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## Title

# Enhancing feasibility: incorporating a socio-ecological systems framework into restoration planning


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## Abstract

Forest restoration is the counterforce to deforestation. In many parts of the world it mitigates forest loss and degradation, but success rates vary. Socio-political variables are important predictors of effectiveness of restoration activities, indicating that restoration strategies need to be locally adapted. Yet, contextual assessments of the biophysical, social and political characteristics of forest restoration are rare. Here, we integrate a social-ecological systems framework with systematic decision-making to inform forest restoration planning. We illustrate this approach through a prioritization analysis in a community-based forest restoration context in Paser District, East Kalimantan, Indonesia. We compare the solutions of our integrated framework with those identified on the basis of biophysical criteria alone. We discover that incorporating a socio-political context alters the selection of priority areas. While the social feasibility and political permissibility can be enhanced, ecological benefits are likely to be reduced and/or opportunity costs of alternative land uses are to be increased. Our conceptual framework allows the appraisal of potential trade-offs between social and ecological outcomes of alternative options, and has the potential to evaluate the efficiency of existing policies. Empirical testing in a range of contexts is required to ensure broad applicability and transferability of our conceptual framework.


*Keywords:* forest landscape restoration; feasibility; social-ecological systems; spatial prioritisation; Kalimantan, Indonesia; tropical forest.

## 1. Introduction

Tropical deforestation has been the primary contributor to forest loss globally over the last decade (Hansen et al., 2013). An estimated 500-600 million hectares (or 30-40%) of tropical forest is considered to be in a degraded state (Blaser et al., 2011). In South East Asia, primary forest represents a small proportion of total forest cover, with most forests having experienced some form of logging or extraction (Sodhi et al., 2009). As such, the goods and services provided by forests, such as timber and non-timber forest products, habitat for biodiversity and water regulation, have deteriorated, often with severe consequences for forest-dependent communities (Lamb et al., 2005; Wells et al., 2013; Abram et al., 2014). Forest restoration to mitigate forest loss and/or degradation has had variable success, with performance strongly moderated by country-specific socio-ecological and political contexts (Lamb et al., 2005; Lamb, 2010; FAO, 2011; Meyfroidt and Lambin, 2011).

When implementing forest restoration, either through afforestation or reforestation, context is especially important in countries such as Indonesia that are ecologically and socio-culturally heterogeneous (Fearon, 2003; Nagendra, 2007; Lamb, 2010; Ostrom and Cox, 2010). For example, the Government of Indonesia has implemented a variety of forest restoration programmes since the 1950s, mainly using a top-down approach (Murniati et al., 2007). While most restoration programmes are considered unsuccessful (Murniati et al., 2007), remarkable success has been achieved in central Java through reforestation using teak (*Tectona grandis*) on severely degraded lands on drought-prone limestone soils (Nawir et al., 2007b). This achievement is largely due to familiarity with teak planting (with the practice dating back to the 1800s), highly motivated communities seeking to enhance the provision of water, and compatibility of the programme with the capacity of local communities (e.g. the communities have other sources of income while the planted trees reach a harvestable size). Conversely, a lack of fit toward prescribed species (including teak) with local experiences and resource needs contributes to limited success of reforestation programmes in other regions such as in Sumatra and Kalimantan (Indonesian Borneo), along with other factors including unclear tenure and complicated funding mechanisms (Nawir et al., 2007a).

The methods available for planning restoration activities are increasingly sophisticated, accounting for both spatial and temporal heterogeneity (e.g. Birch et al., 2010; Budiharta et al., 2014). Most of restoration design studies have focused on ecological criteria with few analyses incorporating social elements (e.g. Orsi and Geneletti, 2010; Jellinek et al., 2014). Furthermore, spatial heterogeneity in the social context of where restoration will be undertaken has not been captured. Instead, the social or political feasibility of restoration is assumed to be homogenous across large geographic extents, even including entire nations or continents, ignoring the local context of the planning region (e.g. Egoh et al., 2014; Carwardine et al., 2015). While contextual assessments that account for both the socio-political and ecological characteristics of a region are becomingly available in the environmental management literature (e.g. Basurto et al., 2013 in fisheries; Baur, 2013 in pasture; Cox, 2014 in irrigation systems), similar analyses for planning forest restoration activities are lacking.

The social-ecological systems (SES) framework proposed by Elinor Ostrom (Ostrom, 2009; Ostrom and Cox, 2010) has potential utility for diagnosing the local nuances of natural resource management and informing restoration projects. In this framework, the motivations for restoration are seen as being locally unique, analogous to the unique symptoms associated with a patient in medical practice. While individuals may exhibit similar symptoms, the treatments prescribed by a medical practitioner vary depending on the individual physiological attributes of the patient, such as age and blood pressure. Similarly, restoration activities are more likely to be effective if the planning process is based on a diagnostic style of investigation. This approach would seek to characterise the socio-political and ecological context and provide insight into the opportunities and constraints that could influence the effectiveness of restoration activities.

Here we develop an analytical framework for operationalising a contextual and systematic approach to restoration planning that employs Ostrom's SES framework in conjunction with methods for systematic decision-making (Figure 1). This approach enables priority areas for restoration to be identified by integrating information on ecological suitability, social feasibility and political permissibility. We illustrate our analytical framework into developing forest restoration plan in Paser District in the province of East Kalimantan, Indonesia, where a recently developed community forestry programme aims to achieve both ecological recovery and improved livelihoods provision through increased benefits from forests (Sardjono et al., 2013).

## 2. Methods

### *2.1. Analytical framework*

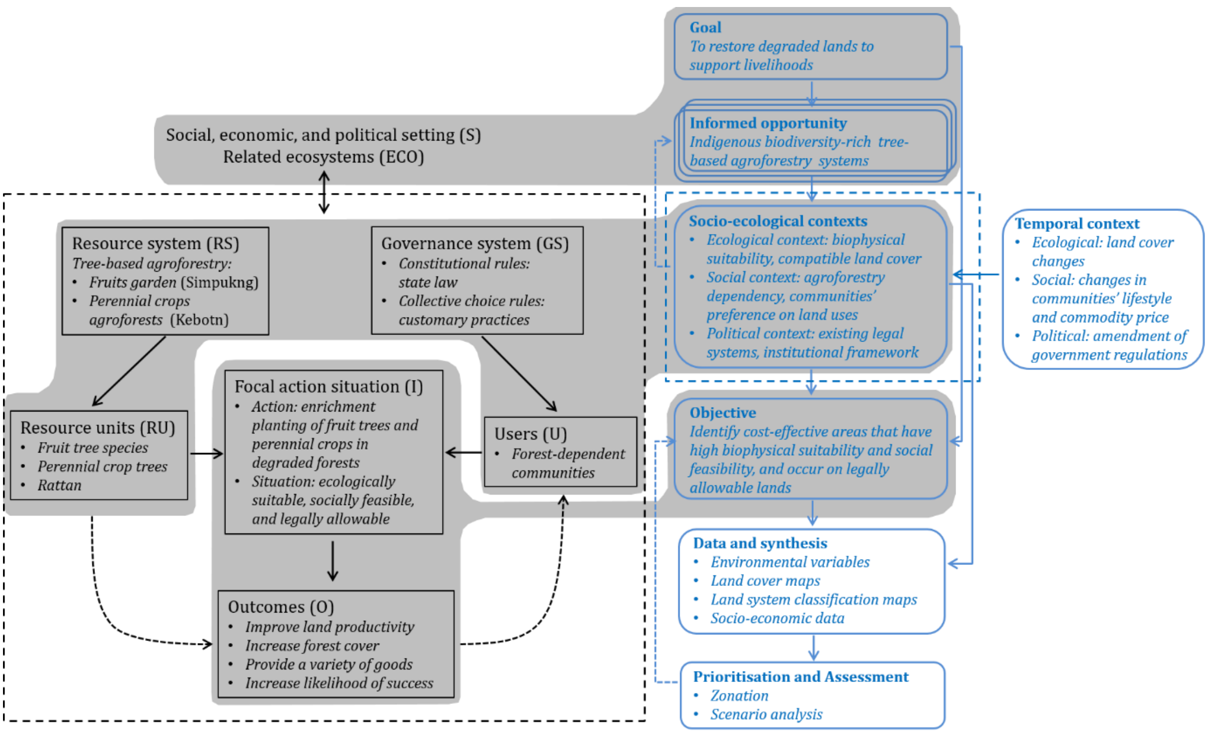


Figure 1. Analytical framework for operationalising social-ecological systems concepts in restoration planning. Italic text illustrates applications to the contextual setting in the case study area (Paser District, East Kalimantan) in relation to a specific goal. Black boxes depict the social-ecological systems framework adapted from Ostrom (2009) including direct links (solid arrows) and feedbacks (dashed arrows). Blue boxes depict steps in systematic decision-making, adapted from Gregory et al. (2012) and Ban et al. (2013). Grey shading shows the links between elements of the two frameworks.

