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Ecosystem services reinforce Sumatran tiger conservation in land use plans

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ABSTRACT

Ecosystem services have clear promise to help identify and protect priority areas for biodiversity. To leverage them effectively, practitioners must conduct timely analyses at appropriate scales, often with limited data. Here we use simple spatial analyses on readily available datasets to compare the distribution of five ecosystem services with tiger habitat in central Sumatra. We assessed services and habitat in 2008 and the changes in these variables under two future scenarios: a conservation-friendly Green Vision, and a Spatial Plan developed by the Indonesian government. In 2008, the range of tiger habitat overlapped substantially with areas of high carbon storage and sediment retention, but less with areas of high water yield and nutrient retention. Depending on service, location and spatial grain of analysis, there were both gains and losses from 2008 to each scenario; however, aggregate provision of each ecosystem service (except water yield) and total area of tiger habitat were higher in the Vision than the Plan, likely driven by an increase in forest cover in the Vision. Sub-watersheds with high levels of several ecosystem services contained substantially more tiger habitat than random subsets of sub-watersheds, suggesting that prioritizing ecosystem services could benefit tiger conservation. Our analyses provided input to government-led spatial planning and strategic environmental assessments in the study area, indicating that even under time and data constraints, policy-relevant assessments of multiple ecosystem services are feasible.

1. Introduction

Many parts of the world are experiencing high rates of biodiversity loss (Butchart et al., 2010). Biodiversity decline is accompanied by ecosystem degradation, which in turn impacts human well-being through the loss of benefits (‘‘ecosystem services’’) that ecosystems provide (Díaz et al., 2006). Ecosystem services are difficult to quantify, and have often been ignored or undervalued in development decisions (Daily et al., 2009).

Of late, there has been substantial interest in exploring synergies between the goals of securing ecosystem services and conserving biodiversity (Turner et al., 2007; Naidoo et al., 2008; Mace et al., 2012). Conservation practitioners are being called upon to assess the social impacts of interventions (Springer, 2009). Accordingly, several conservation organizations have made the concept of ecosystem services a cornerstone of their strategies (Tallis et al., 2008).

Assessing these synergies in a way that provides rigorous but practical guidance for conservation interventions (e.g., zoning, payments for ecosystem services) requires several key steps. First, ecosystem service provision by areas of conservation significance must be quantified. Second, society’s preferences for these services should be identified (Martín-López et al., 2012). Third, there is a need to assess the extent to which conservation goals would be served by interventions for securing ecosystem services. Together, this information can help design credible and potentially effective policies that meet conservation goals and also maintain ecosystem services.

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However, the data and capacity to carry out such detailed analyses are often extremely limited (Eigenbrod et al., 2010), especially in the world's most biodiverse and imperiled areas. The time windows for conducting such analyses can also be narrow, due to rapid declines in the state of biodiversity and ecosystems, and evolving policy windows (Kingdon, 1995). In such situations, even relatively simple analyses that provide a rough overview of the distribution of ecosystem services, and potential changes to these services under alternative policies, may usefully inform decisions (Ruckelshaus et al., 2013), especially in the earlier stages of planning.

The analyses reported in this paper arose from such a context. They were initiated at the invitation of Indonesian government authorities interested in incorporating ecosystem services information into spatial plans for several districts and provinces in central Sumatra (Roosita et al., 2010; Bhagabati et al., 2012). This region contains some of the last remaining forest habitat of the critically endangered Sumatran tiger, *Panthera tigris sumatrae* (Wibisono and Pusparini, 2010; Sunarto et al., 2012), and has experienced among the highest deforestation rates in the world (Uryu et al., 2008; Miettinen et al., 2011), driven primarily by forest conversion to oil palm and *Acacia* plantations. Forest loss has led to Indonesia becoming one of the world's leading producers of deforestation-linked carbon emissions, especially from peat soils (Harris et al., 2012). Land use change in Sumatra has also led to water quality degradation (Rixen et al., 2008) and interacts in complex ways with soil and hydrological function (Rodenburg et al., 2003; Verbist et al., 2005).

Although conservation faces many challenges in Indonesia, there has been some recent political momentum for it, including a 2009 commitment by Indonesia's president to substantially reduce deforestation (Busch et al., 2012), and national policies (Indonesia Laws No. 26/2007 and No. 32/2009) requiring environmentally sustainable spatial plans at national, provincial and district levels (Craig Kirkpatrick, personal communication). Payment schemes and pilot projects based on ecosystem services have also emerged. These include funding commitments from Norway to help Indonesia to reduce emissions from deforestation (Government of Norway, 2010), and the RUPES (Rewarding Upland Poor for Environmental Services) program of the World Agroforestry Center, aimed at aligning ecosystem services with poverty alleviation through programs including payments for watershed services (Leimona et al., 2009; Van Noordwijk and Leimona, 2010). These developments have helped set the stage for mainstreaming ecosystem services into Indonesian policies, and provide the context that motivated our study.

We use readily available datasets to assess the current (as of 2008) distribution of ecosystem services and their overlap with the range of tiger habitat in central Sumatra. We examine whether areas providing high levels of ecosystem services are also important as tiger habitat, thereby suggesting synergies between the goals of securing ecosystem services and conserving tigers. We then assess potential changes in ecosystem services and tiger habitat from 2008 to two alternative future scenarios, one of which explicitly prioritizes conservation, whereas the other does not.

Finally, we reflect on the potential of our analyses to influence conservation policy. We describe how the technical input that we provided policy-makers based on these analyses, and the accompanying advocacy, have already influenced decision-making.

