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Remote sensing combined with social-ecological data: the importance of diverse land uses for ecosystem service provision in north-eastern Madagascar

Keywords: land use; remote sensing; social-ecological systems; household surveys; Masoala National Park; Makira Natural Park

Abstract

Through ongoing deforestation in the tropics, forest-related ecosystem services are declining, 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. Combining land use data obtained through remote sensing with social-ecological 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 rice production systems. We further characterized landscapes in terms of "ecosystem service bundles" linked to specific land uses, as well as in terms of ecosystem service benefits to households. The map of landscape types could help direct future conservation and development efforts towards places where there is potential for success.

1 Introduction

Despite decades of international conservation efforts, tropical forests are still shrinking to make way for agricultural land (Hansen et al., 2013; Malhi et al., 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 et al., 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 social-ecological 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 et al., 2009). While in spatial analysis new approaches for generalization and upscaling exist that allow a better representation of land use (e.g. Hett et al., 2012; Messerli et al., 2009; Zaehringer et al., 2016), 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 et al., 2001; Myers et al., 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 ecosystems 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 and Martin, 2015; Villamagna and Giesecke, 2014). Especially in a developing-country context, where poverty alleviation is a major objective to sustainable development planning, we see the following as the most important weaknesses in ES research. First, often only individual 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 their analysis on ES provided by forests only (for Madagascar e.g. Brown et al., 2013; Kari and Korhonen-Kurki, 2013; Kramer et al., 1997; Wendland et al., 2010). However, 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. Second, an individual ES can have various different values to different land users based on its contribution to their well-being (Daw et al., 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 et al., 2013). Third, 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 and 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 various other factors such as available resources or access (Daw et al., 2011; Leach et al., 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 et al., 2010; Gibbs et al., 2010; Lambin and Meyfroidt, 2011; van Vliet et al., 2012), the eastern coast of Madagascar presents a clear exception to this trend (Laney and Turner, 2015; Urech et al., 2015; Zaehringer et al., 2015). The largest remaining continuous surfaces of humid forest in Madagascar are still under threat, mainly due to agricultural expansion (Ganzhorn et al., 2001; Myers et al., 2000; 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 these forests (Kull, 2014; Kull et al., 2007). Several protected areas have been established, the two largest and most recent of which are the Masoala National Park (est. 1997) and Makira Natural Park (est. 2005). To reduce agricultural land expansion and deforestation, intensification of smallholders' irrigated rice production has long been perceived as a solution (in addition to strict protection measures) by conservation and development actors (smallholders being defined as farmers with limited resource endowments who produce mainly for subsistence). Although it has been questioned (Vandermeer and Perfecto, 2007), this approach is based on the assumption that households producing more rice in irrigated paddy fields will abstain from converting any more forests into shifting cultivation rice fields. However, landscapes in north-eastern Madagascar 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 et al., 2015; Messerli, 2004; Pollini, 2009; Poudyal et al., 2016).

The overall goal of this study is to reveal the importance of different land uses for the provision of ES benefits to local land users in the biodiversity hotspot of north-eastern Madagascar. To achieve this goal we use a regional-level approach combining 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' rice production systems, obtained through survey data?

(2) do "ES bundles" (the sets of ES provided by a certain land use type [Raudsepp-Hearne et al., 2010]) 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?

We also 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) comprises mainly 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 has a hot and humid climate with an average temperature of 24°C and about 3,600 mm of rainfall per year (Jury, 2003). Rice production is at the very centre of life in the culture of the Betsimisaraka population, the dominant ethnic group in this region. They produce hill rice through shifting cultivation and permanent irrigated paddy rice for subsistence; in addition, they grow a number of commercial cash crops (mainly clove and vanilla). Prices paid for these cash crops show high inter-annual variability (FAO, 2014). 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 (Institut National de la Statistique INSTAT, 2014). While large contiguous forests today are restricted to the core zones of protected areas, smaller forest fragments are dispersed throughout the agricultural matrix. 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).

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).

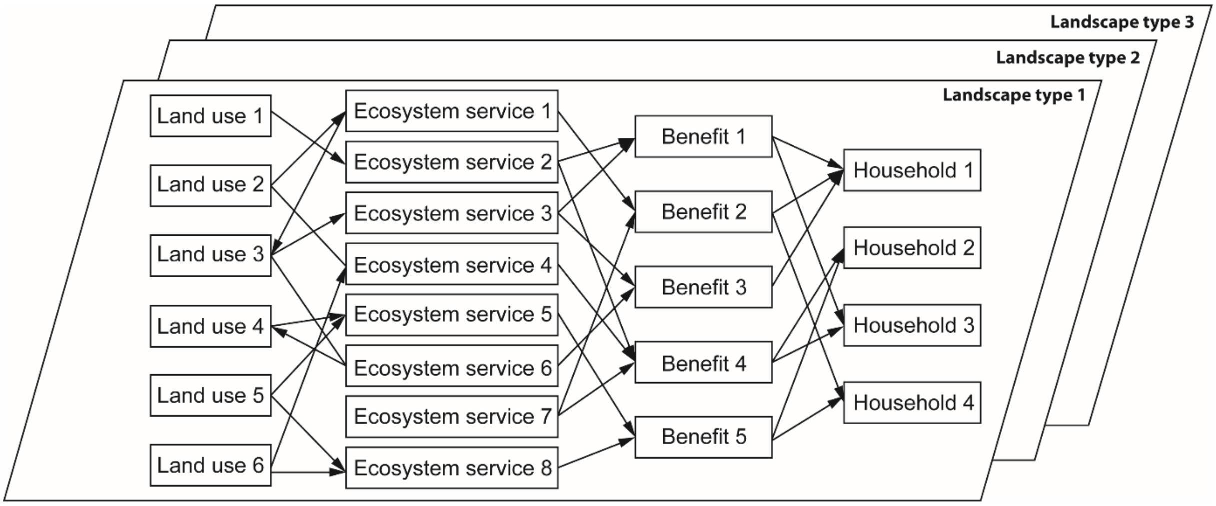

Figure 1. Conceptual framework to link land use with ES, ES benefits, and households. Different land uses provide ES while at the same time requiring ES provided by other land uses. One land use can provide several ES; one ES can have several benefits; and different households can obtain different benefits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

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 ES beneficial to a certain land use (as opposed to ES provided by a land use), first by asking land users about constraints to a certain land use. We then conceptualized them as indicating an unfulfilled demand for ES using the CICES (European Environment Agency 2013) classification (Table 1, SI 1). For example, if a land user mentioned floods as a constraint to irrigated rice production, we conceptualized this as an unfulfilled demand for the ES of flood protection. The link between a land use providing a certain ES and a land use requiring this ES was then established by the researchers.

