if the benefit from said service was generated through subsistence use or revenues from sale, which stakeholders were related to the provision and consumption of the service, and if there were any conflicts around the use of the service. In the control site without PAs the key informants were asked, instead, which ecosystem service groups had disappeared from their area. Qualitative content analysis was used to analyze the results from the semi-structured interviews.

2.3. Household surveys among people living in the vicinity of PAs

Households were randomly selected in all villages. The questionnaire was intended for the head of the household, whether male or female. We gathered information on household characteristics (such as age, education of head of household and household expenses), their main livelihood activities (such as farming, fishing, hunting, etc.), and their level of income and expenditure. We obtained information about their use of provisioning ecosystem services and about their attitudes towards environmental issues. To get information on preferences for PAs, we adopted a hypothetical choice experiment procedure. We proposed the following hypothetical scenario to the respondents: “Imagine that we would like to get your opinion before the implementation of a project that aims to redevelop PAs in your region. If you were presented with the following choices that will have an impact on biodiversity (number of animal as well as plant species), ecosystem services (crop pollination and water and flood regulation), forest industry employment and livelihood activities in the forest (hunting, firewood collection, and crop production), which option would you choose?” The alternatives were:

(a) Completely deregulate PAs. This scenario implies the loss of the legal protection status for the entire PA (Mascia and Pailler, 2011). Levels of biodiversity and regulating/supporting ecosystem services would become very low. There would be a rise in forest industry employment and no restrictions on livelihood activities (provisioning ecosystem services) in the forest.

(b) Partially deregulate PAs. This scenario implies the loss of the legal protection status for part of the PA. Levels of biodiversity and regulating/supporting ecosystem services would be considerably reduced. There would be a small rise in forest industry employment. There would be fewer restrictions on livelihood activities (provisioning ecosystem services) in the forest.

(c) Expand PAs. This scenario implies an increase in area of the PA. Levels of biodiversity and regulating/supporting ecosystem services would increase considerably. There would be a decrease of forest industry employment. There would be restrictions on livelihood activities (provisioning ecosystem services) in the forest.

Each alternative, with its advantages and disadvantages, was presented using pictures (available under Supplementary Materials). We included the status quo among the options, in case the respondents preferred to choose none of the other alternatives. To minimize complication in the measurement of preferences and to elicit the true preferences, we used follow-up questions after respondents made their choice, allowing them to indicate why they made the choice they did.

2.3.1. Preferences measurement

We measured household preference with a multinomial variable, y, which could take the values of 1, 2, or 3. To minimize the nay-saying acquiescence bias in negative preferences, we decided that a respondent has a negative preference ($y = 1$) if the respondent chose alternative (a) or (b), and if he gave an answer different from “I don’t know” to the question “What is the main reason you want the partial or total deregulating of PAs?” To minimize the yes-saying acquiescence bias in positive preferences, we decided that a household has a positive preference ($y = 2$) if the respondent chose alternative (c) and if he had a positive willingness to pay (WTP) for the question, “Are you aware that the implementation of your choice could demand a contribution on your part? In this case, what is the maximum amount you could afford in surplus of your household consumption expenses, given your income level?” To minimize the status quo bias, we decided that a household’s choice is status quo ($y = 3$) if the respondent chose the status quo and gave the answers, “I understood everything and it was my choice to do nothing” or “There are already enough PAs” to the question, “What is the main reason you want no action be taken?”

2.3.2. Preferences models specification

Since the dependent variable is not continuous and there is, *a priori*, no clear ordering of the three outcome variables, unordered multinomial models are appropriate for the analysis. The choice of multinomial specifications for each model was based on Small-Hsiao and Haussmann tests for Independence of Irrelevant Alternatives (IIA) assumptions and on three Lagrange Multiplier tests for heteroscedasticity.

We defined three ranges of explanatory variables for the preference models. First, we examined whether PA management type influences households' choices. We defined a variable "site," which took the values 1, 2, 3, or 4 for community based (IUCN category IV), national park (IUCN category II), classified forest (IUCN category V), and a control site (without forest cover), respectively. We included a control site to evaluate whether preferences for PAs in rural areas are different for people who a priori don't directly perceive the costs and benefits of conservation.

Second, we examined whether socio-economic variables influence households' decisions. We used respondents' age (Age). We defined 4 classes for the level of education: illiterate (Illiterate), primary level (Educ_prim), lower secondary level (Educ_sec1), and upper secondary level (Educ_sec2). We used consumption expenses adjusted for household size (Cons_exp), given the fact that households are less uncertain about this information compared to other expense measures, thus making it more reliable. However, we used a household's total expenses (House_exp) and total income (Income) as other income variables.

