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FOREST BIODIVERSITY AND ECOSYSTEM SERVICES

Mixed policies give more options in multifunctional tropical forest landscapes

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Summary

1. Tropical forest landscapes face competing demands for conserving biodiversity, sustaining ecosystem services and accommodating production systems such as forestry and agriculture. Land-sparing and land-sharing have emerged as contrasting strategies to manage trade-offs between production and biodiversity conservation. Both strategies are evident in land-management policies at local-to-international scales. However, studies rarely report the impacts of these strategies, assessed for multiple stakeholders and multiple ecosystem services, particularly in real landscapes.

2. Using a case study from a high-priority region for forest protection, restoration and rural development in Central Kalimantan, Indonesia, we analysed the potential outcomes under 10 alternative policy scenarios, including land-sharing, land-sparing and mixed strategies. We used a novel optimization process integrating integer programming with conservation-planning software (Marxan with Zones) to identify production possibility frontiers (PPFs), highlighting the trade-off between smallholder agriculture and oil palm, subject to achievement of a set of carbon, timber and biodiversity conservation targets.

3. All policy scenarios modelled proved to be capable of achieving all targets simultaneously. Most strategies resulted in an expansion of the PPF from the baseline, increasing the flexibility of land allocation to achieve all targets. Mixed strategies gave the greatest flexibility to achieve targets, followed closely by land-sparing. Land-sharing only performed better than the baseline when no yield penalties were incurred, and resulted in PPF contraction otherwise. Strategies assessed required a minimum of 29–37% to be placed in conservation zones, notably protecting the majority of remaining forest, but requiring little reforestation.

4. *Policy implications*. Production possibility frontiers (PPFs) can evaluate a broad spectrum of land-use policy options. When using targets sought by multiple stakeholders within an ecosystem services framework, PPFs can characterize biophysical, socio-economic and institutional dimensions of policy trade-offs in heterogeneous landscapes. All 10 policy strategies assessed in our case study are biophysically capable of achieving all stakeholder objectives, provided at least 29–37% of the landscape is conserved for biodiversity. This novel methodological approach provides practical options for systematic analysis in complex, multifunctional landscapes, and could, when integrated within a larger planning and implementation process, inform the design of land-use policies that maximize stakeholder satisfaction and minimize conflict.

Key-words: biodiversity conservation, Borneo, ecosystem services, integer programming, Kalimantan, land-sharing, land-sparing, land-use allocation, production possibility frontier, wildlife-friendly farming

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Introduction

Agricultural development, including intensification and expansion of agricultural land use and management, is a primary driver of forest and biodiversity loss in tropical forests (Rudel *et al.* 2009; DeFries *et al.* 2010; Hosonuma *et al.* 2012). In many tropical countries where developing and sustaining agricultural economies are both economic and political priorities, the production–biodiversity conservation trade-off is becoming increasingly critical and complex to manage (Hamblin 2009; Laurance, Sayer & Cassman 2014; Newbold *et al.* 2015). In such 'multifunctional' landscapes, where many stakeholders seek a variety of benefits, target achievement for multiple objectives is likely to entail competition and conflict between stakeholder groups (McShane *et al.* 2011; Law *et al.* 2015a,c). Effective land-use planning provides an approach to resolve such tensions. However, weak governance and institutions mean that plans often meet the aspirations of only a subset of stakeholders, leading to dissatisfaction of some stakeholder groups (Bryan *et al.* 2015).

Land-sparing and land-sharing have emerged as alternative strategies to improve compatibility and achievement of both production and biodiversity outcomes, and represent the endpoints of a land-use spectrum with a focus on specialization and integration of conservation and production, respectively (Fischer *et al.* 2014). Land-sparing involves specialization of land uses, setting aside land primarily for conservation, for example in protected forests, and implies intensification of agriculture elsewhere to compensate for a reduction in area available for production (Green *et al.* 2005; Fischer *et al.* 2008; Phalan *et al.* 2011, 2016). Such intensification often involves actions that could negatively impact biodiversity and other societal values (Green *et al.* 2005; Cunningham *et al.* 2013; Phalan, Green & Balmford 2014). In contrast, land-sharing is an integrative approach, defined as making production lands more conducive to biodiversity conservation (Lindenmayer & Cunningham 2013). Land-sharing can include a variety of methods to increase heterogeneity and multifunctionality into farming systems, for example agroforestry practices (Green *et al.* 2005; Macchi *et al.* 2013), as well as reducing harmful impacts of fertilizers, pesticides and other on-farm activities (Kremen & Miles 2012; Mahood, Lees & Peres 2012). However, land-sharing strategies may, in some cases, also result in lower agricultural yield or profit (relative to pursuing high-yield agriculture), and create pressure to increase the area under agricultural production to enable meeting the demand for food and fibre (Green *et al.* 2005).