2. Methods

For assessing current patterns, we (a) mapped and compared the spatial distribution of ecosystem services and tiger habitat in 2008; (b) quantified ecosystem service provision by tiger habitat relative to other areas; and (c) determined whether land parcels with high levels of ecosystem services contain substantially more tiger habitat than under a random expectation. For assessing future change, we (a) mapped potential land use and land cover (LULC) under two alternative scenarios; (b) mapped and compared the potential future distribution of ecosystem services and tiger habitat corresponding to each scenario; and (c) quantified relative change in these variables from 2008 to each scenario. Below we summarize data inputs and analysis steps; further details are in the Appendices.

2.1. Study area

Our study area encompasses six watersheds in Sumatra covering portions of Riau, Jambi and West Sumatra provinces (Fig. 1). The Barisan mountain range comprises the western edge of the watersheds, while peat swamps predominate in the east. The central area consists mostly of lowlands and scattered hills. We obtained a LULC map for our baseline year of 2008 from WWF Indonesia, derived by manual classification of Landsat and IRS-P6 satellite imagery at 30 m resolution and validated through ground checks (Setiabudi and Budiman, 2008). The map contained 89 LULC classes (Appendix A), with 33% of the area under forest, 42% under plantations (predominantly oil palm and *Acacia*), and the rest under agriculture, settlements, mining and other uses (Fig. 2a).

2.2. Scenarios

We compared two alternative, spatially explicit future LULC scenarios. Scenarios are widely used to understand uncertain futures (McKenzie et al., 2012) and in this analysis are intended not as predictions, but rather to assess possible consequences of alternative land use decisions being discussed by stakeholders in Sumatra. The first scenario (Fig. 2b), the Sumatra Ecosystem Vision (referred to hereafter as the Vision) represents a future that would balance conservation and human needs by protecting and restoring areas important for biodiversity and ecosystem services, while also accommodating sustainable economic development. This scenario, which would double the area under forest relative to 2008 through protection and restoration, is based on the Sumatra 2020 Roadmap (Roosita et al., 2010), a vision for sustainable land use advanced by the Sumatra Spatial Planning Forum, a coalition of representatives from government, civil society and academia. The second scenario (Fig. 2c), the Government Spatial Plan (referred to hereafter as the Plan), is based on province-level zoning plans developed by the Indonesian Ministry of Public Works on a five year cycle under the National Spatial Planning Law of 2007 (No. 26/2007). It is similar to past plans, does not prioritize biodiversity or ecosystem services, and would maintain the natural forest present in 2008, with the remaining area assigned to plantations, production forestry and other uses. Notably, the Plan would allocate over twice the area allocated in the Vision to plantations. Both scenarios are simplified depictions of the future; for instance, they both assume full implementation of proposed zoning designations, and do not take into account drivers of LULC change such as climate, commodity prices, and governance. Still, these scenarios reference actual discussions among stakeholders about alternative land uses, and are useful as conservative assessments of the future. LULC classes were extrapolated from 2008 based on zoning designations specified in each scenario (Appendix B).

2.3. Modeling ecosystem services and tiger habitat

We used a modeling tool, InVEST (Integrated Valuation of Environmental Services and Tradeoffs version 1.004; Tallis et al., 2010), to map and quantify tiger habitat quality and five ecosystem services. InVEST maps ecosystem services and the quality of species

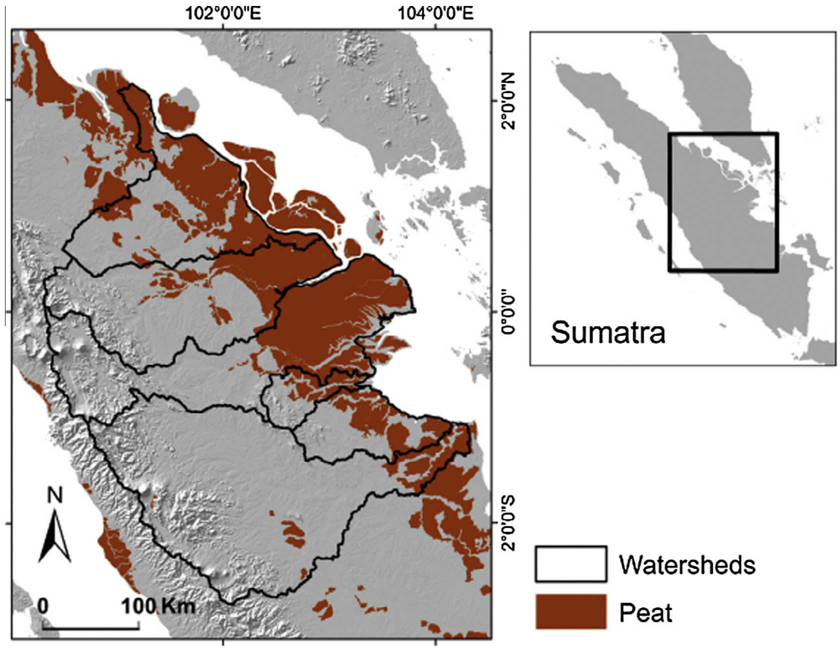

Fig. 1. Relief map of the study area in central Sumatra showing the spine of the Barisan mountains in the west and the extensive peatlands in the east.