Finally, we examined the influence of dependence on provisioning ecosystem services on household decisions. We considered that a household is dependent on firewood (Fwd_dep) if wood is the fuel source most often used by the household and if the main mode of supply is the collection and/or gathering of wood. Dependence on water (W_dep) was observed if the household's drinking water supply comes from rivers, lakes or ponds, or wells with or without pumps. Households whose main supply of protein (Pro_dep) is assured through fishing and/or bush meat hunting were defined as being dependent on these provisioning services. Households that use medicinal plants (Med_dep), obtained mainly through collection and/or gathering, as their primary remedy were identified as being dependent on medicinal plants.

We introduced each category of factors — first independently and then as a whole — in order to identify the effects of each category of factors independently, as well as the cumulative effect of the factors on household choice.

In addition, in all models we used two control variables: a dummy variable (Interwr) to control for the degree of measurement noise due to the interviewer and a continuous variable (Res_year) to measure the number of years of residence in the region to control for respondent involvement in community issues. A data summary is provided under Supplementary Materials.

Following Cameron and Trivedi (2009), with N alternatives, the probability that the response for the i^{th} observation is equal to the j^{th} alternative is:

$$\Pr(y_i = j) = \left\{ \frac{\exp(X_i \beta^j)}{\sum_{m=1}^{N} \exp(X_i \beta^m)} \right\} \qquad [1]$$

where X_i is the row vector of observed values of independent variables for the i*th* observation and β^j is the coefficient vector for alternative *j*.

We checked whether the econometric models as a whole fit significantly better than empty models (i.e., models with no predictors) with the likelihood ratio chi-square test for Logit models and with a Wald chi-square test for Probit models.

3. Results and discussion

3.1. Local perception of ecosystem services and their trade-offs

3.1.1. Local perception of ecosystem services

Out of the list of 20 different ecosystem service groups, key informants from the three study sites surrounding PAs perceived eight as important with regard to ecosystem service provision from the protected forest area. From those eight ecosystem service groups, 15 ecosystem services were freely named by key informants (see Table 2). The most important ecosystem service, as perceived by 15 out of the 21 key informants, was the regulation of microclimate, and more specifically, precipitation. The interviewees either stated directly that, in their opinion, the presence of forest increased precipitation around the PA or, indirectly, that they related the perceived decrease in precipitation to the ongoing deforestation within the PA. Medicinal plants growing within the PAs were referred to as the second most important forest ecosystem service by eight of the 21 key informants. However, around the National Park of Azagny, nobody perceived medicinal plants as a benefit, while in the surroundings of the Classified forest of Dassioko, six out of eight respondents mentioned it.

The importance of PAs for protecting cultural heritage was mentioned by four of the 21 key informants. One man in a village bordering the national park expressed his appreciation for this benefit by stating that the forest was "a souvenir for everyone." The bequest value of safeguarding biodiversity for future generations was also mentioned by four of the 21 key informants. One woman living next to the national park stressed that she appreciated the PA because it gave shelter to certain animal species that her child otherwise would never have been able to know about. In line with this, another respondent feared that without the presence of the community-based PA, his children would never have the experience of seeing wild animals with their own eyes. Only a few key informants (three out of 21) attributed a spiritual value to the forest within PAs. One respondent from the community-based PA stated that "all

Table 2. Ecosystem services from protected forest areas; ordered by number of key informants who mentioned the respective ecosystem service type

Ecosystem service theme	Ecosystem service group	Ecosystem service type	No. of resource persons (n = 21)
Regulating / supporting	Climate regulation	Microclimate regulation (precipitation)	15
Provisioning	Biotic raw materials	Medicinal resources	8
Cultural	Intellectual interactions	Protection of cultural heritage	4
Cultural	Other cultural outputs	Bequest	4
Cultural	Spiritual	Sacred places	3
Provisioning	Biotic raw materials	Lianas for fish trap construction	1
Provisioning	Biotic raw materials	Construction wood	1
Regulating / supporting	Lifecycle maintenance and habitat protection	Pollination and seed dispersal	1
Regulating / supporting	Lifecycle maintenance and habitat protection	Nursery habitat protection	1
Regulating / supporting	Air flow regulation	Protection against strong winds	1
Regulating / supporting	Pest and disease control	Pest and disease control	1
Regulating / supporting	Climate regulation	Microclimate regulation (water temperature)	1
Cultural	Intellectual interactions	Esthetic	1
Cultural	Intellectual interactions	Education	1
Cultural	Intellectual interactions	Scientific	1

Table 3. Ecosystem services perceived as having decreased over the past 10 years in the control site; ordered by number of key informants who mentioned the respective ecosystem service type