Recently there have been several syntheses of the efficacy of land-sharing against land-sparing (Phalan *et al.* 2011; Balmford, Green & Phalan 2012; Grau, Kuemmerle & Macchi 2013; Kremen 2015) with the conclusions varying with context, both in empirical (Edwards *et al.* 2010; Ekroos *et al.* 2014; Kremen 2015; Law *et al.* 2015c) as well as theoretical studies (Martinet & Barraquand 2012; Law & Wilson 2015). Simple rules of preference are sought (e.g. Grau, Kuemmerle & Macchi 2013), but have proven difficult to identify, as outcomes depend on multiple considerations that are frequently confounded within empirical studies (Law & Wilson 2015), and that vary across heterogeneous landscapes.

Landscapes are typically heterogeneous, with variability in production potential, and in environmental and social values due to biophysical conditions and historical use (Fahrig *et al.* 2011). This heterogeneity is a common tenant of the argument for mixed policies that integrate elements of both land-sharing and land-sparing (Fischer *et al.* 2014; Kremen 2015), but such strategies have received limited investigation. One recent study with a biodiversity focus (Butsic & Kuemmerle 2015) shows mixed policies including both land-sharing and land-sparing land uses can be preferable in specific situations, but the contexts analysed were dramatically simplified. Studies showing that an optimal distribution of effort ought to include both specialization and diversification of farming systems are more common in agricultural economics, though typically use environmental metrics not directly reflecting biodiversity (e.g. Mallawaarachchi & Quiggin 2001). Heterogeneous landscapes mean that solutions considering the whole landscape are not necessarily a simple sum of the parts (Seppelt & Voinov 2002). Yet few land-sharing land-sparing studies have compared strategies at the scale of whole landscapes (for exceptions, see Hodgson *et al.* 2010; Chandler *et al.* 2013; Law *et al.* 2015c; Macchi, Grau & Phalan 2015), and none assess mixed policies at this scale.

Assessments of land-sharing and land-sparing strategies in heterogeneous landscapes where two or more objectives are in competition can be informed by an analysis of production possibility frontiers (PPFs) (Groeneveld 2003; Daily *et al.* 2009). PPFs trace the maximum achievable production for two or more goods or services, that is the Pareto-optimal points (where it is impossible to increase one without decreasing production of the others, assuming fixed factors of production). PPF analyses thereby identify feasible, infeasible and optimal solutions, allowing evaluation of the compatibility of land-use targets expressed by multiple stakeholders. It also allows for the determination of opportunity costs of moving along or away from the Pareto-optimal frontier, thereby indicating the level of inefficiency present in current or proposed land-use configurations (Groeneveld 2003; Smith *et al.* 2012; Seppelt, Lautenbach & Volk 2013; Bryan *et al.* 2015).

Estimation of PPFs in the context of heterogeneous, multifunctional, multiple-objective land-use analyses can be complex due to the large potential solution space and likelihood of nonlinearity. Several approaches to develop PPFs in this context have emerged, generally involving simplification of the problem primarily for technical reasons. Examples include full simulations within limited solution space (Mallawaarachchi & Quiggin 2001), for example limiting the study to a single homogeneous area (Robert & Stenger 2011), or integer programming (IP) with a reduced or simplified set of optimization objectives and constraints (Polasky *et al.* 2008; Bryan *et al.* 2015, 2016). For more complex problems, heuristic methods such as genetic algorithms (Holzkämper & Seppelt 2007; Bekele *et al.* 2013; Lautenbach *et al.* 2013) can deliver near-optimal solutions, but can be difficult to parameterize for complex problems and do not reveal how close to optimal the solutions are (Park & Kim 1998; Seppelt & Voinov 2003; Groot, Jellema & Rossing 2010). In the case of tropical developing countries that have high species richness and diverse land-use systems, the heterogeneity of the biophysical and social landscape is a critical component of the problem context. Here, we utilize a new technique for developing PPF curves that combines IP optimization methods iteratively within a minimum-set problem formulation (Watts *et al.* 2009).

In this paper, we construct PPF curves for a multiple-objective trade-off problem in the Ex-Mega Rice Project (EMRP) region of Central Kalimantan, Indonesian Borneo (Fig. 1). Prior analyses have suggested that even with high levels of land-sharing or land-sparing, no current or prospective land-use plan for the region would achieve all biodiversity, ecosystem service and production targets (Law *et al.* 2015c). The potential for conflicts between smallholder agriculture and oil palm have also been identified, due to a common reliance of these production values on land suitable for agriculture within the case study region (Law *et al.* 2015a). We use PPFs to assess the performance of alternative land-sharing and land-sparing strategies, including mixed strategies, in satisfying the needs and desires of multiple stakeholders. We focus on describing the trade-off between oil palm and smallholder agriculture, conditional on the achievement of biodiversity, carbon and timber objectives. We assess 10 different land-sharing and land-sparing strategies in terms of their potential to fully satisfy all stakeholder targets and the area of forest that would require reforestation in order to do so.