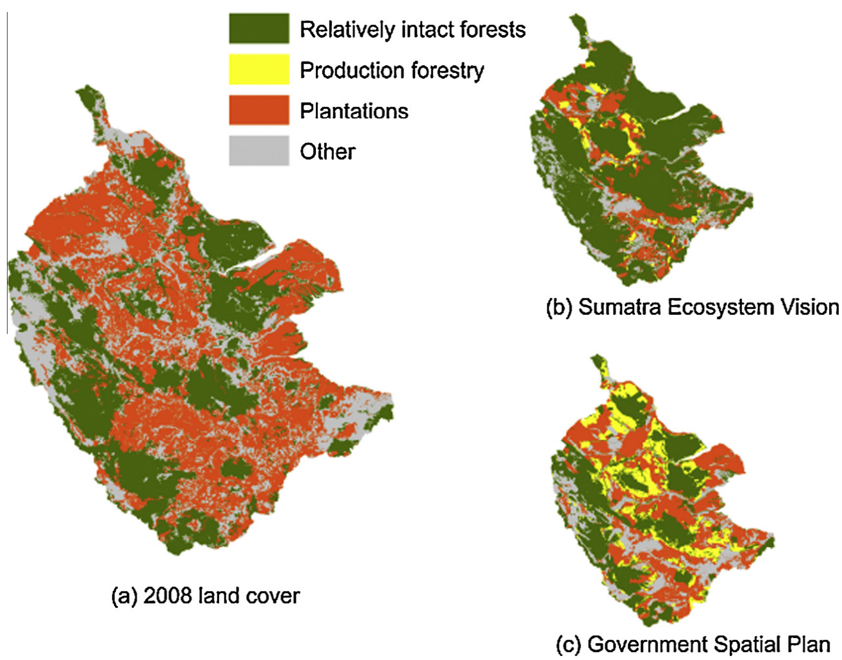

Fig. 2. Broad patterns of LULC (classes aggregated for display) in 2008 (a) and two alternative future scenarios (b, c). We considered forests to be relatively intact if they had closed or medium open canopy cover in 2008, and assigned the same designation to strictly protected forests in the future scenarios. The production forestry class in the scenarios designates future forested areas where some activities such as logging would be permitted; however, plantations and other non-forest land cover would not be legally allowed in these areas.

habitat as production functions of LULC using simple biophysical models. Models were parameterized using data from regional agencies, literature surveys, global databases, site visits and prior field experience (Table 1).

We briefly describe our models for tiger habitat and the five services included in this study; detailed descriptions are in Appendices C–E and Tallis et al. (2010). **Tiger habitat quality**: InVEST maps habitat quality (a score between zero and one), as a function of the suitability of a given LULC class as habitat for the target species, and the spatial distribution of threats such as infrastructure and settlements to the integrity of that habitat. **Carbon storage and sequestration**: We mapped biomass carbon by assigning carbon values (in ton ha^{-1}) for aboveground, belowground, and dead organic matter to each LULC class based on values from literature, as described in Tallis et al. (2010). We mapped soil carbon separately, as large quantities of carbon are stored in peat soil (Page et al., 2011). We estimated total losses in peat carbon over 50 years into the future scenarios, using reported annual emission rates for specific LULC transitions on peat (Uryu et al., 2008). **Water yield**: The InVEST water yield model evaluates how LULC affects annual

Table 1
Representative subset of data sources used in modeling tiger habitat and ecosystem services in Sumatra. A full list is in Appendices C–E.

Habitat or ecosystem service output variable	Input data type	Unit	Source
Carbon			
Above ground	Table values	ton ha^{-1}	Uryu et al., 2008
Peat	Vector	ton ha^{-1}	Wahyunto et al., 2003
Peat carbon emission rates	Table values	ton ha^{-1} y^{-1}	Uryu et al., 2008
Hydrological models			
Digital elevation model	Raster	m	HydroSHEDS (www.hydrosheds.org)
Precipitation	Raster	mm y^{-1}	WorldClim (www.worldclim.org)
Potential evapotranspiration	Raster	mm y^{-1}	FAO GeoNetwork (http://www.fao.org/geonetwork/srv/en/main.home)
Soil erodibility (K factor)	Raster	ton h MJ^{-1} mm^{-1}	Regional Development Planning Board, Jambi province Division of Water Management, Riau Forestry Department
Crop (C) and practice (P) factor	Table values	Dimensionless	Tallis et al. (2010) and Regional Development Planning Board, Jambi province
Nutrient export coefficients	Table values	g ha^{-1} y^{-1}	Reckhow et al., 1980
Tiger habitat quality			
Roads	Vector		Indonesian National Coordinating Agency for Surveys and Mapping (BAKOSURTANAL, Badan Koordinasi Survei dan Pemetaan Nasional)
Other threat locations	Raster		2008 LULC map
Habitat suitability and threat scores	Table values	Dimensionless between 0 and 1	Expert input from tiger researcher

water yield across a landscape. The model calculates water yield, defined here as all precipitation that does not evapotranspire, as an annual average runoff depth (mm y^{-1}). **Sediment retention**: The sediment retention model is based on the Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978). It estimates erosion as ton y^{-1} of sediment load, based on the energetic ability of rainfall to move soil, the erodibility of a given soil type, slope, erosion protection provided by vegetated LULC, and land management practices. The model routes sediment originating on each land parcel along its flow path, with vegetated parcels retaining a fraction of sediment with varying efficiencies, and exporting the remainder downstream. **Nutrient retention**: Our nutrient retention model estimates nitrogen and phosphorus loading (kg y^{-1}), leading causes of water pollution from fertilizer application and other activities, using the export coefficient approach of Reckhow et al. (1980). The model routes nutrient runoff from each land parcel downslope along the flow path, with some of the nutrient that originated upstream being retained by the parcel according to its retention efficiency. For assessing variation within the same LULC map (2008 and each scenario), we compared sediment and nutrient retention across the landscape. However, for assessing change to scenarios, we compared sediment and nutrient export between the relevant LULC maps, as the change in export (rather than in retention) better reflects the change in service experienced downstream.

Although InVEST reports ecosystem services in biophysical units, its simple models are best suited to understanding broad patterns of spatial variation (Tallis and Polasky, 2011), rather than for precise quantification. Additionally, we lacked field measurements against which to calibrate our outputs. Therefore, we focused on relative spatial distribution across the landscape, and relative change to scenarios.