### *Case study*

Paser District has a total extent of 1.16 million hectares (Figure 2; Paser Statistics Service, 2014a). In 2013, approximately 256,000 people inhabited 144 villages within 10 sub-districts (Paser Statistics

Service, 2014a). The population is represented by numerous ethnic groups including Paser indigenous people (Dayak Paser) who mainly live in forest frontier areas, and migrant communities such as those from Java (Javanese), Sulawesi (Buginese) and southern Borneo (Banjarese) who commonly reside in coastal zones and lower plains (Belcher et al., 2004; Bakker, 2008). 'Dayak' is an anthropological term that refers broadly to indigenous ethnic groups living in the interior of Borneo who mainly practice cultivation (Levang et al., 2005). Dayak Paser are believed to be part of the wider Dayak Benuaq, who inhabit the upper Mahakam River and have been practicing complex rotational cultivation systems for centuries (Gönner, 2000; Saragih, 2011).

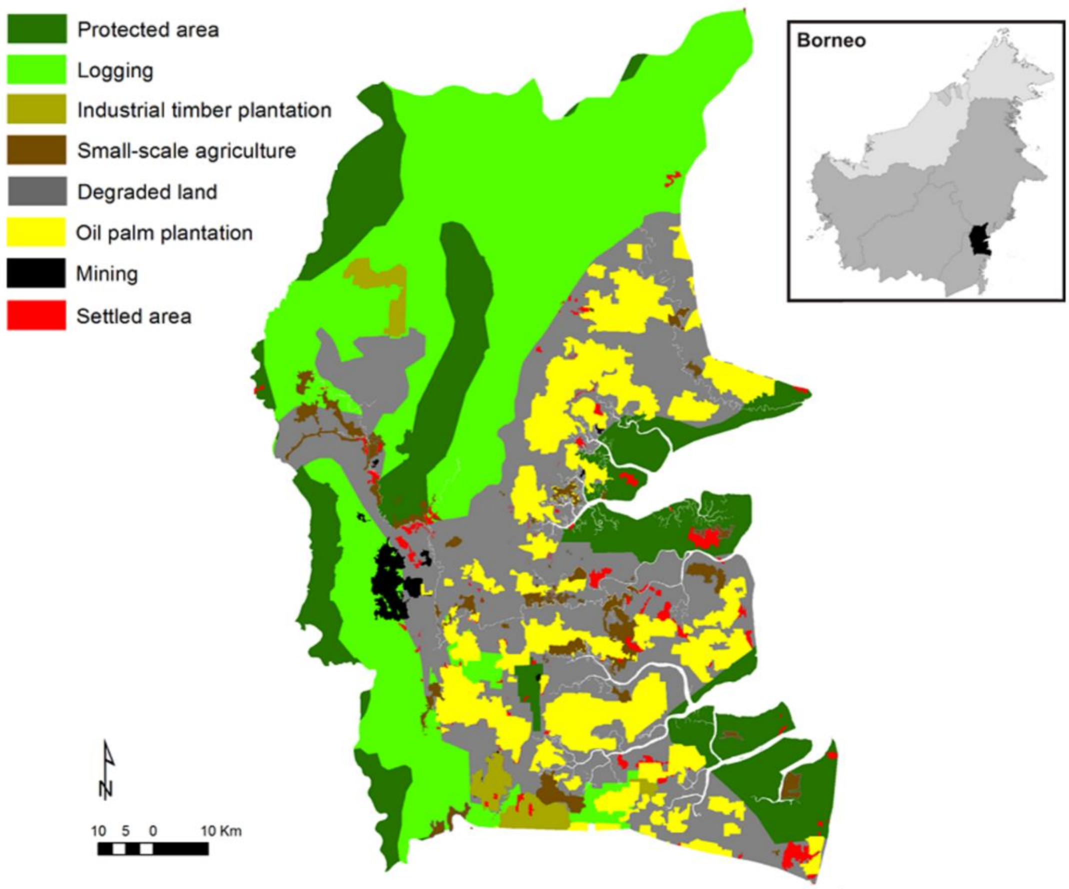


Figure 2. The land uses of Paser District as of 2011. Protected areas (covering 209,355 hectares) consist of two categories: Conservation Forest (e.g. National Park and Nature Reserve) and Protection Forest (for protecting hydrological services). Areas for logging have either active concessions (302,239 hectares) or are without any concession licenses (70,253 hectares). Other land uses include industrial timber plantations (18,323 hectares), small-scale agriculture (32,771 hectares), degraded lands/severely logged forests (260,570 hectares), oil-palm plantations (145,312 hectares), mined areas (8,150 hectares) and settled areas (12,937 hectares). Data sources are from Ministry of Forestry (2012a, 2012b, and 2012c) and Gaveau et al. (2014).

Paser District was previously densely forested, but is undergoing rapid land-use change and economic transition from a forest-based economy to a more diverse economy including rapid development of oil palm plantation (Dewi et al., 2005; Saragih, 2011; Gaveau et al., 2014). Logging operations in Paser began in the 1970s, involving 13 concessions at its peak (Saragih, 2011). Through logging however, many areas have depleted timber stocks resulting in degraded forest, which has led to these areas being converted to non-forested land uses mainly for oil palm plantation.

However, some logged areas remain in degraded conditions and are not currently managed by any timber concessions (Saragih, 2011; Ministry of Forestry, 2012b). As of 2011, there were eight broad land uses within the Paser District (Figure 2) with this landscape including traditional communities who are dependent on forest resources and subsistence dryland agriculture (often referred to as agroforestry); as well as more modernised communities who employ various livelihood practises (Dewi et al., 2005).

### *2.2. Diagnosing the social-ecological systems that represent an opportunity for restoration*

The goal of restoring degraded lands in order to support rural livelihoods (Figure 1) align with the Indonesia's government vision that forest restoration programmes should enhance community empowerment and livelihoods (Article 42 par. 2 of Law No. 41/1999). The explanation (*Penjelasan*) of this law also states a paradigm shift in forest management from a timber focused one, to a view of deriving multiple forest benefits. This vision is supported by Article 48 par. 1 of Law No. 26/2007 on National Spatial Planning, which states that spatial planning for rural areas should maintain ecosystem services, conserve biodiversity and sustain food security.

Using background information about the planning region (e.g. Dewi et al., 2005; Saragih, 2011; Paser Statistics Service, 2014a, 2014b), we apply Ostrom's (2009) diagnostic approach to investigate social-ecological systems that represent potential restoration opportunities (Gregory et al., 2012; Moon et al., 2014). For this study, we focused on local tree-based agroforestry systems that are compatible with our stated goal, which is to restore degraded lands while providing livelihoods for local communities (Figure 1). Although we acknowledge other land management such as oil palm plantation could provide livelihood benefits, we do not include this as restoration opportunity in our study as it is unlikely to deliver ecological benefits (Fitzherbert et al., 2008; Carlson et al., 2014). The agroforestry systems we use herein, are locally known as *awa pangeramu* or *simpukng* and *awa pangekulo* or *kebotn* (herein called *simpukng* and *kebotn* as these are more popular terms) (Gönner, 2000; Saragih, 2011). The elaboration of Ostrom's framework (i.e. Ostrom and Cox, 2010) is used to unpack the social-ecological systems of *simpukng* and *kebotn* into multi-scale subsystems (i.e. resource system, resource units, governance system, users, action situation and outcomes) to identify the contexts for restoration prioritisation (Figure 1; Supplementary Table 1).

*Simpukng* and *kebotn* are integral parts of a wider system of agroforestry in Paser which has been practiced by Dayak Paser for more than 300 years (Gönner, 2000). Both resource systems are commonly established through enrichment planting in degraded forests or young secondary forests using seedlings and wildlings of various tree species grown alongside other naturally regenerating vegetation (Saragih, 2011). *Simpukng* forms a complex agroforest, containing more than 90 species of tree per hectare, mainly important fruits such as a variety of durian species (*Durio* spp), jackfruit (*Artocarpus* spp.) and rambutan (*Nephelium* spp.), creating a multi-layered canopy similar to natural forest (Gönner, 2000; Crevello, 2003). *Kebotn* generally has a simpler floristic structure and composition, as the vegetation is dominated by perennial crops such as rubber (*Hevea brasiliensis*) and coffee (*Coffea* spp) (Crevello, 2003; García-Fernández and Casado, 2005).