2.3 Remotely sensed information on land use

To spatially represent land use at the scale of our 20,507 km^2 region, we used a 2011 landscape mosaic map developed by Zaehringer et al. (2016). Each 30x30 m pixel in the landscape mosaic map represents the combination of land cover categories in a 5x5 km window surrounding the pixel. The landscape mosaic map describes the entire region in terms of five different landscape types, based on the ratio between shifting and paddy rice cultivation in the landscape. Mixed shifting and mixed paddy cultivation landscapes designate landscapes with, respectively, more shifting cultivation or more irrigated paddy cultivation. In paddy landscapes, only irrigated paddy rice cultivation is present. Shifting landscapes where shifting cultivation is the only mode of rice production are rare in the study region. Landscapes with no signs of either rice production system are restricted to the core zones of the protected areas.

2.4 Social-ecological data from household surveys

We collected social-ecological data through a stratified sampling of 45 villages distributed among the three most common landscape types 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 (Foiben-Taosarintanin'I Madagasikara FTM, 1998) and distributed throughout the region, taking into consideration that villages were only accessible on foot. This is a semi-random sample, as no prior knowledge about these villages was available.

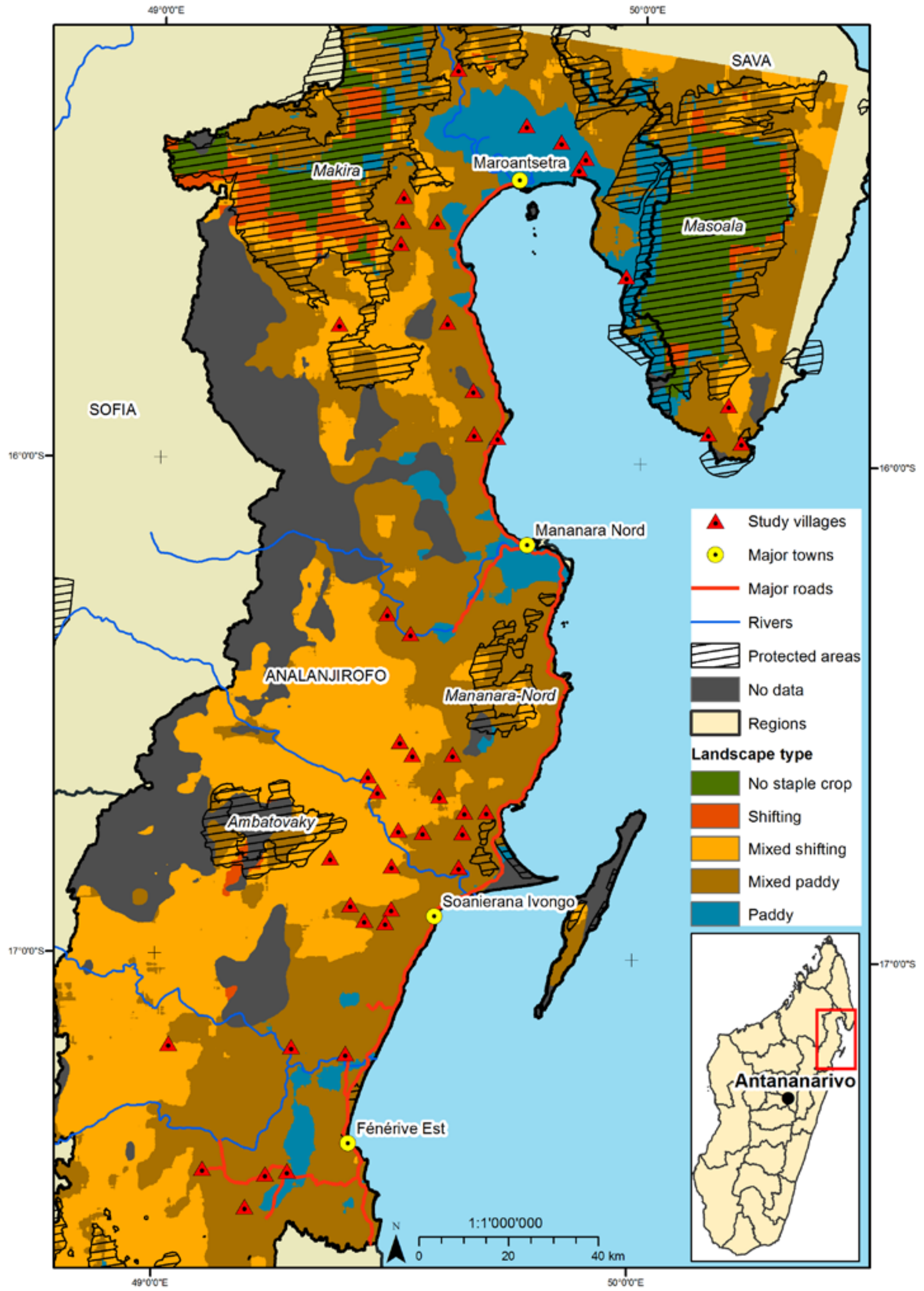

Figure 2. Distribution of study villages along the three main landscape types of mixed shifting, mixed paddy, and paddy-based landscapes in north-eastern Madagascar (adapted from Zaehringer et al., 2016).