Ecosystem service theme	Ecosystem service group	Ecosystem service type	No. of resource persons (n = 6)
Regulating / supporting	Climate regulation	Microclimate regulation (precipitation)	3
Provisioning	Materials for fishing / hunting	Trees for canoe construction	3
Provisioning	Materials for energy provision	Firewood	3
Regulating / supporting	Biodiversity	Animal species	1
Provisioning	Food	Wild fruits	1

people living on the bank of the lagoon believe that their god exists in the water [. . .] and where there is a forest connected to the lagoon they go to this forest to worship him.” In this case, the esthetic value of the forest was linked to the spiritual significance, as the same interviewee explained: “First of all, I think that nature itself is beautiful. And we believe in the existence of a god. Nature gives us this belief and a god. Our landscape is something extraordinary.” Other ecosystem services provided by PAs were mentioned by single respondents only. One key informant from the community-based PA noted a decrease in people’s life expectancy, which he related, on one hand, to the decrease of medicinal plant availability but, on the other hand, to the forest’s physical protection function: “There are some illnesses that are linked to the disappearance of the forest. For example, the forest used to block the wind, but nowadays there is no protection from the wind and we receive everything that the wind brings with it.” Furthermore, in the community-based PA study site, where the PA protects a swampy forest ecosystem, one of the respondents explained that the presence of forest increased the water quantity in streams and when discharged into the lagoon, would cool the water temperature and, therefore, positively impacts the reproduction of fish. At the same study site, another respondent mentioned the importance of the lianas that grow in the forest as a construction material for fish traps. Near the national park, one of the respondents perceived large-scale oil palm plantation owners to be the main beneficiaries of ecosystem services from the PA as, in his view, they profited from increased precipitation, as well as pollination services. Also at the same study site, one key informant mentioned the importance of the forest, regarding both the education of national schoolchildren through visits as well as the knowledge increased through research activities by national and international scientists. Construction wood was mentioned as a service by one key respondent near the classified forest. In this case, the benefit was financial, and accrued indirectly through the involvement of certain village members in the sale of forest exploitation permits to external logging companies.

In the control site with no PA and, thus, no forest cover left, several key informants talked about the decrease of ecosystem services due to deforestation (see Table 3). Three out of the six key informants mentioned the decrease or perturbation of precipitation as a major problem. The same number of key informants stated that the quantity and quality of firewood had decreased, and that today people have to buy firewood on the market. Furthermore, large trees required for the construction of canoes had disappeared and as a consequence, fishermen have to buy ready-made planks on the market. One respondent mentioned that primates, such as chimpanzees, and other animals have disappeared. Previously, the local people who lived mainly from fishing for subsistence and for commercialization would buy meat from local hunters to diversify their diet. However, along with the disappearance of the forest and its fauna, the hunters have disappeared as well. The loss of wild fruit trees was another ecosystem service mentioned by a single key informant.

However, not only key informants from the control site, but also some of the 21 key informants from the three study sites surrounding the PAs, were concerned about the loss of ecosystem services mainly due to deforestation. At the study site of the national park, one respondent mentioned that animals he used to see before have now become rare. As a consequence, the price for bush meat has increased; for example, for bushrats, which now cost six times more than a few years ago. Also, around the community-based PA, the decrease of bush meat availability was an important issue. At the same time, the decrease of wild animals was also mentioned as a benefit, as crop raiding by wild animals from the forest has been substantially reduced. Around the community-based PA, fishermen also mentioned the disappearance of large trees needed for canoe construction. While earlier, such large trees could be found around the villages outside the forest, this is not the case anymore, as they can now only be found inside the protected forest. One key informant from the national park explained that the spiritual value of the PA, which was linked to a small sacred lake in the middle of the forest, had disappeared because the lake had dried out over the course of the years. In the surroundings of the classified forest, an interviewee confirmed that through the ongoing disturbance and destruction of the forest, its spiritual value was being devaluated and he therefore feared immediate repercussions on people's lives.

3.1.2. Local perception of ecosystem service trade-offs

Despite the variety of ecosystem services mentioned, many of the key informants perceived a strong trade-off between forest conservation and alternative land use options. Even around the community-based PA where the forested land was said to be unsuitable for crop cultivation due to its wet soils, according to some of the key informants it would still be feasible to exploit the forest's wood resources. As one interviewee put it very clearly, "if it weren't for the conservation project we would all throw ourselves at this forest to exploit the wood, because it sells very well in [neighbouring] Ghana." One of the interviewees from the national park stated that the local population had no benefits whatsoever from the PA, and that the PA constituted a complete disadvantage to them, especially because the cutting and collecting of firewood and construction wood was not permitted. Although he admitted that it made him very sad to think that the future generations would never see wild animals, he was convinced that without access to forest resources poverty would increase. Near the classified forest one of the elders requested that in order to satisfy the need for agricultural land to cultivate subsistence crops, part of the protected forest area should be deregulated to "allow people to eat."