2.4. Spatial units of analysis

InVEST calculates carbon stocks and habitat quality for each LULC pixel, but for hydrological services it sums results by sub-watersheds. Sub-watersheds are therefore the smallest spatial grain at which all ecosystem services are quantified. Given potentially higher uncertainty at finer resolutions, we did not attempt to interpret variation within sub-watersheds. We sub-divided the six watersheds into 68 sub-watersheds using ArcSWAT (http://swat.tamu.edu/software/arcswat/). We aggregated pixels whose tiger habitat quality score as computed by InVEST was above a threshold (see Section 2.5) into polygons designating potentially suitable tiger habitat; these polygons were the spatial units for subsequent analyses of tiger habitat. For some analyses, we summed ecosystem services over the entire landscape. We also assessed variation by districts and provinces in our report for decision-makers (Bhagabati et al., 2012); however, given the primarily biophysical focus of this paper, we do not report those results here.

2.5. Calibrating the tiger habitat model

To map areas potentially suitable for tigers in future scenarios, we first identified a threshold tiger habitat quality score from our model that reliably discriminated between areas of confirmed tiger presence and other areas in 2008. We compared our modeled habitat quality scores for 2008 at randomly placed points ($n = 904$) on our study area with the current distribution of Sumatran tigers reported in Wibisono and Pusparini (2010). For these points, we assessed sensitivity (true positive rate) and specificity (true negative rate) of classification by different threshold quality scores from our model, where points with scores above the threshold were classified as areas of tiger presence. We thus identified a minimum threshold score (0.6) that reliably distinguishes areas of confirmed tiger presence from other areas (Appendix F). For subsequent analyses, we assumed that all areas with habitat quality scores of 0.6 or higher represent potential tiger habitat. Using sensitivity and specificity scores to set thresholds for species occurrence is a standard approach to modeling species distribution (Liu et al., 2005; Pearson, 2007). While a more detailed assessment of tiger presence / absence prediction accuracy would be needed for a rigorous predictive model, our calibration provides a basis for this initial analysis of potential tiger habitat overlap with ecosystem services.

2.6. Comparing ecosystem services within and outside tiger habitat

Within each LULC map, we calculated the relative concentration of an ecosystem service within tiger habitat, compared to outside it, as the normalized percent difference between the concentration (amount ha^{-1}) of that service inside and outside tiger habitat:

$$(\text{Concentration}_{\text{within}} - \text{Concentration}_{\text{outside}}) * 100/\text{Concentration}_{\text{outside}}$$

2.7. Assessing coverage of tiger habitat by sub-watersheds that contain high levels of ecosystem services

We conducted a randomization test using the R package (http://www.r-project.org/) to assess whether the top 10%, 25% and 50% of sub-watersheds for single or multiple ecosystem services also include substantially higher amounts of tiger habitat than bootstrapped samples of sub-watersheds. We developed an index to represent multiple service provision as follows: For each service, we scaled the total amount provided by a sub-watershed in 2008 between 0 and 1, where 1 represents the highest amount of that service provided by any sub-watershed. We then summed these five scaled quantities within each sub-watershed; higher values of this summed index indicate higher overall provision of multiple ecosystem services by a given sub-watershed.

Next we created a null expectation by calculating the mean ± s.d. area of tiger habitat contained within 100 bootstrapped samples of *n* sub-watersheds, for each n where n ranged from 1 to 68. To this null expectation, we compared the total area of tiger habitat contained within the top 10%, 25% and 50% of sub-watersheds ranked by (a) each ecosystem service individually, (b) the multiple ecosystem service index, and (c) area of tiger habitat.

2.8. Representing service change from 2008 to scenarios

We calculated ecosystem service changes to scenarios as a normalized percent difference, comparing the total amount of a service in 2008 to the total amount in the scenario within the relevant spatial unit of analysis. For carbon and water yield, we calculated the change in service in a given area as a percent of the total amount in 2008:

$$(\text{Total}_{\text{scenario}} - \text{Total}_{2008}) * 100/\text{Total}_{2008}$$

For assessing changes in sediment and nutrient, we calculated the percent change in export rather than retention; this expresses the change in service as a potential avoided or increased damage in each scenario relative to 2008. Here, a decrease in export from 2008 corresponds to an increase in the service of avoided damage:

$$(\text{Export}_{2008} - \text{Export}_{\text{scenario}}) * 100/\text{Export}_{2008}$$

3. Results

3.1. Distribution and spatial overlap of tiger habitat and ecosystem services in 2008

In 2008, there was marked spatial variation in the distribution of tiger habitat and services over the study area (Fig. 3). There were 4.3 million hectares of tiger habitat. Blocks of tiger habitat remained in the western mountains, the northeastern peat swamps, and isolated patches in the central lowlands and hills (Fig. 3a). The eastern peatlands contained 83% of the total carbon stocks on the landscape (Fig. 3b). Elsewhere, relatively high above-ground biomass carbon stocks were concentrated in the western and central areas. Sediment retention was also spatially clustered (Fig. 3d), with the largest amounts of sediment retained in the west, and relatively little in the east. The highest levels of nutrient retention were primarily in the central region (Fig. 3e and f). Water yield was more spatially dispersed across the landscape (Fig. 3c).

Areas providing high levels of some services overlapped with parts of the tiger range. Specifically, areas of tiger habitat overlapped with areas of high carbon stocks in the east, and sediment retention in the west (Fig. 3b and d). In the central lowlands, areas with high nutrient retention overlapped to a small extent with tiger habitat (Fig. 3e and f).