A variety of products generated from *simpukng* and *kebotn* provide a broad range of livelihood options in response to social and ecological uncertainties such as market dynamics, forest fires, prolonged droughts and pest outbreaks (Gönner, 2010). As access to markets and dispensaries in rural areas is limited, this form of land management also provides a variety of goods for subsistence needs. For example, agroforestry systems in rural Paser provide between 47 and 88 plant species for consumption, 38 to 56 species for medicinal purposes and between 15 to 23 species for traditional ceremonies (Saragih, 2011).

The governance system in Paser District (as in many regions of Indonesia) has developed from the interplay between informal and formal systems, represented by customary rules and state law, respectively. As agroforestry has been developed by Dayak Paser over many generations, this system has been integrated with their unwritten traditional customary practices (*adat*). Community matters, such as decisions and disputes related to land tenure, are discussed in a meeting (*berinok*) led by the community's customary head (*kepala adat*) (Saragih, 2011). Trust and reciprocity are common, and group members are often willing to share labour resources voluntarily (*gotong-royong*) on farming-related works (Gönner, 2000; Saragih, 2011). However, many agroforestry lands in Paser and other areas in Indonesia are under legal ownership of the central government, and controlled by the Ministry of Forestry as part of the 'Forest Estate' (Peluso, 1995; Saragih, 2011).

### *2.3. Identifying the context for restoration activities*

#### *2.3.1. Ecological context*

There are two important ecological considerations for the establishment of *simpukng* and *kebotn*: biophysical suitability and compatibility with existing land cover (Supplementary Table 1). Biophysical suitability depends on species-specific responses to factors such as topography, climate and soil (Ritung et al., 2007). The biophysical requirements for 11 of the most important tree species commonly cultivated in *simpukng* and *kebotn* in Paser were available (Saragih, 2011; Supplementary Table 2). Eleven biophysical attributes of each site were used to classify suitability for each species into four categories: not suitable, marginal, moderate and high - for which ordinal values from 0 to 3 were assigned (Ritung et al., 2007; Ministry of Agriculture, 2012) (Supplementary Table 3). Data on slope was generated from the CIAT-CGIAR digital elevation model v. 4.1 based on the Shuttle Radar Topography Mission (Jarvis et al., 2008). Annual average temperature and rainfall data were obtained from the WorldClim database (Hijmans et al., 2005). Data on soil properties including drainage, soil texture, coarse material, base saturation and organic carbon were extracted from the Harmonised World Soil Database version 1.2 (FAO/IIASA/ISRIC/ISSCAS/JRC, 2012). Soil cation exchange capacity and pH were obtained from ISRIC (ISRIC – World Soil Information, 2013), while soil depth data was obtained from the World Resources Institute (Gingold et al., 2012). All datasets had 1x1 km spatial resolution, except for slope and soil depth, which was resampled to the 1x1 km resolution.

To identify land covers compatible with *simpukng* and *kebotn* agroforestry, we primarily used a land cover map derived from LANDSAT ETM+7 (Ministry of Forestry, 2012c). This map classifies land cover into 23 categories. To simplify, we merged some classes into broader categories; for example the classes for irrigated rice field, fish pond, freshwater swamp and mangrove were merged into 'wetlands'. In addition, locations of oil palm and industrial timber plantations were identified from LANDSAT ETM and ALOS PALSAR data (Gaveau et al., 2014). In the final map, we defined 'compatible land cover types' as logged forest, severely degraded forest/bush (*semak belukar*) and mixed garden (*kebun campur*), and excluded primary forest, wetlands, oil palm and pulp plantations, settled and cleared areas, and mines.

#### *2.3.2. Socio-economic context*

We identified four important socio-economic characteristics for *simpukng* and *kebotn*, for which spatial information could be collated and synthesised (Supplementary Table 1):

1. The communities' economic dependency on agroforestry systems, measured by the prevalence of agroforestry as the main occupation.
2. The communities' cultural dependency on agroforestry systems, expressed as the use of non-timber forest products (NTFPs) to support subsistence needs and traditional customs.
3. The communities' preference regarding the role of agroforestry compared to other competing land uses.
4. The location of *simpukng* and *kebotn*.

Economic dependency on agroforestry was calculated using the proportion of the village workforce whose primary occupation is in the agroforestry sector (Dewi et al., 2005), based on 2010 national census data (Central Bureau of Statistics, 2014). This dataset differentiates occupational sectors into 19 categories. Agroforestry is not defined as a distinct sector and thus we employed a combination of the agriculture, horticulture and plantation sectors (Paser Statistics Service, 2014b). Forestry was excluded as this sector is associated specifically with jobs in timber industries such as logging concessions and wood processing. As the plantation sector statistics relate to a combination of oil palm and agroforestry (e.g. rubber and coconut), the proportion of the workforce employed in agroforestry plantations was estimated using the extent of agroforest relative to the total extent of plantations (Paser Statistics Service, 2014a). We calculated an adapted version of the Importance Value Index that is commonly used in ecology (Cottam and Curtis, 1956) to obtain an index ranging from 0 (no workers in the agroforestry sector) to 1 (all workers in the agroforestry sector).

Cultural dependency on agroforestry was estimated by the proportion of people in each village who use agroforestry products, assuming that enrichment planting of 11 tree species described above would also generate agroforestry products in a broader sense (i.e. various NTFPs including fruits, vegetables and medicinal plants; Saragih 2011). These estimates were provided by Abram et al. (2014) who mapped local villagers' perceptions on forest ecosystem services and land cover changes using interview data for 1837 individuals within 185 villages in Kalimantan conducted between 2008 and 2012. Spatial predictions of these perceptions throughout the landscape used 39 social-economic and ecological predictors. For our analysis, we incorporated a map representing the use of a combined set of 29 NTFPs, which included products such as small/fire wood, rubber, fruits and vegetables. Specifically, this map classified the use of at least one or more of these NTFPs into three classes: low, moderate and high.

Among communities in Paser District, there are conflicting opinions on land management between maintaining traditional agroforestry system or converting their lands to oil palm (Belcher et al., 2004; Saragih, 2011). To represent individual communities' preference for agroforestry over competing land uses we used spatial estimates of villagers' negative perceptions of large-scale clearing for agriculture and plantations (Abram et al., 2014). For our analysis, we classified this perception into three levels: weak, moderate or strong negative perceptions.

To allow for movement of labour and harvested goods, both *simpukng* and *kebotn* are generally established in the vicinity of transportation networks, such as roads and rivers (Gönner, 2000), but not necessarily in close proximity to towns. This is because the commercial products, such as dried rubber latex and coffee seeds, can be prepared locally and do not require sophisticated post-harvest technologies and processing factories (Saragih, 2011), unlike oil palm fruits (Meijaard and Sheil, 2013). Instead, in the case of *simpukng* and *kebotn*, traders from nearby towns regularly visit villages or local markets to purchase crops (Saragih, 2011). We mapped the proximity to transportation networks as the Euclidean distance to roads (including logging and village roads) and rivers, using data obtained from the Development Planning Agency (*Bappeda*) of East Kalimantan Province. We classified distance from transportation networks into four classes (Gönner, 2000): 0-0.5 km; 0.5-1 km; 1-2 km, and >2 km.

### *2.3.3. Political context*

There are two possible legal contexts for the establishment of *simpukng* and *kebotn*: one on lands outside the Forest Estate (*Area Penggunaan Lain/APL*), and the other on state lands inside the Forest Estate and under the institutional arrangement of community forest (*hutan kemasyarakatan/HKm*) (Supplementary Table 1). In community forest, a farmer group is given rights to manage and utilise forest resources over a 35 year contract which can be extended every five years when the contract expires (Ministry of Forestry, 2007). However, community forest involving tree planting, such as required for establishing s*impukng* and *kebotn*, can only be granted in areas designated as Production Forest (i.e. Forest Estate designated to generate forest products such as logging concession) without an active concession.