Field research was conducted between November 2013 and March 2015. In each village, we conducted face-to-face interviews with land users at household level, administering a standardized survey questionnaire (SI 2). The questionnaire was structured according to the six distinct land uses present in the region (Figure 3). The questionnaire included open questions to allow respondents to explain what benefits and challenges they associated with each land use activity. Questions about quantifiable household resources 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 (Table 2, SI 1).

Figure 3. The six main land uses present in the study region (Source: Julie Zaehringer).

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. Along every row of houses in a village we sampled every second household, if people were present and willing to participate. 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. 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 Combining spatially explicit land use information with social-ecological data

Each sampled village was assigned to one of the three landscape types, depending on its spatially explicit location (Table 1). 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 village level before testing for differences between landscape types. For each land use, we considered the benefits households obtain from provisioning ES as well as their unfulfilled demand for regulating ES.

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 and Discussion

3.1 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 (Table 2). In mixed shifting landscapes, more than 85% of households produced rice through shifting cultivation, with about one-third of 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 used shifting cultivation, and only in paddy landscapes did 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. Rice sufficiency was significantly higher in paddy landscapes than in mixed paddy landscapes. Although the differences were not significant, mixed paddy landscapes seemed to have a lower average duration of rice sufficiency and lower total rice production than the other two landscape types. This suggests that households in mixed paddy landscapes were less self-sufficient in rice 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). As they did not have a higher degree of rice commercialization or a higher income from cash crops (Table 3, SI 3), we cannot assume that they have replaced subsistence rice production through rice bought with monetary income. 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.

Table 2. Differences between landscape types regarding rice production systems

		Landscape type			Significance
		MS	**MP**	**P**	
Rice production mode [% HH]		(n=285)	(n=713)	(n=160)	***
	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
Commercializing rice [% HH]		$(n=285)^{ac}$	$(n=713)^{b}$	$(n=160)^{bc}$	*
	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. (MS=Mixed shifting, MP=Mixed paddy, P=Paddy, HH=Households, SD=Standard Deviation).

3.2 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 showed that although the overall composition of different ES linked to each land use was similar in all landscape types, the importance of different ES in the perception of households differed widely (Figure 4).

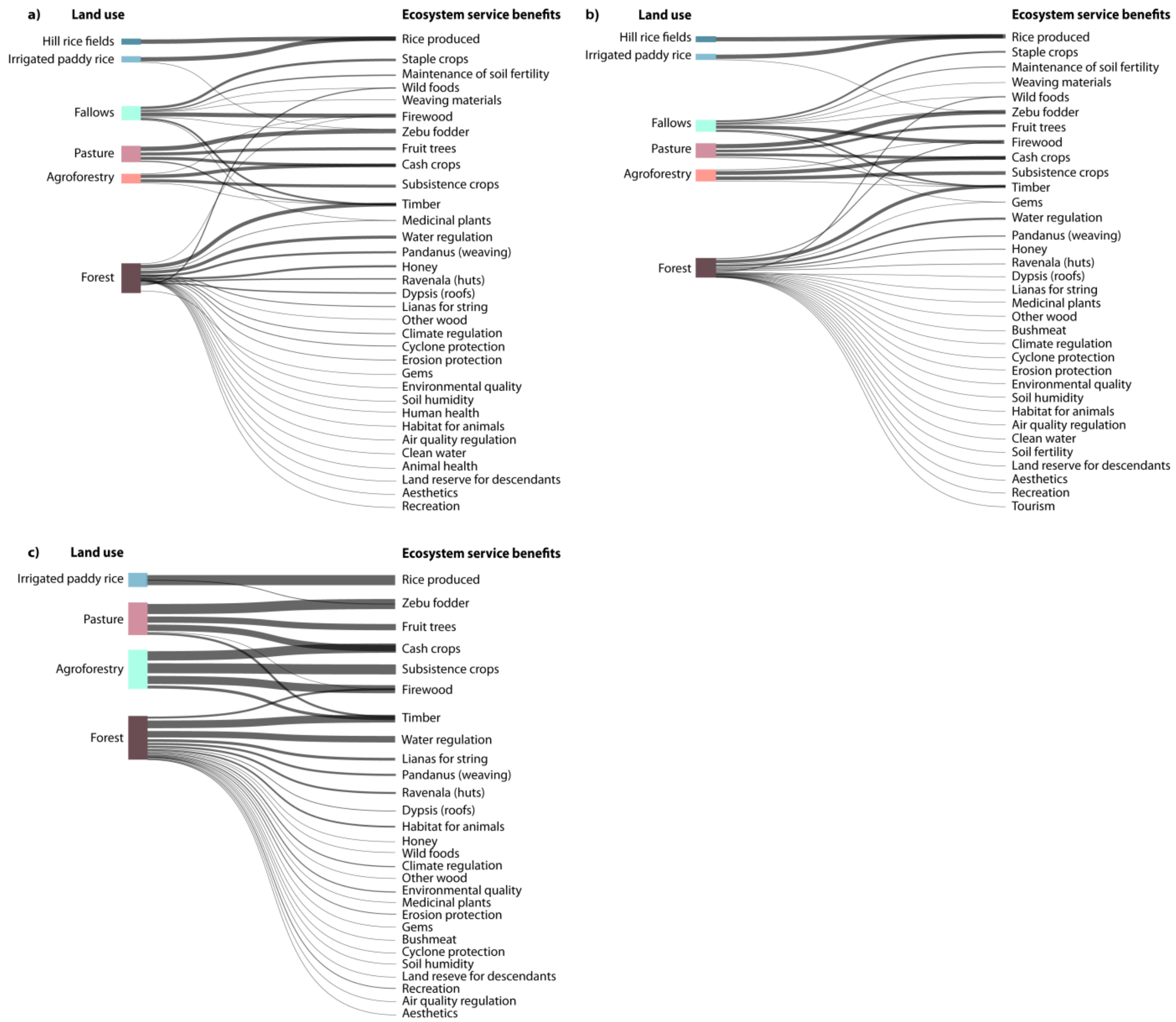

Figure 4. Overview of ES benefits provided by different land uses in the three landscape types of a) mixed shifting landscapes, b) mixed paddy landscapes, and c) paddy landscapes. The width of each link represents the percentage of land users which perceived a certain benefit from a land use. (Produced with Sankey.js and D3.js).