Some areas outside tiger habitat also contained high levels of services. These included areas of high soil carbon stocks in the eastern peatlands (Fig. 3b), and much of the area high in nutrient retention (Fig. 3e and f). Comparing the total area within tiger habitat to the rest of the landscape, tiger habitat contained substantially higher concentrations of carbon storage and sediment retention, similar concentration of water yield, and lower concentrations of nitrogen and phosphorus retention (Fig. 4, white bars).

3.2. Coverage of tiger habitat by sub-watersheds with high levels of ecosystem services in 2008

Sub-watersheds with high levels of some ecosystem services (carbon, water yield, sediment retention and the multiple service index) covered substantially more tiger habitat than under a random expectation (Fig. 5). In most cases, the tiger habitat area contained in the set of top-ranked sub-watersheds for ecosystem service levels was at least a standard deviation more than the mean habitat area over 100 random samples of the same number of sub-watersheds. Nitrogen and phosphorus retention were the only two services for which the top sub-watersheds performed no better than random, in terms of tiger habitat included. While the most tiger habitat was obtained by explicitly selecting top sub-watersheds for the area of tiger habitat they contained, the same number of sub-watersheds selected for the highest amounts of a single service covered 69–83% of that area.

3.3. Change to scenarios

Relative to 2008, there were landscape-wide gains and losses in tiger habitat and ecosystem services under each scenario (Fig. 6). Under the Vision, there were increases in area of tiger habitat, total carbon stock and avoided nutrient export, but decreases in water yield and avoided sediment export. Under the Plan, tiger habitat remained unchanged, avoided nutrient export increased modestly, and other services decreased. Regardless of increase or decrease from 2008, the amounts of all services except water yield were higher under the Vision than the Plan.

Tiger habitat in the Vision would expand primarily around habitat that existed in 2008, potentially increasing connectivity, while the Plan would maintain the same habitat as in 2008 (Fig. 7a). Both scenarios would lead to increases and decreases in ecosystem services depending on location (Fig. 7b–f). More sub-watersheds would show substantial gains under the Vision than under the Plan for habitat and all services except water yield (Table 2); conversely, more sub-watersheds would lose habitat and services under the Plan than under the Vision. Water yield would decline for almost all sub-watersheds regardless of scenario.

In both scenarios, as in 2008, tiger habitat would contain substantially higher concentrations of carbon storage and sediment retention than areas outside (Fig. 4, black and grey bars). Notably, in the Vision, carbon concentration within tiger habitat would substantially exceed that in 2008 and the Plan. Water yield and nutrient retention within tiger habitat would be at lower concentrations relative to the surrounding landscape in both scenarios.

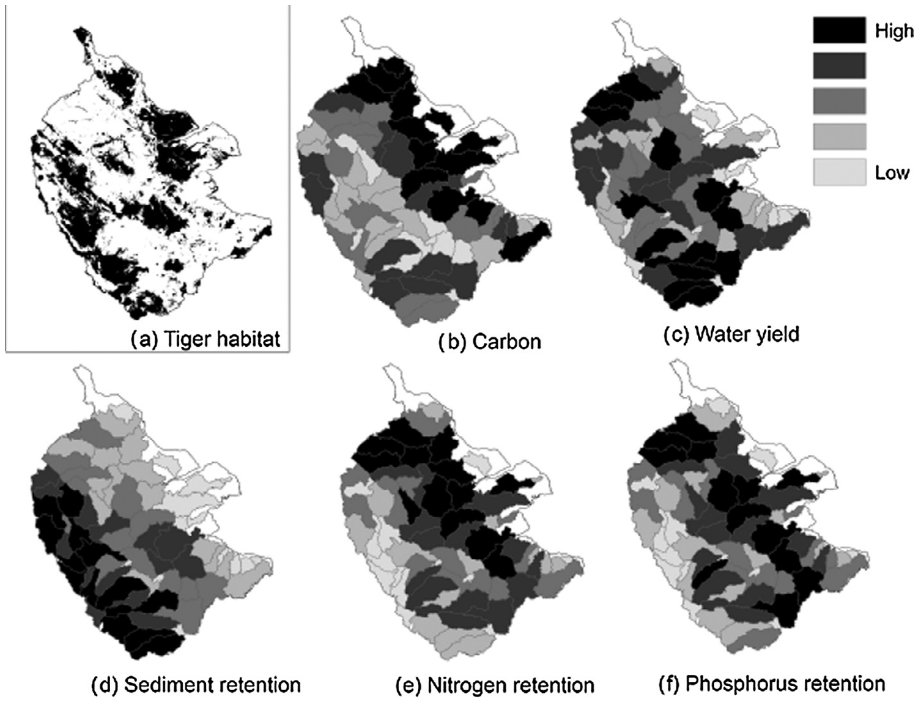

Fig. 3. Distribution of tiger habitat (a) and ecosystem services (c-f) in central Sumatra in 2008. Ecosystem services are aggregated by sub-watersheds, and shaded based on quintile breaks. No services are displayed in small areas in the northern and eastern edges, as we were not able to delineate sub-watersheds there.

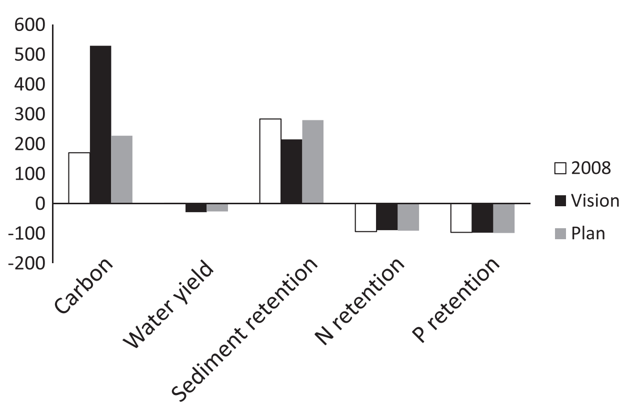

Fig. 4. Relative concentration of ecosystem services per hectare within tiger habitat versus the rest of the study area, expressed as a normalized percent difference. A *y*-value of zero indicates no difference in concentration within and outside tiger habitat.