However, trade-offs did not only occur between forest conservation and the need for forest resources and agricultural land within the PA but, to a large extent, between the use of cultivable land for subsistence crop cultivation versus commercial crop plantations outside the PA. Near the community-based PA, the decreasing availability of land for subsistence crop production outside the protected forest was perceived as a major problem. Although cassava (*Manihot esculenta*) constitutes the dietary base for the population in this zone, the local land users' demand for land to grow commercial crops, especially rubber (*Hevea brasiliensis*), is so high that there is less and less space dedicated to the main subsistence crop. Around the national park, the situation is very similar. One respondent confirmed that in the area surrounding his village there was almost no cassava being cultivated anymore, as the whole cultivable land was now occupied by oil palm (*Elaeis guineensis*) and rubber plantations. The "chief of land" in one of the villages in the same study site confirmed that the whole cultivable land was occupied by rubber plantations, which are unsuited for association with other crops. Around the classified forest, several respondents stated that "rubber plantations cover everything now; there is no cultivable land anymore." This trade-off between the uses of cultivable land for subsistence crops versus commercial crops was also observed in the control site, where there is no forest cover left. Almost the entire cultivable land is covered in oil palm and rubber plantations. One woman phrased the problem very clearly "the men take all agricultural land for their commercial crop plantations and leave none for us to cultivate cassava, but if they come home from their work in the plantations they want to have a plate of Attiéke (local staple made from cassava) on the table". The women are therefore forced to buy cassava on the market.

The discussion of trade-offs with the key informants suggests that although people are aware of the long-term benefits of forest conservation, especially with regard to microclimate regulation, provision of medicinal plants and cultural services, the pressure on land for both commercial and subsistence crop cultivation is so high that in the absence of PAs, the remaining forest would most likely be transformed into agricultural land very quickly.

3.2. Local perception of and preferences for PAs and related ecosystem services: determinants and drivers

The quantitative analysis enables us to answer two questions. First, which factors influence the likelihood of having a negative or positive preference rather than choosing status quo? In other words, "who is the typical local respondent who perceives a direct link between PA changes and, hence, changes in ecosystem services and his wellbeing and around what type of PA does he live?" Second, how do the different factors influence the probability of positive or negative preferences? In other words, "how do management types of PAs, the socio-economic profile of households, and dependence on provisioning services influence the preference for PAs?"

3.2.1. What factors determine perception of and preferences for PAs and related ecosystem services?

The significance of the coefficients in the "positive/status quo" and "negative/status quo" comparisons, presented in Table 4,[1] allows us to differentiate between respondents who perceive a direct link between PA changes and their wellbeing and those who perceive utility with no changes in PAs.

Compared to "community based," the variables "classified forest" and "control site" are significant in model 1, while the variable "national park" is significant in model 4. The results suggest that the likelihood of perceiving a link between PA changes and livelihoods differed among respondents, depending on the type of PAs around which they live. It seems that, in our case, management rules of PAs matter in the perception of local people for conservation.

The coefficients of all socio-economic variables were not statistically significant, except for the variable age. The results suggest that the probability of perceiving a direct link between PA changes and wellbeing increases with age, but is independent of the socio-economic status of the household, measured through literacy skills and daily consumption expenses. The coefficient of the variable age is positive and significant in both comparisons, and the effect is robust for the different specifications.

The dependence on provisioning ecosystem services also had an influence on households' perception for PAs. Among all the dependence variables tested, only the variables of "dependence on drinking water (w_dep)" and "dependence on medicinal plants (Med_dep)" were statistically significant in all models. The coefficient for "w_dep" was negative and significant in both "negative/status quo" and "positive/status quo" comparisons. It suggests that getting drinking water from rivers, lakes, ponds, or wells (with or without pump) reduces the likelihood of perceiving a relationship between PAs and wellbeing. The coefficient for "Med_dep" was positive and significant in both comparisons. It suggests that using medicinal plants, obtained through collection and/or gathering, as a primary remedy increases the likelihood of perceiving a relationship between PAs and wellbeing.

[1] We set status quo as base outcome, then the coefficients measure the change relative to status quo. The relative probability of y_*i* = *j* is then: $\frac{\Pr(y_i = j)}{\Pr(y_i = 3)} = \exp(X_i \beta^j)$.

Estimates excluding the observations of the control site yielded similar results as those obtained using the full sample. The major difference was that taking into account only people living near PAs, in the category of socio-economic factors in addition to age, the level of secondary education had a significant influence on positive preferences and "status quo."

Our results suggest that the difference between a given head of household who perceives impacts from PA redevelopment and then changes in ecosystem services on his livelihood could be explained by the difference in age, the difference in management type of the PA, and by the difference in their dependence on water and medicinal plants.

3.2.2. How do the PA management type, household's socio-economic profile, and dependence on provisioning services affect preferences for PAs?