For the land uses of hill rice fields and fallows (which together form a shifting cultivation system), we only compare indicators between mixed shifting and mixed paddy landscapes (Table 3), as not enough households in paddy landscapes used shifting cultivation to allow for comparison. In terms of benefits from hill rice fields, only the provisioning ES of rice was mentioned. Households in mixed shifting cultivation landscapes seemed to produce more hill rice per year than households in mixed paddy landscapes. By far the most important constraints to hill rice production mentioned by land users were weeds, animal pests, decreased land availability, and crop damage through cyclones, which all indicate an unfulfilled demand for ES. All of these constraints were perceived by a higher percentage of households in mixed shifting than in mixed paddy landscapes. In the literature, 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 et al., 2001; Messerli and 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 in mixed shifting than in mixed paddy landscapes. Fallows are an integral part of shifting cultivation systems and ensure the replenishment of soil fertility (Kull 2004). In mixed shifting landscapes, a higher proportion of households reported soil fertility maintenance as a regulating ES provided by fallows, 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 (Laney 2002; Messerli 2004; Styger et al. 2009)), 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 et al., 2012). Timber was an important ES from fallows in both landscape types. Wild foods, medicinal plants, and gems were mentioned only by a small percentage of households. This shows that shifting cultivation, through the presence of fallows, delivers a range of important ES benefits.

Table 3. Summary of the main differences between the six land uses in three different landscape types in terms of reported benefits from ES, and constraints indicating unfulfilled demand for ES

			Landscape type			
			MS	MP	P	Significance
Hill rice fields	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 [% HH]	Reduced soil fertility	71 (n=242)	59 (n=471)		**
			(n=246)	(n=494)		
		Weeds	82	73		*
		Animal pests	23	17		ns
		Decreased land availability	16	4		***
		Crop damage through cyclones	15	9		*
Fallows	ES benefits [% HH]		(n=267)	(n=519)		
		Firewood	95	84		***
		Staple crops	56	42		***
		Timber	42	37		ns
		Maintenance of soil fertility	32	21		**
		Weaving materials	1	7		***
Irrigated paddy rice	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 [% HH]	Reduced soil fertility	61 (n=166)	73 (n=585)	88 (n=140)	***
			(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}	**
Agro-forestry	ES benefits [% HH]		(n=237)	(n=667)	(n=150)	
		Number of cash crops cultivated per HH: 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
		Subsistence crop cultivation	(n=238) 70	(n=648) 86	(n=153) 99	***
			(n=225)	(n=523)	(n=65)	
		Timber	10^{a}	11^{a}	29^{b}	***
		Firewood	1	14	80	***
	Constraints reported [% HH]		(n=249)	(n=676)	(n=152)	
		Plant pathogens	17^{a}	16^{a}	41^{b}	***
		Animal pests	14^{a}	12^{a}	24^{b}	*
		Crop damage through cyclones	8^{a}	5^{a}	25^{b}	***
Pasture	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]	71^{a} (n=24)	54^{b} (n=65)	63^{a} (n=82)	*
	Constraints reported [% HH]		(n=30)	(n=114)	(n=84)	
		Shortage of herbs	20^{ac}	4^{b}	26^{c}	***(b/c) *(ac/b)
		Weeds (spiny plants)	18^{ac}	2^{b}	18^{c}	***(b/c) **(ac/b)
Forest	ES benefits [% HH]	**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 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}	**
		Regulating ES:	(n=194)	(n=456)	(n=162)	
		Water regulation	72^{a}	52^{b}	64^{ac}	***(a/b),*(b/ac)
		Climate regulation	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)

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. Here we only show the main ES benefits and constraints, for the full lists of ES benefits and constraints mentioned see SI 3. (MS=Mixed shifting, MP=Mixed paddy, P=Paddy, HH=Households, SD=Standard Deviation).

The average surface area of paddy rice fields per household was just below one hectare in all three landscape types. However, irrigated paddy rice production was significantly more intensive (i.e. land users cultivated irrigated rice twice per year instead of only once) in paddy landscapes than in mixed shifting landscapes ($p \leq 0.001$). The lower intensity in mixed shifting landscapes is probably due to the time and labour constraints of households using both types of rice production. 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. Paddy landscapes featured the highest degree of fully rice-sufficient households, although the mean duration of rice sufficiency was similar to that of the other landscape types, and the total quantity of rice produced per year was not much higher than in mixed shifting landscapes (Table 2). Also, about the same proportion of households in paddy landscapes was selling part of their 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 did not allow households to produce more. The second ES benefit from irrigated rice fields was the provision of fodder for zebu cattle after harvest, which seemed most important in paddy landscapes. In terms of constraints, 88% of households in paddy landscapes stressed that soil fertility had declined since they started cultivating their fields, a proportion significantly 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. Water shortage was the second most important constraint for irrigated rice production 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 shortages 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 was the absence of appropriate technical infrastructure such as canals and watergates, as well as of a functioning management system, which reduced households' access to this important ES. Animal pests (rats, birds, insects, and worms) and weeds were perceived as more of a constraint to irrigated rice production 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.