4. Discussion

We provide evidence for synergies in pursuing goals of conserving species and securing ecosystem services, but also indicate limitations of this approach. Tiger habitat overlaps substantially with areas that provide high levels of some ecosystem services (Figs. 3, 4 and 7), indicating that spatial planning based on securing ecosystem services can reinforce tiger conservation. The Vision offers a path toward higher amounts of tiger habitat and most ecosystem services relative to 2008 and the Plan (Table 2; Figs. 6 and 7). Prioritizing areas for conservation based on ecosystem service provision can provide substantial coverage of tiger habitat, but will likely not include all areas critical for tiger conservation, indicating important but expected tradeoffs (Fig. 5). Our simple models of ecosystem services appear able to inform spatial plans and development options, using available data to respond to policy opportunities.

4.1. Explaining patterns of spatial synergy and mismatch in baseline distributions of ecosystem services and tiger habitat

In 2008, tiger habitat coincided with the location of forests (Figs. 2a and 3a). These forests held substantial carbon stocks in vegetation, and also below the ground in peatland areas. Where forests occurred on mountain slopes, they served to retain sediment (most noticeably in the west, Fig. 3d).

High levels of carbon, water yield and nutrient retention also occurred outside tiger habitat (Figs. 3 and 4). For carbon, this is explained by substantial stocks still present in deforested peat swamps (Fig. 3b), although these are rapidly emitting carbon dioxide to the atmosphere due to peat burning and decomposition (Uryu et al., 2008; Miettinen et al., 2011). Tiger habitat has been largely eliminated from the lowlands, where most nutrient-exporting plantations are located. Therefore, there is little downstream tiger habitat left to retain nutrients, leading to low landscape-wide overlap with this service. Spatial variation in water yield primarily reflected the distribution of annual average rainfall (a model input) rather than variation in LULC.

4.2. Understanding changes under future scenarios

Both scenarios showed gains and losses that varied by service, location and spatial grain of analysis (Figs. 6 and 7; Table 2), suggesting that neither scenario would meet environmental and social goals across the entire landscape. This underscores the need for further refining land use plans to better adapt them to local contexts.

The higher aggregate levels of tiger habitat and most ecosystem services (except water yield) in the Vision (Fig. 6) are likely driven primarily by the increase in forest cover relative to the Plan. Areas of tiger habitat are important for carbon storage and sediment retention in both scenarios (Fig. 4); their role in sequestering soil carbon is especially significant in the Vision, likely because this scenario requires the restoration of substantial areas of forest on

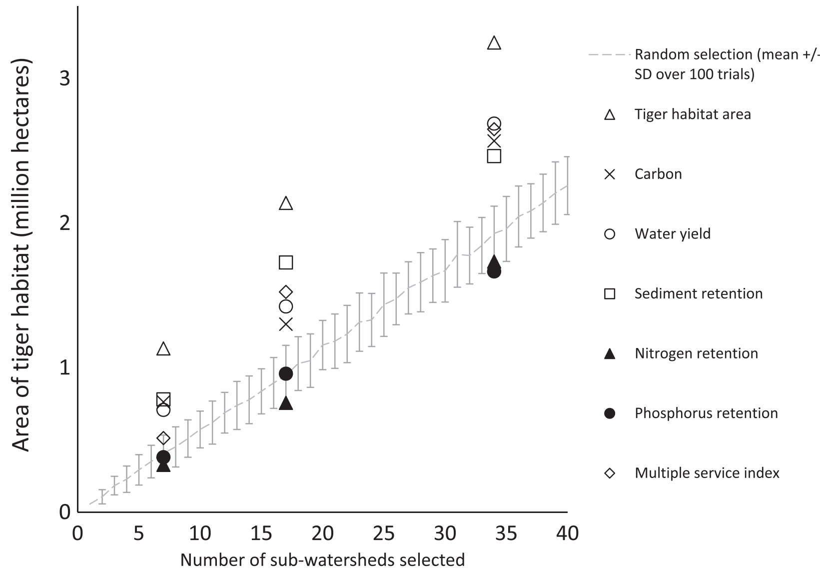

Fig. 5. Coverage of tiger habitat in 2008 obtained by selecting the top 10%, 25% and 50% of sub-watersheds ($n = 7$, 17 and 34 respectively) based on area of tiger habitat, ecosystem service amount, or random selection.

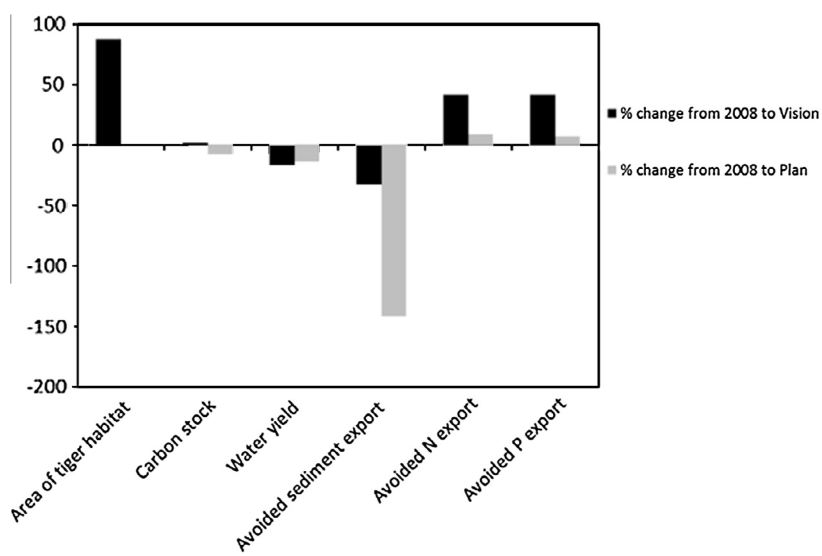

Fig. 6. Normalized difference in tiger habitat area and ecosystem service levels between 2008 and the two scenarios, expressed as percent change.