As explained above in section 2.3.1, we assumed that a respondent has a negative preference (positive preference) if he perceives a negative (positive) link between PAs and his wellbeing and chose to deregulate (to expand) PAs in the region.

Figure 2 presents plotted predicted probabilities (from equation (1)) of choosing to deregulate or expand PAs for each explanatory variable, holding all other variables in the model at their means. We use the fully specified model (model 4 in table 4) for the figure.

For instance, what we observed in the first graph is "for a common respondent (all variables at their mean, except the variable site), what will be the probability of the respondent having a negative preference for PAs if he lives near the 'community-based PA,' the 'national park,' the 'classified forest,' or the 'control site?' "

We found that while positive preference for PAs is the lowest for people living next to the national park, the probability of having a negative preference is lowest for those living near the community-based PA. Rural households seem to be more favourable towards PAs around the community-based PA, and less favourable towards PAs around the national park. This can be explained by the fact that the emphasis of the community-based management scheme is on the sustainable use of environmental products and services, and benefits are directly perceived by the local community. However, in the national park, the restriction of access to forest resources is stricter, and local people are less involved in its management. Community-based management seems to be a favourable option for the acceptance of PAs for local communities bordering PAs. This PA management type is still almost nonexistent in Côte d'Ivoire (Roe *et al*., 2009). We noted that around the control site both the negative and positive preferences are strongest. One explanation for positive preference could be that people living in an area where forests have largely been cleared are those who suffer most from the consequences of the total conversion of forests into agricultural land.

Table 4. PAs' redevelopment mode multinomial choice: multinomial logit and probit estimates

	Preferences and management types[a]		Preferences and basic human capabilities[b]		Preferences and ecosystem services dependence[a]		Full model[b]	
	Model 1		Model 2		Model 3		Model 4	
	Negative vs Status quo	Positive vs Status quo	Negative vs Status quo	Positive vs Status quo	Negative vs Status quo	Positive vs Status quo	Negative vs Status quo	Positive vs Status quo
Community based	0	0					0	0
	(.)	(.)					(.)	(.)
National Park	0.119	−0.148					−0.565	−0.864*
	(0.25)	(−0.37)					(−1.15)	(−1.90)
Classified Forest	0.924*	0.580					0.727*	0.571
	(1.84)	(1.34)					(1.68)	(1.43)
Control site	1.419**	1.126**					0.633	0.202
	(2.37)	(2.13)					(0.98)	(0.34)
age			0.0347***	0.0369***			0.0359***	0.0377***
			(3.27)	(3.64)			(3.14)	(3.46)
illiterate			0	0			0	0
			(.)	(.)			(.)	(.)
educ_prim			−0.160	0.148			−0.536	−0.0742
			(−0.45)	(0.46)			(−1.37)	(−0.21)
educ_sec1			−0.186	0.472			−0.466	0.407
			(−0.42)	(1.20)			(−0.96)	(0.98)
educ_sec2			0.00970	0.693			−0.0870	0.695
			(0.02)	(1.53)			(−0.15)	(1.37)
cons_exp			−0.0305	0.0107			−0.0254	0.0527
			(−0.18)	(0.07)			(−0.14)	(0.32)
fwd_dep					0.250	−0.290	−0.140	−0.488
					(0.54)	(−0.73)	(−0.35)	(−1.32)
w_dep					−0.856**	−0.635*	−0.782*	−0.698*
					(−2.30)	(−1.94)	(−1.87)	(−1.78)
pro_dep					0.396	−0.319	0.590*	−0.0362
					(0.97)	(−0.79)	(1.65)	(−0.11)
med_dep					0.762*	0.882**	0.668*	0.898***
					(1.88)	(2.49)	(1.92)	(2.86)
Res_year	−0.306	0.0190	−0.372**	−0.0498	−0.346	0.00976	−0.506**	−0.198
	(−1.38)	(0.09)	(−2.05)	(−0.27)	(−1.55)	(0.04)	(−2.48)	(−0.99)
Interwr	−0.104	0.143	−0.0726	0.146	−0.218	0.0804	−0.0598	0.173
	(−0.61)	(0.97)	(−0.52)	(1.15)	(−1.20)	(0.52)	(−0.39)	(1.24)
_cons	0.490	−0.523	−0.0817	−2.126	1.349	0.305	0.540	−1.424
	(0.52)	(−0.56)	(−0.04)	(−1.12)	(1.42)	(0.33)	(0.22)	(−0.63)
N	228		223		228		223	
Log likelihood	−237.9		−226.7		−235.3		−210.4	
chi2	16.97*		24.33**		22.27**		49.67***	
Small Hsia (IIA test)	for H0		—		for H0		for H0	
Hausman (IIA test)	for H0		for H0		for H0		—	
LM robust	H1		H1		H1		H0	
LM OPG	H0		H1		H0		H0	
LM	H0		H1		H0		H0	