To identify areas legally allowable for establishing *simpukng* and *kebotn*, we employed the forest classification map (Ministry of Forestry, 2012a) to delineate the Forest Estate. The Forest Estate was then further differentiated into Production Forest and Protected Areas (which consist of Protection Forest and Conservation Forest). A map of forest concessions (Ministry of Forestry, 2012b) was used to delineate areas of Production Forest without an active concession.

### *2.3.4. Opportunity costs of restoration*

We defined costs as the profits forgone from alternative land uses (i.e. opportunity cost bear by competing land-based industries eminent in Paser District) if a land parcel is managed for *simpukng* and *kebotn* (Wilson et al., 2012). We considered two competing land uses when estimating the opportunity cost: oil palm plantations and logging. We assumed that if a land parcel is suitable for oil palm, the opportunity cost is calculated as the net present value (NPV) of oil palm plus additional revenues generated from harvesting timber during land clearing. Conversely, if a land parcel is not suitable for oil palm, we assumed the opportunity cost is equal to the value of timber that would be obtained either through selective logging (of existing logged forest) or clear cutting (of existing mixed gardens). We used data from Irawan et al. (2013) as a baseline NPV for oil palm (i.e. US$6,355 per hectare). We adjusted the NPV of oil palm according to land suitability assuming that highly suitable land would produce full yield (i.e. 100% NPV), while moderately and marginally suitable land would generate 75% and 50% of full of the NPV, respectively. Land suitability for oil palm was mapped using a similar method as for the agroforestry species described above. We estimated the NPV of timber extraction for each compatible land cover using data from Ruslandi et al. (2011). For logged forest, the NPV of logging was adjusted to US$1,292 per hectare as commercial timber volumes in already-logged forests in Kalimantan are in average 57% of unlogged areas (Putz et al., 2012). For areas that are currently under mixed gardens, a conservative opportunity cost of US$300 per hectare was assigned (assuming smallholder timber extraction since large-scale commercial logging is unlikely to be feasible), while for severely degraded forest we assumed no timber of value remains (Budiharta et al., 2014).

### *2.4. Prioritisation analysis and planning scenarios*

We assigned an ordinal value for biophysical suitability, cultural dependency, community preference and accessibility; and an index for economic dependency (continuous over the range 0 –1). We employed the decision support tool *Zonation v.4* (Moilanen et al., 2009) to produce a ranking of priority areas for restoration (through the establishment of *simpukng* and *kebotn* agroforestry). We prioritised land parcels with the highest aggregate values for social feasibility (across four social variables) and biophysical suitability (across 11 fruit and perennial crops) while minimising opportunity cost (Moilanen et al., 2009). All spatial inputs had a 1x1 km grid size to produce planning unit with spatial extent of 100 hectares, reflecting the scale of land management systems (e.g. community forest), and the resolution of the spatial datasets used to generate the social and biophysical suitability layers.

We tested four scenarios to explore the influence of different socio-ecological perspectives on restoration priorities, and to investigate the trade-offs in term of social and ecological benefits gained, and costs incurred under each scenario. In Scenario 1, we accounted only for biophysical suitability layers. We incorporated both social and biophysical suitability layers in Scenario 2, with equal weight for these two classes of information. In Scenario 3, we incorporated the political context by assuming that priority areas for restoration are constrained by current legal systems for land use. For this scenario, areas that occur in either the non-Forest Estate or in Production Forest without active concessions were prioritised over areas in Production Forest with active logging concessions and protected areas. In Scenario 4, we allowed agroforestry restoration on all Production Forests, disregarding the location of active logging concessions. For this scenario, we assumed that if priority areas occur in active concessions, the land use would need to change from a logging concession to a community forest.

For each scenario, restoration sites were selected as the top 20% of potential areas in the ranked prioritisation. For each set of selected sites, we calculated the value for each variable (e.g. biophysical suitability of a specific crop, index of economic dependency on agroforestry) as a proportion of its summed value across the areas potentially available for restoration, and the overall value across all variables in each class (social or ecological) was calculated as the mean of these proportions. We also calculated cost-effectiveness of each scenarios formulated as total cost required if the summed values of all variables in each social or ecological class was retained.

## 3. Results

We identified 515,300 hectares of land in Paser District that could potentially be restored for agroforestry to achieve our goal. These areas are suitable for at least one of 11 the fruit/crop types of commonly employed in *simpukng* and *kebotn* for which suitability criteria are known, and the present land cover is compatible (Figure 3). The top 20% priority sites (103,060 hectares) under Scenario 1 (considering only biophysical criteria) had the overall greatest biophysical suitability but low social feasibility (Figure 4). This is due to the selection of areas in the eastern part of the region that were adjacent to oil-palm plantations (Figure 3a), which have a low cultural dependency on agroforestry and high economic dependency on the oil-palm sector. Consequently, the areas selected under Scenario 1 incurred the greatest opportunity cost, equating to US$605 million (Figure 4). The areas selected also encompassed at least 8,500 and 1,500 hectares of Conservation Forest and Protection Forest respectively.

When incorporating both social and ecological variables concurrently (Scenario 2), priority areas showed a more distributed pattern, with many high priority areas in the central and south-west portions of the Paser District (Figure 3b). The overlap in land areas selected in Scenarios 1 versus 2 was only 54.9% (56,600 hectares) of top 20% priority areas, and these areas were primarily in the central-west of the district. As expected, the integration of social variables increased the social feasibility (Figure 4) and the areas selected had higher economic and cultural dependency on agroforestry (Figure 3b). Conversely, the biophysical suitability of the areas selected was lower than for other scenarios (Figure 4), mainly due to the selection of extensive areas in the south-western tip of Paser District. Scenario 2 incurred the lowest opportunity cost of US$480 million, which was approximately 20% less than Scenario 1. Under this scenario, at least 1,400 and 12,200 hectares of prioritised areas occurred in Conservation Forest and Protection Forest areas respectively, reflecting the high level of cultural and economic dependency on Protection Forests (e.g. for collection of non-timber forest products).

Under Scenario 3, both social and ecological variables were incorporated, but the selection was constrained to areas where restoration was legally permitted (i.e. non-Forest Estate/*APL*, or Production Forest without an active logging concessions; Figure 3c). As a result, only 46,500 hectares (45.1%) of the priority areas under Scenario 2 were selected under Scenario 3. Scenario 3 also had low social feasibility and incurred a higher opportunity cost (US$598 million; Figure 4) in part due to the selection of areas in the central and eastern part of the region where the opportunity cost for the oil-palm sector is high. Under this scenario, at least 23,500 hectares occurred in Production Forest without an active concession, and could therefore be allocated for community forest to establish *simpukng* and *kebotn*.

Scenario 4, where we assumed a legal framework that allows agroforestry restoration in any area of Production Forest (regardless of concessions), delivered the best outcome across ecological, social and cost criteria. This would offer greater social feasibility, and a reduction in opportunity costs in the order of US$70.6 million (11.8%) compared to Scenario 3 (Figure 4). Under this scenario at least 10,800 hectares occurred in Production Forest with no concessions, while 49,800 hectares overlapped with active logging concessions. Many of these overlapping areas occurred on severely logged forests with limited opportunity costs for timber harvesting.