More than 80% of interviewed households used at least one agroforestry plot to cultivate cash crops (Table 3, SI 3). In mixed shifting landscapes, the percentage of households doing so was significantly lower than in the other two landscape types ($p \leq 0.01$). Only provisioning ES were mentioned as benefits from agroforestry plots including cash crops, subsistence crops, timber, and firewood (Table 3). Households cultivated between one and five cash crops, of which the three main ones were clove, vanilla, and coffee. Other cash crops cultivated included lychee, sugar cane, orange, banana, sweet potato, taro, cucumber, African aubergine, cola nut, and several edible leaves. In mixed shifting landscapes, significantly more households only cultivated one cash crop (clove) than in mixed paddy and in paddy landscapes. The percentage of households cultivating vanilla as a second cash crop increased 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 relied on collectors coming to their villages to buy their products and take them to the main traders' shops in district capitals. However, average annual revenue from the sale of cash crops was about US$ 340 in all landscapes (Table 3, SI 3). 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 pathogens (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 were perceived as a major risk, which could 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, sugar cane, and tubers such as cassava, yam, and sweet potato) also increased from mixed shifting to mixed paddy to paddy landscapes. In mixed shifting landscapes, households relied more on forests to collect wild foods than households in paddy landscapes. Another peculiarity of paddy landscapes was that most households collected firewood and even timber from agroforests; this is probably because there were no fallows, which deliver these ES benefits in the other two landscape types.

Only in paddy landscapes did all households with zebus also own pastures for grazing (Table 4, SI 3). In the other two landscape types, only about half of the zebu-owning households used pastures to graze them. There, zebus mainly grazed in irrigated rice fields after harvest and on fallows. In paddy landscapes, more than half of all households raised zebu cattle. This is significantly higher than in mixed paddy and in mixed shifting landscapes ($p \leq 0.001$). This can be explained by an increasing focus on irrigated rice production, which requires zebu cattle for ploughing. In terms of ES benefits from pastures, households mentioned zebus as well as a number of tree products (Table 3). Households owning zebus had 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 provided edible fruits, cash crops (mainly clove), and timber (e.g. *Eucalyptus* sp., Bamboo, and *Intsia* sp.). In paddy landscapes, a few households grew *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. In mixed paddy landscapes, only few households mentioned constraints in relation to pastures.

While about half of the interviewed households used forest in all landscape types (Table 5, SI 3), the reasons for households not using them differed significantly in paddy landscapes ($p \leq 0.001$). 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 because 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 the households using forests, a much lower percentage collected honey, wild foods, and medicinal plants than in the other two landscape types (Table 3), supports this hypothesis. In mixed shifting landscapes, a larger proportion of households obtained ES benefits from plants (such as *Pandanus* sp., *Ravenala madagascariensis,* and *Dypsis* sp.) used for handicrafts or for the construction of traditional houses than in the other two landscapes. Possibly 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 significantly 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 the only other source of firewood apart from forests is 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; 2014) have shown the importance of bushmeat in the diet of households in the vicinities of the Makira and Masoala protected areas. 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. On the other hand, the 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 (Table 5, SI 3). 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 from forest were mentioned in our study region, although only by a small percentage of households in each landscape type (Table 5, SI 3). 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.

3.3 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 differed in terms of several socio-demographic household characteristics (SI 4). Mixed shifting landscapes were 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 represented 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 employed wage labour might be related to the fact that in paddy landscapes almost all households focused entirely on irrigated rice production. By contrast, labour needs can be very high in the case of households cultivating hill rice and irrigated rice during the summer months.

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 4).

Table 4. 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-istics	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)

The cluster analysis showed that for tailoring future conservation and development interventions to specific areas, we should still consider the heterogeneity of households inhabiting different landscapes (Figure 5). In mixed shifting landscapes, the two more subsistence-based household types of “Shifting and Forest” and “Diverse Subsistence”, of which the first relied on shifting cultivation only and the second on both types of rice production, 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 dominated the study region in terms of area, also featured the highest diversity of household types. In these landscapes, special attention should be given to the household type of “Low Irrigated Subsistence” 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 had comparatively high production of irrigated rice but rather low income from cash crops and a few zebus. However, almost 25% of interviewed households in paddy landscapes could be attributed to the “Commercial Livestock” type, representing relatively well-off households with high incomes from cash crops, rice sufficiency, and a higher number of zebus. To devise more sustainable development interventions, further research should attempt to understand what allowed these households to benefit more from ES than others.

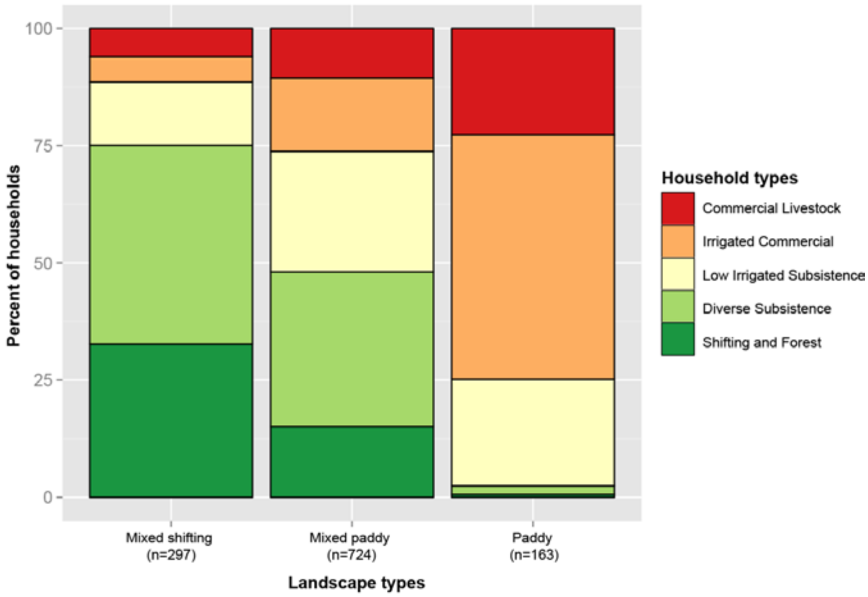

Figure 5. Characterization of landscape types in terms of ES benefits to households in north-eastern Madagascar. Household types were revealed through the hierarchical cluster analysis.

3.4 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 perceived 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, led to major constraints for the production of both subsistence rice as well as cash crops for monetary income. In terms of regulating 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 were well-aware of the indirect benefits forests provide to food security as well as to income from agriculture. However, in the 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.