Notes: Dependent variable y = 1, 2, 3 depending on which of the three options is chosen; t statistics in parentheses, * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$; Independence of irrelevant alternatives (IIA) test: H0 = Odds are independent of other alternatives; When the two tests for IIA assumption are conclusive, we estimate a multinomial Logit (MNL)[a], when not conclusive we estimate a multinomial Probit (MNP)[b]; LM test: H0 = homoscedasticity. Educ_prim: primary level education, Educ_sec1: lower secondary level education, Educ_sec2: upper secondary level education, cons_exp: consumption expenditure; fwd_dep: dependence on firewood; w_dep: dependence on water; pro_dep: dependence on proteins; med_dep: dependence on medicinal plants, Interwr: interviewer dummy; Res_year: number of years of residence.

For instance, these populations benefit less from free provisioning services such as food, timber, or firewood, and have to pay to obtain these resources. Qualitative data from interviews with key resource persons showed that in the control site without any PA, and thus no remaining forest, quantity and quality of firewood have decreased and, today, most people have to buy firewood on the market. An explanation for the negative preferences in the control site could be the fact that pressure on agricultural land is high. Indeed, the land areas without conservation status have

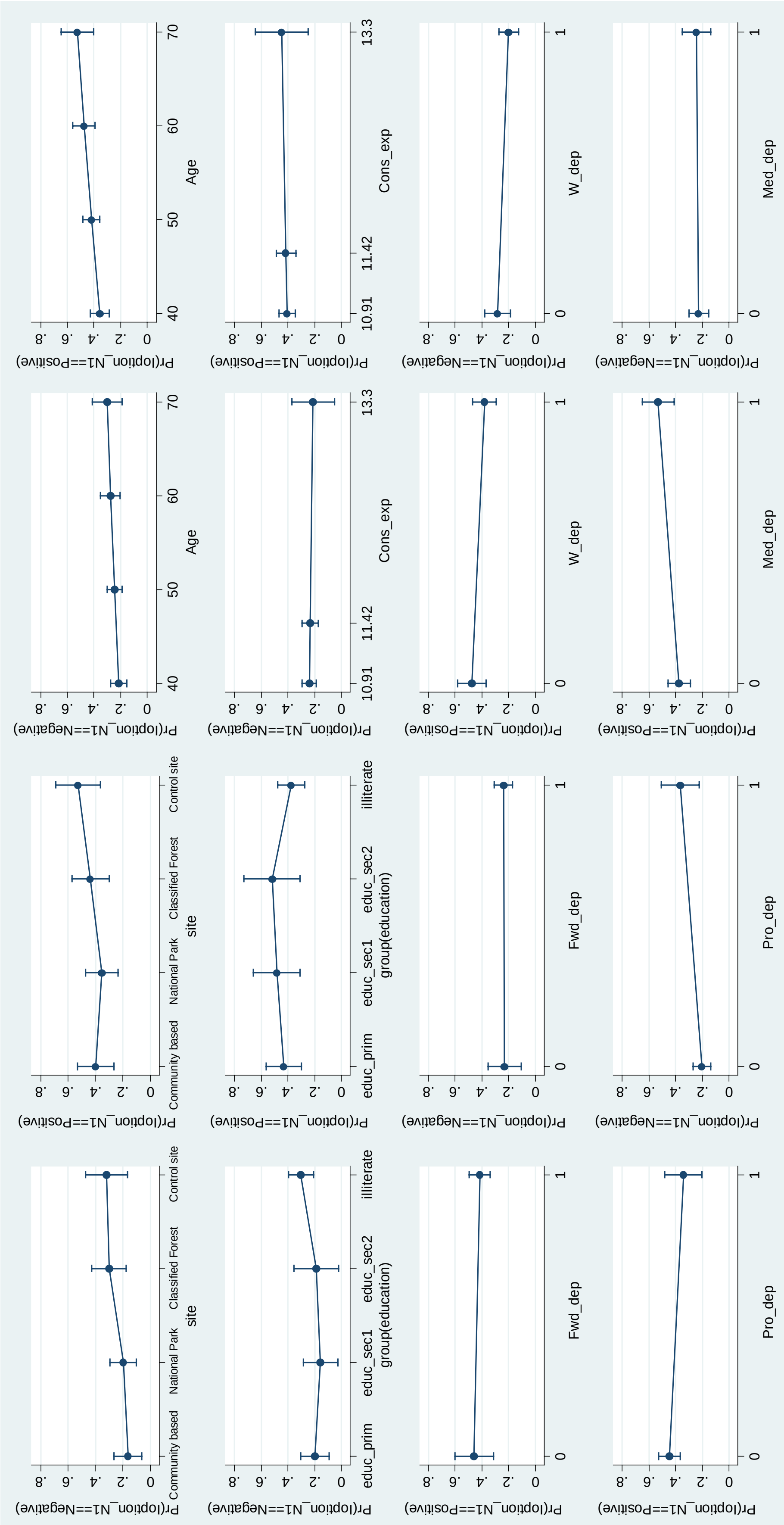

Figure 2. Marginal effects: adjusted predictions with 95% confidence intervals of having negative or positive preferences for each level of factor variables and dichotomous variables; predictive margins with 95% confidence intervals for different values of continuous predictor variables.