peatland, which should reduce peat carbon emissions. Afforestation in the Vision would also increase biomass carbon stocks and reduce sediment and nutrient export. The larger decrease in nutrient export in the Vision (Fig. 6) is also partly explained by the smaller area under plantations, and hence fewer nutrient sources, relative to the Plan.

Water yield exhibited similar and widespread losses in both scenarios. This is likely due to our simplified annual time-step model, in which differences in water yield between scenarios are largely driven by evapotranspiration, with the presence of more vegetation (restored forests in the Vision, expanded plantations and production forests in the Plan) leading to higher levels of water loss through increased evapotranspiration in both scenarios. The relationship between water yield and forest cover is likely more complex, with large-scale deforestation possibly resulting in reduced precipitation (Ellison et al., 2012), which we did not model, and seasonal water yield changes not captured by our annual model (Tallis et al., 2010).

4.3. Relevance to conservation and sustainable development

Given substantial coverage of tiger habitat by areas rich in ecosystem services (Fig. 5), the conservation of tigers and other forest-dwelling wildlife in Sumatra could perhaps be promoted by highlighting these potential co-benefits of forest conservation. Where high levels of multiple ecosystem services co-occur on tiger habitat, there may be opportunities to broaden support for conservation by addressing diverse stakeholder priorities. Wide-ranging carnivores on densely populated landscapes typical of South and Southeast Asia are not necessarily confined to large tracts of intact forest, but also use more marginal habitat (Athreya et al., 2013). Sumatran tigers use small forest patches and some plantations as corridors or stepping stones between core habitats (Sunarto et al., 2012). Given that some areas outside current tiger habitat contain high levels of ecosystem services, conserving these areas for ecosystem service provision may benefit tigers and other species by expanding potential habitat and enhancing connectivity.

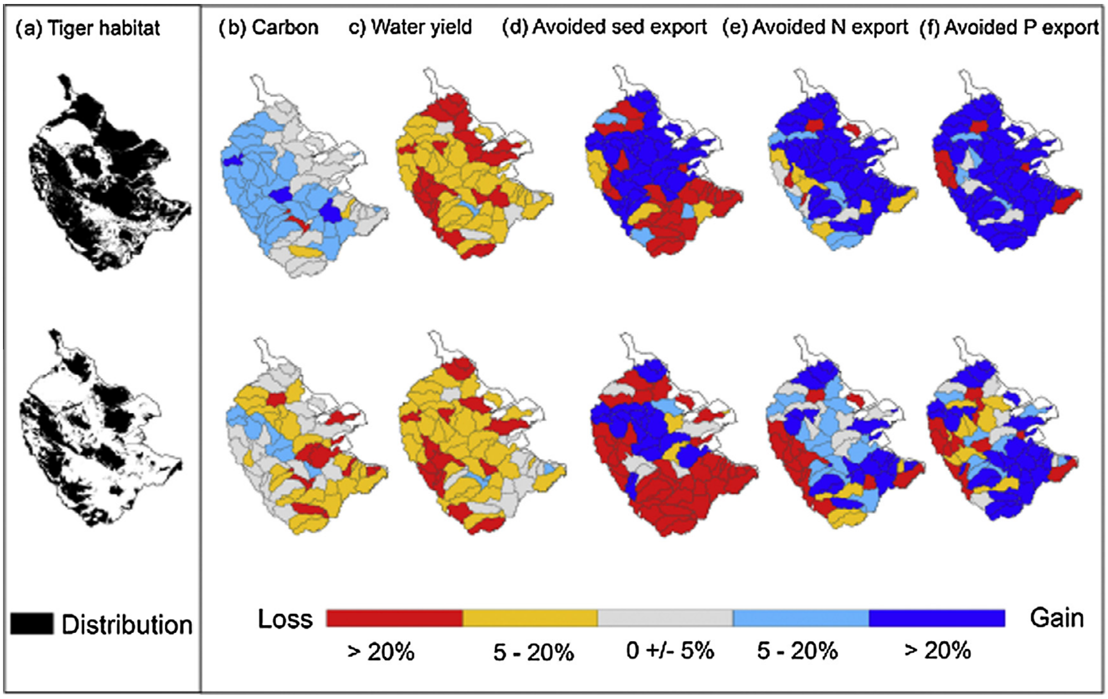

Fig. 7. Changes in tiger habitat (extent) and ecosystem services (percent change within each sub-watershed) from 2008 to the two scenarios.

Table 2
Number of sub-watersheds (percent of total area) gaining or losing more than 5% of tiger habitat area or ecosystem service levels under future scenarios, relative to 2008.