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 no longer be available. Furthermore, fallows are important carbon sinks and can thus contribute to the mitigation of global warming (Bruun et al., 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 in relation 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

Combining land use data obtained through remote sensing with social-ecological 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 these landscape types – could serve as a basis for directing future conservation and development efforts towards places in which and people for whom they have the highest potential for success.

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References

Brimont, L., Ezzine-de-Blas, D., Karsenty, A., & Toulon, A. (2015). Achieving Conservation and Equity amidst Extreme Poverty and Climate Risk: The Makira REDD+ Project in Madagascar. Forests, 6 (3), 748–768. http://doi.org/10.3390/f6030748

Brown, K.A., Johnson, S.E., Parks, K.E., Holmes, S.M., Ivoandry, T., Abram, N.K., … Wright, P. (2013). Use of provisioning ecosystem services drives loss of functional traits across land use intensification gradients in tropical forests in Madagascar. Biological Conservation 161, 118–127. http://doi.org/10.1016/j.biocon.2013.03.014

Bruun, T.B., Neergaard, A. de, Lawrence, D., & Ziegler, A.D. (2009). Environmental Consequences of the Demise in Swidden Cultivation in Southeast Asia: Carbon Storage and Soil Quality. Human Ecology 37 (3), 375–388. http://doi.org/10.1007/s10745-009-9257-y

Costanza, R., dArge, R., deGroot, R., Farber, S., Grasso, M., Hannon, B., … vandenBelt, M. (1997). The value of the world's ecosystem services and natural capital. Nature 387 (6630), 253–260.

Costanza, R., de Groot, R., Sutton, P., van der Ploeg, S., Anderson, S. J., Kubiszewski, I., … Turner, R. K. (2014). Changes in the global value of ecosystem services. Global Environmental Change 26, 152–158. http://doi.org/10.1016/j.gloenvcha.2014.04.002

Daily, G.C. (1997). *Nature's services: societal dependence on natural ecosystems*. Washington DC: Island Press.

Dawson, N., & Martin, A. (2015). Assessing the contribution of ecosystem services to human wellbeing: A disaggregated study in western Rwanda. Ecological Economics 117, 62–72. http://doi.org/10.1016/j.ecolecon.2015.06.018

Daw, T., Brown, K., Rosendo, S., & Pomeroy, R. (2011). Applying the ecosystem services concept to poverty alleviation: the need to disaggregate human well-being. Environmental Conservation 38 (04), 370–379. http://doi.org/10.1017/S0376892911000506

DeFries, R.S., Rudel, T., Uriarte, M., & Hansen, M. (2010). Deforestation driven by urban population growth and agricultural trade in the twenty-first century. Nature Geoscience 3 (3), 178–181. http://doi.org/10.1038/NGEO756

de Groot, R.S., Alkemade, R., Braat, L., Hein, L., & Willemen, L. (2010). Challenges in integrating the concept of ecosystem services and values in landscape planning, management and decision making. Ecological Complexity 7 (3), 260–272. http://doi.org/10.1016/j.ecocom.2009.10.006

FAO. (2014). FAOSTAT. Retrieved 22 July 2014, from http://faostat3.fao.org

Fisher, J.A., Patenaude, G., Meir, P., Nightingale, A.J., Rounsevell, M.D.A., Williams, M., & Woodhouse, I.H. (2013). Strengthening conceptual foundations: Analysing frameworks for ecosystem services and poverty alleviation research. Global Environmental Change 23 (5). http://doi.org/10.1016/j.gloenvcha.2013.04.002

Foley, J.A., DeFries, R., Asner, G.P., Barford, C., Bonan, G., Carpenter, S.R., … Snyder, P.K. (2005). Global Consequences of Land Use. Science 309 (5734), 570–574. http://doi.org/10.1126/science.1111772

Foiben-Taosarintanin'I Madagasikara FTM. (1998). Base de données BD500. Antananarivo, Madagascar.

European Environment Agency. 2013. 'CICES. Towards a Common Classification of Ecosystem Services.' CICES. Towards a Common Classification of Ecosystem Services. http://cices.eu/.

Ganzhorn, J.U., Lowry, P.P., Schatz, G.E., & Sommer, S. (2001). The biodiversity of Madagascar: one of the world's hottest hotspots on its way out. Oryx 35 (4), 346–348. http://doi.org/10.1046/j.1365-3008.2001.00201.x

Gibbs, H.K., Ruesch, A.S., Achard, F., Clayton, M.K., Holmgren, P., Ramankutty, N., & Foley, J.A. (2010). Tropical forests were the primary sources of new agricultural land in the 1980s and 1990s. Proceedings of the National Academy of Sciences 107 (38), 16732–16737. http://doi.org/10.1073/pnas.0910275107

Golden, C.D. (2009). Bushmeat hunting and use in the Makira Forest north-eastern Madagascar: a conservation and livelihoods issue. Oryx 43 (3), 386–392. http://doi.org/10.1017/S0030605309000131

Golden, C.D., Bonds, M.H., Brashares, J.S., Rodolph Rasolofoniaina, B.J., & Kremen, C. (2014). Economic Valuation of Subsistence Harvest of Wildlife in Madagascar. Conservation Biology 28 (1). http://doi.org/10.1111/cobi.12174

Haines-Young, R., & Potschin, M. (2010). The links between biodiversity, ecosystem services and human well-being. In D. G. Raffaelli & C. L. J. Frid (Eds.), *Ecosystem Ecology. A New Synthesis.* Cambridge: Cambridge University Press.