mostly been converted to commercial crop plantations. As the pressure on land is getting stronger, people expect that by deregulating PAs in the region, land pressure will be reduced and/or that they could acquire new land for cultivation. However, the results for the control site must be interpreted with caution, as it cannot be excluded that the preferences of these households, currently not perceiving direct benefits and disadvantages linked to the presence of a PA, may have been over- or underestimated.

Regarding socio-economic variables, the probability of positive/negative preferences significantly increases with age. The effect is, however, more important for positive preferences and less so for negative preferences. It seems that awareness of conservation issues increases with age. Two channels can explain the two different impacts of age on preferences. First, the older respondents, with their past experience, are those most likely to appreciate the local costs of the progressive loss of biodiversity and related ecosystem services due to deforestation. Second, the need for cultivable land is likely to increase with age, due to the growing size of the household. This can explain why negative preferences could also increase with age. Although these two divergent effects of age are plausible, it appears in our case that the positive effect of age on the perception of PAs is more important than the negative one.

The likelihood of having a negative preference for PAs would decrease with higher levels of education. The more educated people are, the less likely they are to opt for deregulating PAs, and the more likely they are to have a positive preference for PAs. Education, therefore, is a relevant factor that could influence awareness for PAs and biodiversity conservation in our case.

We note that there is not much difference regarding the likelihood of having negative or positive preferences between groups of households classified relative to expenditure percentiles (50th, 75th, and 95th). However, it seems that negative preferences are lower for households that spend more on consumption (i.e. the richer households) and that these households have the highest positive preferences. It can then be assumed that being wealthier could increase awareness for PAs in our case.

Overall, the probability of having a positive preference for PAs decreases with increasing dependence on provisioning ecosystem services. It seems that the more dependent households are on natural resources for their livelihoods, the less favourable they are towards PAs. However, the likelihood of having a positive preference is higher for households that depend on medicinal plants. This result can be somewhat explained by the fact that the restriction in PAs is stricter for items such as wood and bush meat, and less strict for the collection of medicinal plants.

We found that the most important dependence variable that would affect the likelihood of having a negative preference is the dependence on proteins. The mean expected probability of having a negative preference increases significantly if the respondent's main supply of protein is assured by fishing and bush meat hunting. For the mostly poor local people, free access to these proteins is vital for their wellbeing. The scarcity of bush meat and fish is already intensifying with population growth, deforestation, and urbanization, and expanding PAs only further exacerbates this scarcity.

These results suggest that negative preferences for PAs from local communities are linked to a top-down management approach for PAs (national park) and positive preferences to a more inclusive approach for PA management (community-based). Negative preferences are expressed mainly by people who are older, illiterate, and dependent on free proteins from natural resources, such as bush meat and fish. Positive preferences are expressed by people who are older, educated (at least having fulfilled the first level of secondary education), and are less dependent on firewood and free natural proteins.

4. Concluding remarks

This study provides qualitative as well as quantitative evidence that local people living near PAs have vastly different perceptions regarding the impact of PAs on their wellbeing. While some people praise the PA for protecting biodiversity and spiritual values, other people demand the same PA to be deregulated in order to use the land for crop cultivation. The qualitative information shows that people do perceive a number of different ecosystem services as benefits from PAs in Côte d'Ivoire. By far, the most frequently reported benefit was that the PA maintains a favourable microclimate, mainly with respect to rainfall quantity. The absence of detailed rainfall records for the region does not allow us to verify the accuracy of this perception. However, other studies have shown that such climate related perceptions are often strongly influenced by PA outreach activities or environmental education programmes from NGOs (Hartter and Goldman, 2011). This is likely to be the case in our study as well, as the key informants interviewed were all in positions that make them prone to participate in such kind of programmes. The provision of medicinal plants was the only provisioning ecosystem service mentioned by more than one key resource person. The importance of medicinal plants from PAs was clearly demonstrated by the quantitative data, as it showed that the more households depend on medicinal plants the more positive they are towards PAs. Other studies from PA benefits in an African context have yielded similar results (Hartter and Goldman, 2011; Zadou *et al*., 2011). Access to most other provisioning services, is restricted through the PA management rules, and that could negatively influence people's attitudes towards PAs (Coad *et al*., 2008). The quantitative analysis confirms these results and shows that the more dependent households are on natural resources (e.g. firewood and bush meat) for their livelihoods, the less favourable they are towards PAs. Interestingly, the other three ecosystem services mentioned by more than one key resource person can all be attributed to the cultural ecosystem service theme. The maintenance of cultural heritage, the bequest value of safeguarding biodiversity for future generations, and the preservation of spiritual values linked to sacred places all turned out to be appreciated and valued by several key resource persons. Cultural ecosystem services are often neglected in ecosystem service assessments, as they are difficult to quantify (Carpenter *et al*., 2009). However, our results call for increased attention towards cultural ecosystem services, as they are widely recognized by local people and could provide incentives for the support of PAs.