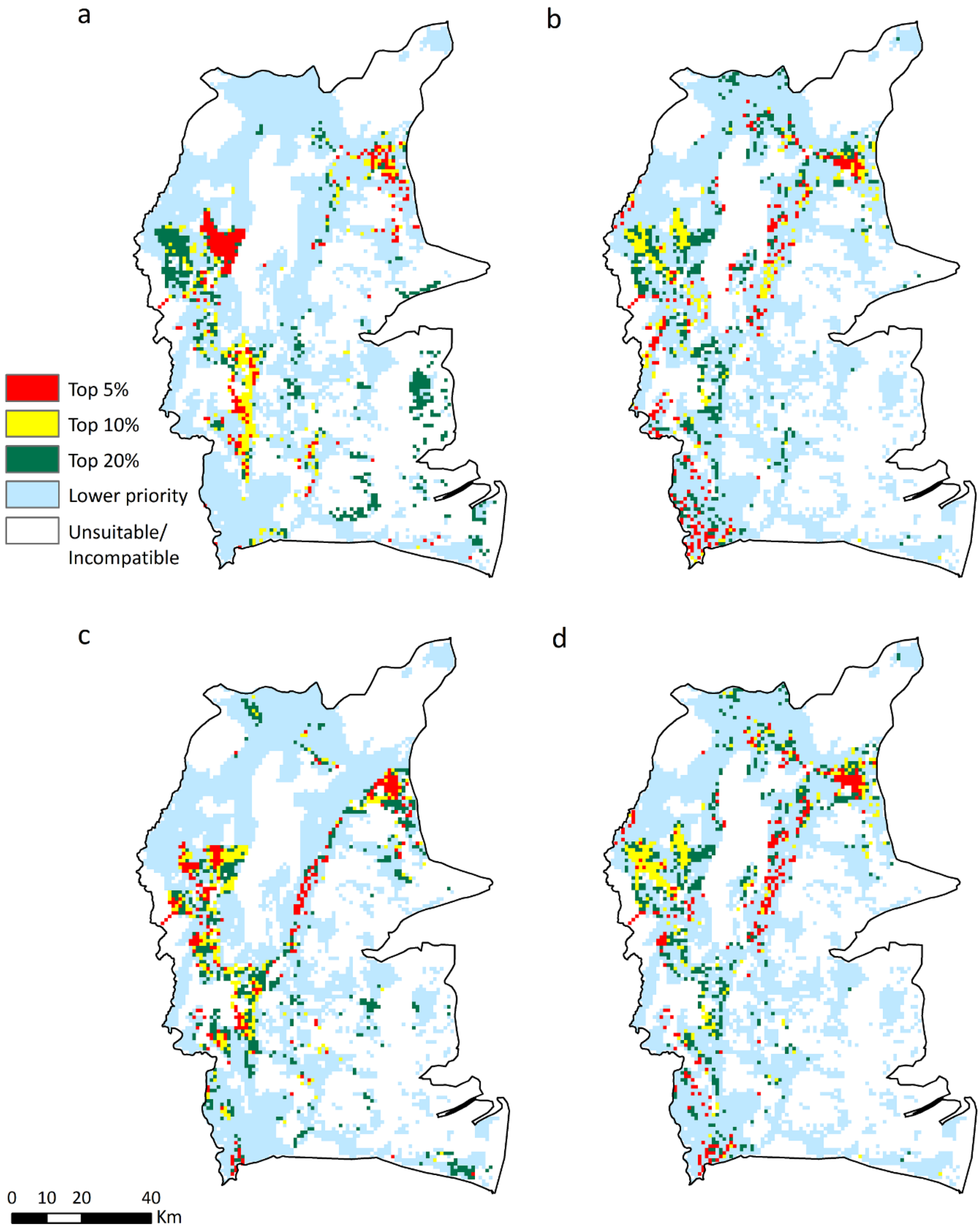


Figure 3. Maps of priority areas for agroforestry restoration under four social-ecological scenarios: (a) Scenario 1 (ecological variables only); (b) Scenario 2 (ecological and social variables); (c) Scenario 3 (ecological and social variables with existing political constraints); (d) Scenario 4 (ecological and social variables with constraints associated with land use removed). The coloured areas (i.e. green and grey) show the potential areas for agroforestry restoration from the ecological context (i.e. areas suitable for at least one fruit/crop type, and where the land cover is compatible).

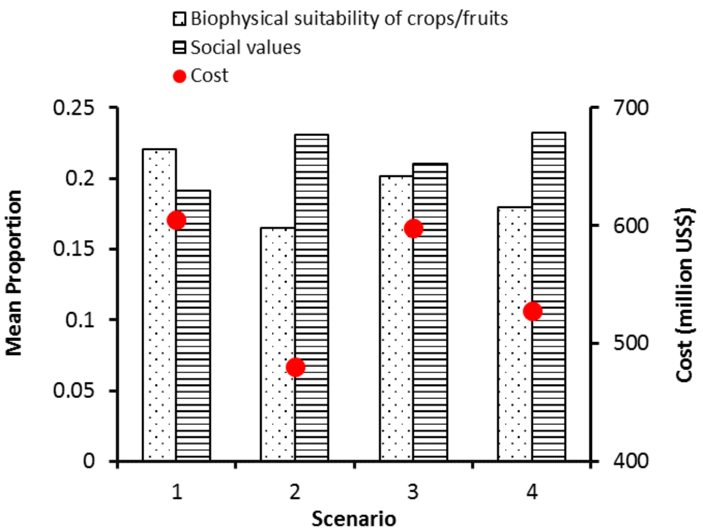


Figure 4. Outcomes for each scenario in regards to biophysical suitability, social feasibility and opportunity cost for the highest priority areas for agroforestry restoration (areas within the top 20%). For each class of values (biophysical or social), the aggregate value is the mean proportion of the landscape's summed potential value that is encompassed by the selected restoration areas. The proportion of total landscape value was calculated separately for each variable in each class, and then the mean taken across all variables within the class.

Scenario 1 was the most cost-effective in selecting areas with high biophysical suitability (Figure 5a), while Scenario 2 delivered the greatest returns in relation to social feasibility (Figure 5b). Differences between scenarios were greatest in terms of social feasibility (i.e. there were large differences in the total cost required to retain all social values). Constrained by the existing political context, Scenario 3 incurred the greatest cost at the point when all legally allowable areas (i.e. on non-Forest Estate or in Production Forest without active concessions) have been selected (Figure 5b: the dashed line).

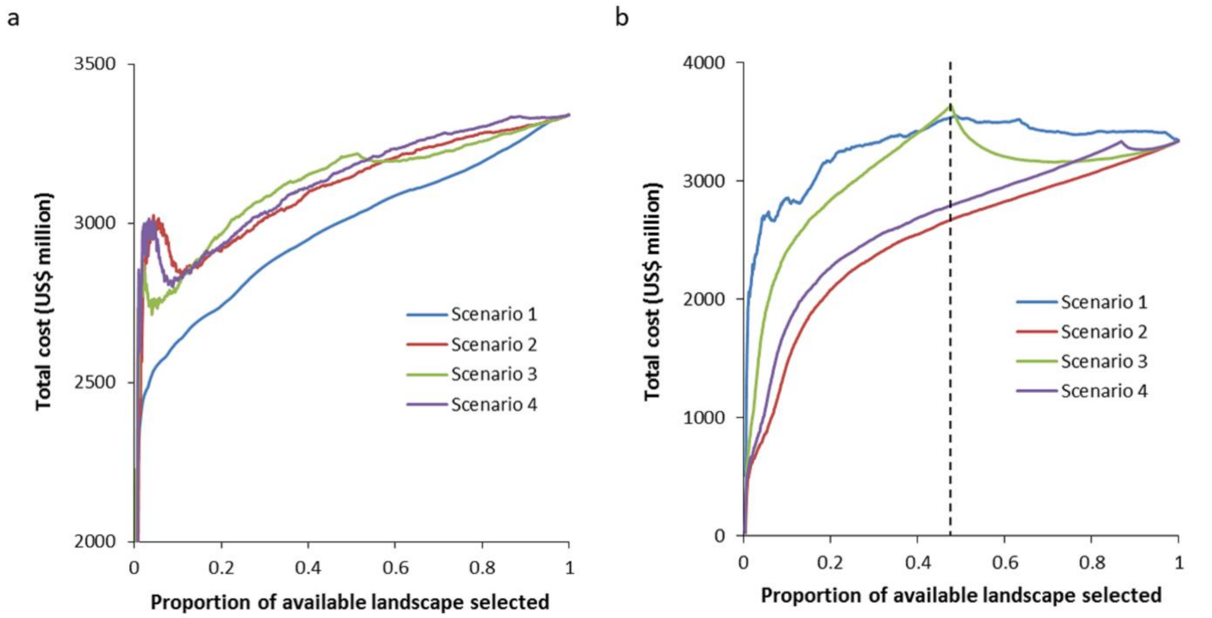


Figure 5. Cost-effectiveness across four scenarios formulated as total cost required to retain total values of (a) crop suitability and (b) social variables, when a given proportion of the available landscape is selected.

## 4. Discussion

Existing studies on assessment and systematic planning for restoration emphasise biophysical aspects (e.g. Birch et al., 2010; Budiharta et al., 2014), with much less attention given to the social characteristics of the region (e.g. McElwee, 2009). We proposed an integrated framework to diagnose socio-political and ecological context of a region and to employ the diagnostic tool to inform the development of forest restoration plans. We discovered that the incorporation of socio-political and ecological contexts in restoration planning altered the selection of priority areas for restoration (Figure 3). This integration revealed trade-offs between the potential social and ecological outcomes, as well as the opportunity costs incurred (Figure 4). Our analysis also provides policy direction to Indonesia's government in the context of allocating lands in the Forest Estate to 'community forests' with the aim of delivering socio-economic benefits for forest-dependent communities.