Hansen, M.C., Potapov, P.V., Moore, R., Hancher, M., Turubanova, S.A., Tyukavina, A., … Townshend, J.R.G. (2013). High-Resolution Global Maps of 21st-Century Forest Cover Change. Science 342 (6160), 850–853. http://doi.org/10.1126/science.1244693

Hett, C., Castella, J.-C., Heinimann, A., Messerli, P., & Pfund, J.-L. (2012). A landscape mosaics approach for characterizing swidden systems from a REDD plus perspective. Applied Geography 32 (2), 608–618. http://doi.org/10.1016/j.apgeog.2011.07.011

Institut National de la Statistique INSTAT. (2014). *Enquête Nationale sur le Suivi des Objectifs du Millénaire pour le Développement à Madagascar. 2012-2013 Etude Nationale. Objectif 01: Eliminer l'extrême pauvreté et la faim*. Antananarivo, Madagascar: INSTAT.

Jax, K., Barton, D.N., Chan, K.M.A., de Groot, R., Doyle, U., Eser, U., … Wichmann, S. (2013). Ecosystem services and ethics. Ecological Economics 93, 260–268. http://doi.org/10.1016/j.ecolecon.2013.06.008

Jury, M. R. (2003). The Climate of Madagascar. In S. M. Goodman & Benstead (Eds.), *The Natural History of Madagascar.* (pp. 75–87). Chicago and London: The University of Chicago.

Kari, S., & Korhonen-Kurki, K. (2013). Framing local outcomes of biodiversity conservation through ecosystem services: A case study from Ranomafana, Madagascar. Ecosystem Services 3 (0), e32–e39. http://doi.org/10.1016/j.ecoser.2012.12.003

Keller, E. (2008). The banana plant and the moon: Conservation and the Malagasy ethos of life in Masoala, Madagascar. American Ethnologist, 35 (4), 650–664. http://doi.org/10.1111/j.1548-1425.2008.00103.x

Kistler, P., Messerli, P., & Wohlhauser, S. (Eds.). (2001). *Culture sur brûlis: vers l'application des résultats de recherche. Actes de l'atelier EPB-BEMA.* Antananarivo, Madagascar.

Kramer, R.A., Richter, D.D., Pattanayak, S., & Sharma, N.P. (1997). Ecological and economic analysis of watershed protection in Eastern Madagascar. Journal of Environmental Management 49 (3), 277–295. http://doi.org/10.1006/jema.1995.0085

Kull, C.A. (2014). The roots, persistence, and character of Madagascar's conservation boom. In I. R. Scales (Ed.), *Conservation and Environmental Management in Madagascar.* (pp. 146–171). Earthscan from Routledge.

Kull, C.A., Ibrahim, C.K., & Meredith, T.C. (2007). Tropical forest transitions and globalization: Neo-liberalism, migration, tourism, and international conservation agendas. Society & Natural Resources 20 (8), 723–737. http://doi.org/10.1080/08941920701329702

Kull, C.A. (2004). *Isle of Fire - The political ecology of landscape burning in Madagascar*. Chicago and London: University of Chicago Press. ISBN 978-0-226-46141-0

Lambin, E.F., & Meyfroidt, P. (2011). Global land use change, economic globalization, and the looming land scarcity. Proceedings of the National Academy of Sciences 108 (9), 3465–3472. http://doi.org/10.1073/pnas.1100480108

Laney, R.M. (2002). Disaggregating Induced Intensification for Land-Change Analysis: A Case Study from Madagascar. Annals of the Association of American Geographers 92 (4), 702-726. http://dx.doi.org/10.1111/1467-8306.00312

Laney, R., & Turner, B.L. (2015). The Persistence of Self-Provisioning Among Smallholder Farmers in Northeast Madagascar. Human Ecology 43 (6), 811–826. http://doi.org/10.1007/s10745-015-9791-8

Leach M., Mearns R., & Scoones I. (1999). Environmental Entitlements: Dynamics and Institutions in Community-Based Natural Resource Management. World Development 27 (2), 225–247. http://doi.org/10.1016/S0305-750X(98)00141-7

Magliocca, N.R., Rudel, T.K., Verburg, P.H., McConnell, W.J., Mertz, O., Gerstner, K., … Ellis, E.C. (2014). Synthesis in land change science: methodological patterns, challenges, and guidelines. Regional Environmental Change 15 (2), 211–226. http://doi.org/10.1007/s10113-014-0626-8

Malhi, Y., Gardner, T.A., Goldsmith, G.R., Silman, M.R., & Zelazowski, P. (2014). Tropical Forests in the Anthropocene. Annual Review of Environment and Resources 39 (1), 125–159. http://doi.org/10.1146/annurev-environ-030713-155141

MEA. (2005). *Millennium Ecosystem Assessment*. Washington DC: Island Press.

Messerli, P. (2004). *Alternatives à la culture sur brûlis sur la Falaise Est de Madagascar: Stratégies en vue d'une gestion plus durable des terres* (Vol. A17). Bern, Switzerland: Geographica Bernensia.

Messerli, P., Heinimann, A., & Epprecht, M. (2009). Finding Homogeneity in Heterogeneity—A New Approach to Quantifying Landscape Mosaics Developed for the Lao PDR. Human Ecology 37 (3), 291–304. http://doi.org/10.1007/s10745-009-9238-1

Messerli, P., & Pfund, J.L. (1999). Improvements of Slash-and-Burn Cultivation Systems, an Experience of systemic Analysis in the Beforona Region, Madagascar. In *African Mountain Development in a Changing World.* African Mountains Association (AMA), United Nations University (UNU) and African Highlands Initiative (AHI).

Myers, N., Mittermeier, R.A., Mittermeier, C.G., da Fonseca, G.A.B., & Kent, J. (2000). Biodiversity hotspots for conservation priorities. Nature 403 (6772), 853–858. http://doi.org/10.1038/35002501

Pollini, J. (2009). Agroforestry and the search for alternatives to slash-and-burn cultivation: From technological optimism to a political economy of deforestation. Agriculture, Ecosystems & Environment 133 (1–2), 48–60. http://doi.org/10.1016/j.agee.2009.05.002

Poudyal, M., Ramamonjisoa, B.S., Hockley, N., Rakotonarivo, O.S., Gibbons, J.M., Mandimbiniaina, R., … Jones, J.P.G. (2016). Can REDD+ social safeguards reach the 'right' people? Lessons from Madagascar. Global Environmental Change, 37, 31–42. http://doi.org/10.1016/j.gloenvcha.2016.01.004

Randriamalala, H., & Liu, Z. (2010). Rosewood of Madagascar: Between democracy and conservation. Madagascar Conservation & Development 5 (1), 11–22.