Habitat/ecosystem service	Vision		Plan	
	Gaining	Losing	Gaining	Losing
Tiger habitat	62 (96)	0 (0)	25 (40)	38 (52)
Carbon storage and sequestration	39 (59)	4 (4)	5 (11)	38 (52)
Water yield	1 (1)	62 (93)	3 (2)	51 (82)
Avoided sediment export	36 (54)	33 (46)	18 (29)	46 (62)
Avoided N export	55 (78)	10 (15)	40 (57)	20 (29)
Avoided P export	60 (84)	6 (9)	42 (57)	21 (32)

The different spatial scales at which services deliver benefits suggest tiered opportunities for advocacy and policymaking. The global recognition of Indonesia's role as a leading source of deforestation-linked carbon emissions has spurred international funding commitments to the country to help it reduce its emissions (Government of Norway, 2010; Millennium Challenge Corporation, 2011). Our analyses of hydrological services highlight potential impacts of spatial plans at regional scales, providing a basis for engaging Indonesian government planners and local communities.

A patchwork of programs tailored to specific locations, based on multiple criteria including level of ecosystem service provision, feasibility of implementation and social equity could open new avenues for conservation. For example, in some areas where tiger range overlaps with areas of high carbon stocks, a "wildlife premium" mechanism (Dinerstein et al., 2013) could help finance conservation, where payments for forest carbon are supplemented with additional funds whose disbursement is linked to performance in achieving wildlife conservation goals. In deforested eastern peat swamps, restoration of peat hydrology and vegetation might help to arrest emissions, and over time, allow these areas to function as carbon sinks and tiger habitat again (Page et al., 2009). Watershed management schemes, including payments for watershed services (Bennett et al., 2013), could be implemented in areas critical for hydrological services. Such programs could maintain forest in the western mountains to control erosion, and riparian forest buffers in the central lowlands to reduce nutrient export from plantations to waterways (Klapproth and Johnson, 2009). Lowland forests have historically been under greater threat than their higher elevation counterparts due to easier accessibility (Laumonier et al., 2010; Margono et al., 2012). Highlighting the potential of these forests to filter nutrients exported from nearby plantations may strengthen arguments for their conservation.

4.4. Application to decision-making

WWF Indonesia has used these findings to provide technical input to Indonesian spatial planners. Initial uptake offers reason for cautious optimism. Prior to this analysis, government stakeholders were aware of ecosystem services, but did not consider them in a spatial context. The analysis helped to strengthen their understanding of the spatial dimensions of these services, and therefore, the need to account for them in spatial plans. The study also promoted the incorporation of ecosystem services in strategic environmental assessments of Jambi province and one district in each of Riau and West Sumatra provinces (Craig Kirkpatrick, personal communication; Ruckelshaus et al., 2013). The Indonesian government has designated part of our study area as an "ecosystem corridor" under a presidential decree (Barano and Hadian, 2012), thereby establishing a legal framework for conservation and sustainable land use in the area. While our analysis was not the only factor influencing these decisions, our technical input and related advocacy played a key role. It remains to be seen whether this momentum will translate into tangible improvements in conservation and natural resource management.

4.5. Additional considerations

More detailed analyses, validated with field studies, would help expand upon the broad insights gained from this study, and enable more nuanced recommendations for policy. A partial list of potentially fruitful areas of future research include: (1) using more sophisticated (albeit data and effort-intensive) models to better assess ecosystem services; (2) estimating uncertainty around model outputs; (3) assessing climate impacts on ecosystem services and habitat; (4) including additional relevant services (e.g., non-timber forest products, ecotourism and cultural values); (5) assessing monetary and non-market values of these services as realized by beneficiaries; (6) differentially weighting services based on their relative contribution to beneficiaries' welfare; and (7) accounting for implementation and opportunity costs of land management strategies. The last is particularly pertinent given the profitability of oil palm cultivation in Sumatra (Butler et al., 2009), which may make opportunity costs prohibitive in some areas.

From a conservation standpoint, a focus on ecosystem services may bolster but not replace other strategies. For critically endangered species like the Sumatran tiger that have lost much of their original habitat, approaches such as improving protected area management will continue to be crucial. Furthermore, some of the benefits we assessed (including carbon sequestration and sediment retention) could be provided through land management activities (such as expanding monoculture plantations) that may not be compatible with conservation. Therefore, if conservation is a primary goal, it needs to be explicitly factored into ecosystem service-based strategies.

Connecting our analyses to decision-making will require thoughtful consideration of social and political realities. Land tenure status is often unclear in Sumatra, leading to conflicts between local communities, plantation companies and forest departments (Suyanto, 2006), and to increased deforestation (Linkie et al., 2008). However, there is also evidence that where strong legal or customary land tenure for communities exists in Sumatra, it has promoted land rehabilitation and reduced deforestation (Suyanto et al., 2005; Kusters et al., 2007). Suyanto et al. (2005) suggest that conservation in Sumatra could be incentivized by establishing reward schemes for ecosystem services, where land tenure is granted in exchange for halting deforestation and maintaining services on tenured lands. The modalities of securing land tenure are complex; however, ecosystem services could play a role linking the goals of strengthening tenure and improving conservation outcomes.

Finally, policies based on ecosystem services should account for possible negative impacts on people's livelihoods and other aspects of well-being. For example, ecosystems can be the source of "disservices" such as diseases (Dunn, 2010); and ecosystem service benefits may be unevenly distributed across social groups (Daw et al., 2011).

Caveats notwithstanding, studies based on simple models and limited data can be useful for understanding broad spatial patterns of ecosystem services at scales relevant to decision-making, although they may need to be augmented by more detailed analyses incorporating primary biophysical and socioeconomic data before implementing projects and policies (Eigenbrod et al., 2010). Mapping multiple ecosystem services allows us to consider a diversity of policy incentives tuned to specific places where they have potential to yield both conservation gains and social benefits, while also being explicit about tradeoffs among these goals. More generally, timely analyses of ecosystem services are possible in data-limited situations, and such analyses can provide momentum and practical guidance for decision-making.

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Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.biocon.2013.11.010.

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