We found that considering biophysical criteria alone (Scenario 1) would deliver the greatest ecological benefits in term of biophysical suitability for crops and fruit trees. Priority areas under this scenario had the highest aggregated suitability across 11 species, representing greater opportunities to plant diverse species and attain higher growth rates and yields. However, as the social feasibility was comparatively low, there is a greater risk that agroforestry restoration on these prioritised areas may be unsuccessful in the long term. This failure could arise from a preference for alternative livelihood options, such as in the oil palm or mining sectors, rather than planting and maintaining trees. The planted areas would then likely be converted into oil palm plantations, if communities are in favour of or do not oppose these developments. Many examples exist of restoration programmes being jeopardised because the main actors (e.g. local communities) are either reluctant to implement the prescribed activities, or they undertake activities that are counterproductive to the overall goal even opposing the programmes (Nawir et al., 2007b; Boedhihartono and Sayer, 2012).

Analyses by Le et al. (2014) in the Philippines indicate that community dependency on forest, either as a main income source or to fulfil subsistence needs, has a strong positive relationship with the success of reforestation. In our analysis however, incorporating the variable of community dependency on forest aspect along with two social variables (i.e. community preference on land use and agroforestry location) in order to increase feasibility (Scenario 2) would be at the expense of the biophysical suitability of restored areas. This implies that in some priority areas, such as in the south-western tip of Paser District, rural farmers would have fewer tree species available for planting that could achieve maximum growth or productivity. Furthermore, despite having the greatest social feasibility and the lowest opportunity cost, agroforestry restoration would be legally prohibited and undesired in some areas (e.g. protected areas) and likely to lead to land use conflict.

While the political context is often neglected in restoration studies (Baker et al., 2013), we discovered that integrating the existing legal framework changed the priority areas for restoration, and incurred substantially greater opportunity costs. Despite its poorer performance, Scenario 3 was closest to the actual situation of the current social-ecological system, and so its application would likely entail the smallest legal and political ramifications, for example by avoiding lengthy constitutional amendments, and potential tenure disputes and social conflicts (Baker et al., 2013). Our analysis reveals that current policies may lead to inefficient restoration programme design, because regulations for Forest Estate lands only allow agroforestry restoration (in the form of community forest) to occur in Production Forest areas without active concessions. Our results suggest that re-allocating management of areas with logging concessions and high social-cultural values to community forests (Scenario 4), would increase the cost-effectiveness of agroforestry restoration. As these areas occur mainly in severely degraded forests, the transfer of management would incur minimal forgone opportunity costs from timber harvesting, and this could mitigate potential opposition from large-scale logging concession holders (Saragih 2011). Inefficiency in land-use policies is not restricted to Paser District as it also occurs across Kalimantan (Law et al., 2014; Runting et al., 2015; Sumarga and Hein, 2015). In reality however, changing land-use systems in the region would be challenged by current political practices, which puts great emphasis on patronage and favouritism toward elites, rather than fair and balanced distribution of benefits across stakeholders (Faisal, 2013). For example, severely logged forest in some regions is being speculatively held by timber concessionaires for future opportunities that may arise (e.g. land banking for oil palm plantation or mining; Kartodihardjo and Supriono, 2000).

In our case study, agroforestry restoration using indigenous resource systems offers an opportunity to restore degraded lands in the Paser District. Similar approaches in the Philippines with institutional arrangements for community forestry show promising results, covering 37% (5.9 million hectares) of total state forest lands with more than 4,800 community groups involved (Poffenberger, 2006). This strategy has contributed to a steady increase of forest cover (i.e. 0.75% annually) in the Philippines between 1990 and 2010 (FAO, 2011). The Indonesian Government has set a target for designating two million hectares of their Forest Estate as community forest by 2014, but only 438,000 hectares have been allocated so far (Sardjono et al., 2013; Ministry of Forestry, 2014). Our planning framework provides guidance on how such a policy target could be achieved, for example, in Paser District this could involve allocating 23,000 hectares of Production Forest without active logging concession to community forest. Further government support could be in the form of providing funds (e.g. using the Reforestation Fund and national forest rehabilitation programme/*GERHAN*) for communities to undertake tree planting and maintenance using performance-based funding mechanisms (Government of Indonesia, 2002, 2008). This financial support is important, because there would be time lag for the farmers to generate economic benefits from the fruits or crops planted (Nawir et al., 2007b).

To provide more realistic and meaningful solutions, we would ideally incorporate all of the social variables proposed in Ostrom's diagnostic approach, such as leadership and network structures among stakeholders (e.g. Guerrero et al., 2014), to complement the four social variables employed in this study. The presence of well-coordinated networks involving communities, local forestry service and academic institutions proved to be an important factor for the success of a reforestation programme using teak species in central Java, Indonesia (Nawir et al., 2007b). We were not able to include such variables in our analysis, due to limited availability of this information in a data-poor region, especially in a spatial format.

We demonstrated the operationalisation of our analytical framework using a single restoration goal and a specific social-ecological system (i.e. framed around agroforestry) as a restoration strategy for illustrative purpose. However, multiple restoration goals along with different restoration strategies that interact with related social-ecological systems (e.g. oil-palm plantations and logging concessions) could be incorporated into the framework. This is feasible, pending available data on social and political aspects, to simultaneously incorporate various goals related to the conservation of wildlife habitat and enhancement of carbon stocks using, for example, native species plantings and natural regrowth as restoration strategies, and ecosystem restoration concessions as an institutional arrangement (Budiharta et al., 2014).

We quantified restoration benefits by assigning an ordinal scale for some variables (e.g. biophysical suitability of agroforestry species, cultural dependency, and accessibility to transportation networks), this judgement does not necessarily represent values held by all stakeholders. As such, we suggest that for more transparent and defensible implementation, stakeholders' values be captured during the planning processes, for example through participatory workshop processes (e.g. Gregory et al., 2012). Several rounds of learning processes during the workshops might be required to familiarise stakeholders with our analytical framework and to find consensus among them to yield sound decisions that have wide acceptance (Boedhihartono and Sayer, 2012). Nonetheless, empirical testing in a range of contexts and case study systems is required to ensure broad applicability and transferability of our framework.

## 5. Conclusion

Understanding the social-ecological context of a restoration programme is likely to have a strong impact on its effectiveness, especially in socio-culturally heterogeneous regions such as Indonesia (Fearon, 2003; Lamb, 2010; Meyfroidt and Lambin, 2011). While social and political systems are often viewed as complex, it is possible to explicitly incorporate them into systematic planning for restoration by utilising a social-ecological system framework and systematic decision making. Despite the potential trade-offs between the social feasibility and ecological benefits of restoration, we demonstrate that this integration results in more realistic and feasible solutions. There are, however, challenges in translating existing social variables into relevant and accurate spatially-explicit representations, especially in data-poor regions such as in tropical developing countries.

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Supplementary Table 1. Ontology of social-ecological characteristics of indigenous tree-based agroforestry system (i.e. *simpukng* and *kebotn*) of Dayak Paser (and the related Dayak Benuaq) communities in East Kalimantan. A social-ecological systems diagnostic approach (Ostrom, 2009) is used to unpack the system into subsystems and variables.