Raudsepp-Hearne, C., Peterson, G.D., & Bennett, E.M. 2010. Ecosystem Service Bundles for Analyzing Tradeoffs in Diverse Landscapes. Proceedings of the National Academy of Sciences 107 (11), 5242–47. doi:10.1073/pnas.0907284107.

R Core Team. (2015). *R: A language and environment for statistical computing*. R Foundation for Statistical Computing, Vienna, Austria. URL http://www.R-project.org/.

Reenberg, A. (2009). Land system science: handling complex series of natural and socio-economic processes. Journal of Land Use Science 4 (1-2), 1–4. http://doi.org/10.1080/17474230802645618

Rindfuss, R.R., Entwisle, B., Walsh, S.J., Mena, C.F., Erlien, C.M., & Gray, C.L. (2007). Frontier Land Use Change: Synthesis, Challenges, and Next Steps. Annals of the Association of American Geographers 97 (4), 739–754. http://doi.org/10.1111/j.1467-8306.2007.00580.x

Schuurman, D., & Lowry, P.P. (2009). The Madagascar rosewood massacre. Madagascar Conservation & Development 4 (2), 98–102.

Styger, E., Fernandes, E.C.M., Rakotondramasy, H.M., & Rajaobelinirina, E. (2009). Degrading uplands in the rainforest region of Madagascar: Fallow biomass, nutrient stocks, and soil nutrient availability. Agroforestry Systems 77 (2), 107-122. http://doi.org/10.1007/s10457-009-9225-y

The World Bank. (2016). Living Standards Measurement Study. Retrieved 12 January 2016, from http://econ.worldbank.org/WBSITE/EXTERNAL/EXTDEC/EXTRESEARCH/EXTLSMS/0,,contentMDK:23506656~pagePK:64168445~piPK:64168309~theSitePK:3358997,00.html

Turner II, B.L., Lambin, E.F., & Reenberg, A. (2007). The emergence of land change science for global environmental change and sustainability. Proceedings of the National Academy of Sciences 104 (52), 20666–20671. http://doi.org/10.1073/pnas.0704119104

Turnhout, E., Waterton, C., Neves, K., & Buizer, M. (2013). Rethinking biodiversity: from goods and services to ‘living with’. Conservation Letters 6 (3), 154–161. http://doi.org/10.1111/j.1755-263X.2012.00307.x

Urech, Z.L., Felber, H.R., & Sorg, J.-P. (2012). Who wants to conserve remaining forest fragments in the Manompana corridor? Madagascar Conservation & Development 7 (3), 135-143. http://doi.org/http://dx.doi.org/10.4314/mcd.v7i3.6

Urech, Z.L., Zaehringer, J.G., Rickenbach, O., Sorg, J.-P., & Felber, H.R. (2015). Understanding deforestation and forest fragmentation from a livelihood perspective. Madagascar Conservation & Development 10 (2), 67–76.

Vandermeer, J., & Perfecto, I. (2007). The Agricultural Matrix and a Future Paradigm for Conservation. Conservation Biology 21 (1), 274–277. http://doi.org/10.1111/j.1523-1739.2006.00582.x

van Vliet, N., Mertz, O., Heinimann, A., Langanke, T., Pascual, U., Schmook, B., … Ziegler, A. D. (2012). Trends, drivers and impacts of changes in swidden cultivation in tropical forest-agriculture frontiers: A global assessment. Global Environmental Change 22 (2), 418–429. http://doi.org/10.1016/j.gloenvcha.2011.10.009

Verburg, P.H., Crossman, N., Ellis, E.C., Heinimann, A., Hostert, P., Mertz, O., … Zhen, L. (2015). Land system science and sustainable development of the earth system: A global land project perspective. Anthropocene 12, 29-41. http://doi.org/10.1016/j.ancene.2015.09.004

Verburg, P.H., van de Steeg, J., Veldkamp, A., & Willemen, L. (2009). From land cover change to land function dynamics: A major challenge to improve land characterization. Journal of Environmental Management 90 (3), 1327–1335. http://doi.org/10.1016/j.jenvman.2008.08.005

Villamagna, A., & Giesecke, C. (2014). Adapting Human Well-being Frameworks for Ecosystem Service Assessments across Diverse Landscapes. Ecology and Society 19 (1). http://doi.org/10.5751/ES-06173-190111

Wendland, K.J., Honzak, M., Portela, R., Vitale, B., Rubinoff, S., & Randrianarisoa, J. (2010). Targeting and implementing payments for ecosystem services: Opportunities for bundling biodiversity conservation with carbon and water services in Madagascar. Ecological Economics 69 (11), 2093–2107. http://doi.org/10.1016/j.ecolecon.2009.01.002

Zaehringer, J.G., Hett, C., Ramamonjisoa, B., & Messerli, P. 2016. 'Beyond Deforestation Monitoring in Conservation Hotspots: Analysing Landscape Mosaic Dynamics in North-Eastern Madagascar'. Applied Geography 68, 9–19. doi:10.1016/j.apgeog.2015.12.009.

Zaehringer, J.G., Eckert, S. & Messerli, P. 2015. 'Revealing Regional Deforestation Dynamics in North-Eastern Madagascar—Insights from Multi-Temporal Land Cover Change Analysis'. Land 4 (2): 454–474. http://doi:10.3390/land4020454.

Zhang, W., Ricketts, T.H., Kremen, C., Carney, K., & Swinton, S.M. (2007). Ecosystem services and dis-services to agriculture. Ecological Economics 64 (2), 253–260. http://doi.org/10.1016/j.ecolecon.2007.02.024