In our study region, the coastal belt of Côte d'Ivoire, large-scale monoculture plantations of oil palm and rubber have now replaced most of the natural ecosystems, and the only forests left are included within PAs. Especially older people, who have experienced these landscape changes through the course of the years, seem to be very much aware of the negative impacts that widespread deforestation has on their livelihoods. However, the need for monetary income through the cultivation of oil palm and rubber presents a major trade-off for land use, not only between forest conservation and commercial crop plantations, but also between commercial and subsistence crop cultivation. The influence of age on people's perception of PA benefits was confirmed by the finding from the quantitative analysis that older age increases the likelihood of having a positive preference for PAs. The same was found in other studies in Africa and elsewhere (Allendorf and Yang, 2013; Ezebilo, 2012; Tessema *et al*., 2010).

Our study further demonstrates that people's preferences for PAs in southern Côte d'Ivoire depend on the management type of PAs. The community-based PA management approach that was applied for the protection of the "Forêt Marécageuse de Tanoe-Ehy (FMTE)" influenced people's perceptions of the link between PAs and wellbeing in a positive way. This can likely be attributed to the fact that, in this case, the opinions and needs of local people were integrated in the planning process from the very beginning, and outreach activities have been conducted by researchers and a local NGO (Zadou *et al*., 2011).

Based on these results, we suggest that PAs in southern Côte d'Ivoire do provide at least some (non-financial) benefits for local people. This provides an important foundation for enhancing the sustainability of conservation efforts, on which conservation practitioners should build. Existing, as well as future conservation efforts, should foster the participation of local communities in planning, implementing, and monitoring activities, as our study shows that this can positively influence people's perceptions of PAs. As older people tend to have a more positive attitude towards PAs, they should be encouraged to share their knowledge and experiences about the impacts of deforestation, in order to raise awareness among the younger generation. That education is key to the success of conservation efforts has been shown by several studies (Ezebilo, 2012; Shibia, 2010; Vodouhê *et al*., 2010). Conservation plans in the region must consider substitutes for, or regulated access to, provisioning ecosystem services as a response to local people's dependence on natural resources, thus moderating the induced negative perception towards PAs.

Last, we would also like to call attention to the very prominent land use conflicts around PAs in the region. If left unaddressed, the competing demands for land used for commercial crops, such as rubber and oil palm, versus land used for subsistence crops, might have serious implications for people's food supply, which could also eventually hamper conservation efforts through increased hunting or deforestation for the cultivation of subsistence crops.

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Supporting Information

Additional Supporting Information may be found in the online version of this article at the publisher's web-site:

Table 1. Survey details
Table 2. List of ecosystem service themes, categories and groups based on the Common International Classification of Ecosystem Services (CICES) (Haines-Young and Potschin, 2010) and examples of corresponding ecosystem service types adapted to the local context presented to key informants
Table 3. PA management option multinomial choice: Data definition and summary.
Figure 1. Choice set for the choice experiment.

Erklärung

gemäss Art. 28 Abs. 2 RSL 05

Name/Vorname:	Zähringer Julie Gwendolin
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Bachelor ☐ Master ☐ Dissertation ☑

Titel der Arbeit:	Landscape dynamics and ecosystem service benefits in the biodiversity hotspot of north-eastern Madagascar. Generating knowledge for navigating conservation–development trade-offs.
LeiterIn der Arbeit:	Prof. Dr. Hans Hurni Prof. Dr. Peter Messerli Dr. Gudrun Schwilch

Ich erkläre hiermit, dass ich diese Arbeit selbständig verfasst und keine anderen als die angegebenen Quellen benutzt habe. Alle Stellen, die wörtlich oder sinngemäss aus Quellen entnommen wurden, habe ich als solche gekennzeichnet. Mir ist bekannt, dass andernfalls der Senat gemäss Artikel 36 Absatz 1 Buchstabe r des Gesetzes vom 5. September 1996 über die Universität zum Entzug des auf Grund dieser Arbeit verliehenen Titels berechtigt ist.
Ich gewähre hiermit Einsicht in diese Arbeit.

Bern, 04.02.2016

Julie Zähringer ....