***Resource System (RS)***

| Subsystem | Description | Reference |
|---|---|---|
| a. Sector (RS1) | RS1-a. Fruit gardens (*simpukng*/*awa pangeramu*/*lembo*/*lepu'un*) planted with edible fruit trees including durian, mango, jackfruit, rambutan (*Nephelium* spp.) and langsat (*Lansium* spp.).<br>RS1-b. Perennial crop agroforests (*kebotn*/*awa pangekulo*) enriched with commercial crops of perennial tree species, including coffee, cocoa and jungle rubber. | (Gönner, 2000; Crevello, 2003; Joshi et al., 2004; Saragih, 2011) |
| b. Clarity of system boundaries (RS2) | The traditional boundary of agroforestry system is unclear and rarely recognized formally by the state system. Although not clearly marked, both resource units are informally recognized indicating individual management. | (Gönner, 2000; Nanang and Inoue, 2000; Sardjono et al., 2013) |
| c. Size of resource system (RS3) | The average combined area of fruits garden (*simpukng*) and perennial crop agroforest (*kebotn*) per household is 4 hectares. | (Gönner, 2000; Gönner and Seeland, 2002; Saragih, 2011) |
| d. Human constructed facilities (RS4) | Very limited human constructed facilities support the agroforestry system (e.g. the absence of irrigation systems and processing factories). Commercial products (e.g. dried rubber latex) are prepared locally and sold to traders who regularly visit the villages or the nearby local markets. | (Gönner, 2000; Crevello, 2003; Saragih, 2011) |
| e. Productivity of system (RS5) | Productivity is low compared to alternative, more intensive land-use management.<br>RS5-a. Mean annual productivity from 1.25 ha of *simpukng* is 200 kg of rambutan, 357 kg of langsat, 135 kg of mango, 204 of durian and 557 of jackfruit.<br>RS5-b. Mean annual productivity from 2.62 ha of *kebotn* is 800 kg of rubber and 1,966 kg of rattan. | (Gönner and Seeland, 2002; Crevello, 2003) |
| f. Equilibrium properties (RS6) | *Simpukng* and *kebotn* requires low inputs of capital and labor.<br>*Simpukng* and *kebotn* has been developed to provide a variety of forest goods, and to respond ecological (e.g. prolonged drought) and socio-economic uncertainties (e.g. change in commodity prices).<br>Agroforestry system is perceived as sovereign way of life which is part of culture and identity. | (Gönner, 2000, 2010; Belcher, 2004; Saragih, 2011) |
| g. Predictability of system dynamics (RS7) | *Simpukng* and *kebotn* are highly predictable due to the ease of establishment through enrichment planting, simple maintenance, and high resilience to ecological disturbances (e.g. drought). | (Gönner, 2000; Joshi et al., 2004; Pambudhi et al., 2004) |
| h. Storage characteristics (RS8) | RS8-a. Fruits in the *simpukng* are generally harvested seasonally following mast fruiting event.<br>RS8-b. Perennial crops in the *kebotn* are either harvested regularly throughout the year (e.g. rubber latex, coconut) or harvested seasonally (e.g. coffee). | (Gönner, 2000; Crevello, 2003) |
| i. Location (RS9) | Paser District, East Kalimantan Province, Indonesia. | |

***Resource Units (RU)***

| Subsystem | Description | Reference |
| --- | --- | --- |
| a. Resource unit mobility (RU1) | All units (i.e. various fruit and perennial crop tree species) are immobile (however harvested products are generally transportable). | (Saragih, 2011) |
| b. Growth or replacement rate (RU2) | Growth of tree species planted on *simpukng* and *kebotn* is influenced by land suitability, and has strong relationships with biophysical factors such as soil, climate and topography.<br>*Simpukng* and *kebotn* are established mainly through enrichment planting on degraded forests or secondary forests, which retain some extent of native vegetation cover. These land cover types are suitable for growing both shade-tolerant (e.g. coffee and cocoa) and intolerant (e.g. coconut and durian) species. | (Gönner, 2000; Joshi et al., 2004; García-Fernández and Casado, 2005; Saragih, 2011) |
| c. Interaction among resource units (RU3) | *Simpukng* and *kebotn* provide suitable habitat for wildlife, and this could provide conservation benefit. However, colonisation and movement through agroforests by wildlife could also facilitate killing and hunting for bush meat, either cancelling or negating this conservation benefit. | (Gönner, 2000) |
| d. Economic value (RU4) | Economic value is highly influenced by external factors (e.g. market and policy), and this results in price fluctuations and lower predictability of economic returns for local farmers.<br>RU4-a. Annual income generated from *simpukng* is IDR 6.34 million (~US$526).<br>RU4-b. Annual income generated from rubber and rattan in *kebotn* (assuming current farm gate price) is IDR 3.2 million (~US$267) and IDR 2.99 million (~US$250) per household respectively. At better market condition, income per household from rubber and rattan could reach US$2,000 and US$1,376 respectively. | (Crevello, 2003; Meijaard et al., 2014; Terauchi et al., 2014) |
| e. Number of units (RU5) | RU5-a. One hectare of *simpukng* contains up to 704 fruit trees (DBH>10cm) belonging to 93 species.<br>RU5-b. One hectare of *kebotn* of rubber contains an average of 400 rubber trees and 118 other trees. One hectare of *kebotn* of rattan contains 1750 canes intertwined with 515 trees of various species. | (Gönner, 2000; García-Fernández and Casado, 2005) |
| f. Distinctive markings (RU6) | RU6-a. *Simpukng* is highly similar to the surrounding old growth forest due to high floristic diversity (i.e. abundance and richness with more than 90 species of tree per hectare) and complex structure (i.e. canopy layering).<br>RU6-b. *Kebotn* of rubber is easily recognised due to the dominance of rubber trees (61.1% of total basal area). *Kebotn* of rattan appears similar to old growth forest with slightly lower tree species richness (17.6 species/0.1 ha compared to 22 species/0.1 ha) and canopy cover (66.9% compared to 83.9%). | (Lawrence, 1996; Gönner, 2000; García-Fernández and Casado, 2005) |
| g. Spatial and temporal distribution (RU7) | Both *simpukng* and *kebotn* mainly occur near to transportation networks (e.g. roads, rivers).<br>In many cases, land management may be dynamically shifted between the two types, depending on individual farmer interests and market conditions, for example by intensifying rubber planting in *simpukng* to become *kebotn*, and vice versa. | (Gönner, 2000, 2010; Saragih, 2011) |

***Governance System (GS)***

| Subsystem | Description | Reference |
| --- | --- | --- |
| a. Government organisations (GS1) | Since the New Order Era (1967), the state, through the Ministry of Forestry, has had a full power to control the management of the Forest Estate (i.e. areas designated as permanent forest, whether actually forested or not) and its allocation to formal land use classes (e.g. logging concession and protected area).<br>Since the Reformation Era (1998), some authorities related to forestry (e.g. reforestation programmes supervision) are delegated to provincial and district government through Forestry Services. These government institutions are aimed to reduce bureaucracy complexity and increase the effectiveness of government's programmes. | (President of the Republic of Indonesia, 1999; Nanang and Inoue, 2000; Sardjono et al., 2013) |

*Governance System (GS)* **(Continued)**

| Subsystem | Description | Reference |
|---|---|---|
| b. Non-government organisations (GS2) | Local Dayak people have developed their customary rules regarding forest resources management (e.g. land ownership, land-use classification and viable activities, labour sharing, sanction systems, and conflict resolution). The governance systems are applied informally within the group. | (Gönner, 2000; Crevello, 2003; Sardjono et al., 2013) |
| c. Network structure (GS3) | Agroforestry systems involve strong horizontal networks within the group (usually at village level) but very weak vertical networks connecting resource users with the government (especially at national level).<br>Decentralisation through delegation of power to local government has reduced the distance and complexity of network structure. This, however, impacts variably where in some areas result in more direct connections to official decision makers, whereas in other areas has led to new forms of patronage and political favouritism. | (Nanang and Inoue, 2000; Moeliono et al., 2009) |
| d. Property-rights systems (GS4) | GS4-a. Formally, agroforestry lands are owned by the state when occurring inside the Forest Estate, while those outside the Forest Estate are privately owned.<br>GS-4b. Informally, effective property rights system of agroforestry land has been applied for centuries, which is divided into two categories of ownership: private and community depending on customary consensus. | (President of the Republic of Indonesia, 1999; Gönner, 2000; Nanang and Inoue, 2000; Saragih, 2011) |
| e. Operational rules (GS5) | Daily decisions in managing privately owned agroforest are carried out by individual farmers. | (Crevello, 2003; Saragih, 2011) |
| f. Collective-choice rules (GS6) | Decisions related to communal interests are made in village meetings led by a traditional leader. | (Gönner, 2000) |
| g. Constitutional rules (GS7) | Through Basic Forestry Law No. 41/1999 and its generated regulations (e.g. Ministry of Forestry Decree No. P. 37/2007 jo. P. 18/2009 jo. P. 13/ 2010 jo P. 52/2011), local communities could be given rights to manage the Forest Estate through community forest (*Hutan Kemasyarakatan/HKm*). Community forest involving tree planting can only be designated in parts of Production Forest on condition that no logging concession is active. | (Sardjono et al., 2013) |
| h. Monitoring and sanctioning processes (GS8) | Sanctioning process is conducted in group meetings (*berinok*) at village level if rule breaking only involves internal group members.<br>Sanctioning process is taken to formal institutions (e.g. administrative office) if rule breaking involves any external parties (e.g. government, logging concession holders or oil palm plantations). | (Gönner, 2000; Saragih, 2011; Sardjono et al., 2013) |

***Users (U)***

| Subsystem | Description | Reference |
|---|---|---|
| a. Number of users (U1) | On average, the number of household on agroforestry villages is 185 (with total population of 749 persons). | (Paser Statistics Service, 2014b) |
| b. Socio-economic attribute of users (U2) | Livelihoods are mainly from agroforestry sector with the combination of subsistence and monetary economy.<br>Educational level is generally low with six years of primary school plus three years of secondary school. | (Gönner, 2000; Dewi et al., 2005; Saragih, 2011) |
| c. History of use (U3) | Traditional Dayak group have been practicing agroforestry system for more than 300 years. | (Gönner, 2000, 2010) |
| d. Location (U4) | Village settlements are close to forested areas (at the average distance of 2 km) and have limited access to cities. | (Saragih, 2011; Sihombing, 2011) |
| e. Leadership/ entrepreneurship (U5) | Historically, the group has strong leadership by a traditional leader (*kepala adat*), but this is weakening due to increasing authority held by officials who are appointed by the government (*kepala desa*).<br>Dayak communities have generally low levels of engagement in entrepreneurship outside of traditional livelihoods, and new economic opportunities (e.g. trading sector, oil palm plantation) are mostly dominated by outsiders. | (Gönner, 2000) |

***Users (U)*** **(Continued)**

| Subsystem | Description | Reference |
|---|---|---|
| f. Norms/ social capital (U6) | Strong social cohesiveness through mutual assistance and labour sharing (*gotong-royong*) among group members especially for agricultural activities. | (Gönner, 2000) |
| g. Knowledge of SES/ mental model (U7) | The elderly generally have better knowledge on technical aspects of traditional agroforestry system than younger generation. On the other hand, young members have better access to external information such as resource prices and market development. They are less attracted to swidden agriculture, but remain interested in rubber and rattan cultivation.<br>There is varied preference among forest frontier communities whether continuing agroforestry practices or altering into alternative livelihood options (e.g. oil palm agriculture). | (Gönner, 2000; Belcher et al., 2004; Saragih, 2011) |
| h. Dependence on resource (U8) | Forest frontier people are highly dependent on agroforestry for both economic and cultural benefits:<br>U8-a. Agroforestry sector contributes to 42.2-62.4% (mean 51.5%) of total household incomes.<br>U8-b. High uses of agroforestry products to support their culture and way of life. Agroforestry systems in rural Paser provide between 47 and 88 plant species for food and vegetables, 38 to 56 species for medicinal purposes as well as 15 to 23 species for traditional ceremonies. | (Dewi et al., 2005; Saragih, 2011; Abram et al., 2014) |
| i. Technology used (U9) | Very limited uses of machinery and production materials (e.g. agrochemicals and fertilisers). | (Gönner, 2000) |

***Interactions (I)***

| Subsystem | Description | Reference |
|---|---|---|
| a. Harvesting levels of diverse users (I1) | Harvesting level is decided at household level by individual farmers. | (Crevello, 2003) |
| b. Information sharing among users (I2) | Information sharing among group members is frequent and in-depth, occurring primarily through meetings, social events and religious ceremonies. | (Gönner, 2000) |
| c. Deliberation processes (I3) | Village meetings usually reach full consensus through long discussions. | (Gönner, 2000) |
| d. Conflict among users (I4) | Conflict among group members is low.<br>Conflict with outside institutions is increasing especially with industrial timber plantation and oil palm companies, while conflict with logging concessions is moderate as logging companies provide financial compensation and generally allow indigenous people to access concession forests for hunting and gathering. | (Gönner, 2000; Nanang and Inoue, 2000; Crevello, 2003; Sardjono et al., 2013) |
| e. Investment activities (I5) | Investment is very low due to limited capital and limited access to credit facilities. | (Saragih, 2011) |
| f. Lobbying activities (I6) | Lobbying activities are limited. | |
| g. Self-organising activities (I7) | Self-organisation goes well for activities involving internal group members (e.g. determining land ownership and labour sharing). On the other hand, self-organisation involving external institutions is often challenging due to the mismatch between governance systems (i.e. state legal system versus traditional customary rules). | (Gönner, 2000; Sardjono et al., 2013) |
| h. Networking activities (I8) | Internal networking activities among group members are intense while networking with external institutions (e.g. government, traders) is lacking due to limited access to transportation and information. | (Gönner, 2000; Crevello, 2003) |

***Outcomes (O)***

| Subsystem | Description | Reference |
|---|---|---|
| a. Social performance measures (O1) | *Simpukng* and *kebotn* improve land productivity (compared to degraded forest or exhausted fields) and provides a variety of goods for forest-dependent people<br>Many forest-dependent people still prefer agroforestry systems for their livelihoods and want to expand their s*impukng* and *kebotn* through national reforestation programme*.*<br>Economic value of s*impukng* and *kebotn* is low compared to alternative, intensive forms of land-use management (e.g. oil palm plantation, mineral extraction and industrial timber plantation). | (Belcher et al., 2004; Joshi et al., 2004; Gönner, 2010) |
| b. Ecological performance measures (O2) | *Simpukng* and *kebotn* can maintain forest cover with high biodiversity value and carbon stock.<br>*Simpukng* and *kebotn* are highly resilient from natural disturbances (e.g. forest fire, drought). For example, despite the severe impact of forest fires in 1997, many rubber trees recovered quickly and were tapped in the subsequent weeks. | (Gönner, 2000; García-Fernández and Casado, 2005) |
| c. Externalities to other SESs (O3) | Increasing competition with other land-uses (e.g. development of oil palm and industrial timber plantations, which may be promoted or coerced by the state or companies) has reduced the availability of land for s*impukng* and *kebotn* and resulted in social conflicts between villagers and external entities. | (Nanang and Inoue, 2000; Belcher et al., 2004; Sardjono et al., 2013) |

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Supplementary Table 2. List of tree species of interest for *simpukng* and *kebotn* considered in this study.

| Latin name | Local name | Common name | Uses |
|---|---|---|---|
| *Artocarpus heterophyllus* | Nangka | Jackfruit | Edible fruit and seed, vegetable, medicinal, timber |
| *Artocarpus integer* | Cempedak | - | Edible fruit, vegetable, timber |
| *Cocos nucifera* | Kelapa | Coconut | Edible fruit; condiment, timber |
| *Coffea canephora* | Kopi | Coffee | Beverage |
| *Dimocarpus longan* | Mata kucing | Longan | Edible fruit |
| *Durio zibethinus* | Durian | Durian | Edible fruit, timber |
| *Hevea brasiliensis* | Karet | Rubber | Latex, timber |
| *Lansium domesticum* | Langsat | - | Edible fruit, medicinal |
| *Nephelium lappaceum* | Rambutan | Rambutan | Edible fruit, medicinal |
| *Parkia speciosa* | Petai | - | Vegetable, condiment, timber |
| *Theobroma cacao* | Kakao | Cocoa | Condiment |

Supplementary Table 3. Example of biophysical variables to determine land suitability classes for rubber (*Hevea brasiliensis*). Value ranges for each class are from Ritung et al. (2007). Biophysical variables for other species could be found at http://bbsdlp.litbang.pertanian.go.id/tamp_komoditas.php (Ministry of Agriculture, 2012)

| Biophysical variables | Land suitability class | | | |
|---|---|---|---|---|
| | *High* | *Moderate* | *Marginal* | *Not suitable* |
| Annual temperature ($^{o}$C) | 26-30 | 24-26 and 30-34 | 22-24 | <22 and >34 |
| Annual rainfall (mm/yr) | 2500-3000 | 2000-2500 and 3000-3500 | 1500-2000 and 3500-4000 | <1500 and >4000 |
| Slope (%) | <8 | 8-16 | 16-30 | >30 |
| Drainage (class) | Well | Moderate | Moderate poor, Poor | Very poor, rapid |
| Texture (USDA texture class) | Fine, slightly fine, medium | - | Slightly coarse | Coarse |
| Coarse material (% gravel content) | <15 | 15-35 | 35-60 | >60 |
| Soil depth (cm) | >100 | 75-100 | 50-75 | <50 |
| CEC-clay (cmol/kg) | - | - | - | - |
| Base saturation (%) | <35 | 35-50 | >50 | - |
| Acidity (pH) | 5.0-6.0 | 4.5-5.0 and 6.0-6.5 | >6.5 | - |
| Carbon organic content (%) | >0.8 | ≤0.8 | - | - |