Materials and methods

STUDY REGION, ECOSYSTEM SERVICES AND TARGETS

The EMRP area is a tropical peat forest region with substantial biodiversity but also strong pressures for agricultural development, as well as a globally important area for reducing carbon emissions from land use, particularly from burning peat in recent years (Page *et al.* 2002; Ballhorn *et al.* 2009; Hooijer *et al.* 2010). Local, industrial and global stakeholders are characterized by their focus on local food production, development of local economies and improvement of biodiversity and carbon emissions, respectively. The landscape is strongly heterogeneous, due to both biophysical conditions and past development history, and includes areas of extant forest, degraded forest and abandoned deforested areas, and production land uses (Fig. 1; Law *et al.* 2015a).

Spatial quantifications of ecosystem services were drawn from Law *et al.* (2015a,b,c), for smallholder agriculture, oil palm and timber production, carbon emissions mitigation, and conservation of biodiversity, using a reference year of 2008 and summarized briefly here. The value of smallholder agriculture was determined as the annual maximum potential profit from a set of land systems, each characterized by a specific composition of crops. Oil palm value was defined as profitability using production, price and cost data for a range of land suitability classes. The potential economic returns from timber was estimated based on extant land cover, forest type and the costs of transport to existing mills. The potential for carbon emissions mitigation was modelled over

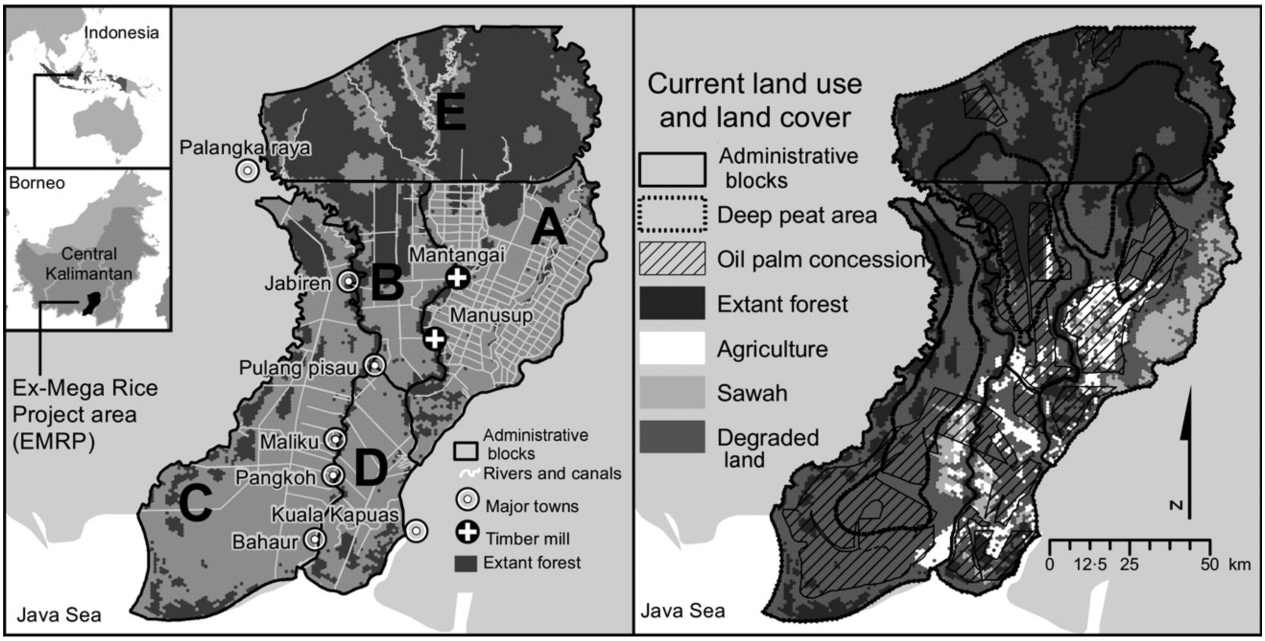

Fig. 1. Study site location, current land use and land cover.

40 years with respect to a baseline of maintaining the current land-use configuration. Biodiversity was represented at an ecosystem level by coverage of the five dominant forest types, and at the species level using modelled distribution data of 11 primate species (Struebig *et al.* 2015) and an index of their abundance in different land covers (Appendix S1 in Supporting information). We specified five land-use zones: smallholder agriculture, oil palm plantation agriculture, forestry, biodiversity conservation (protected area, including both protection of extant forest and reforestation of degraded areas) and unmanaged (in which no management activities for agriculture or biodiversity occur and ecosystems are likely to degrade). The benefits expected in each land-use zone for each ecosystem service or biodiversity feature are presented in Appendix S1 and described in Law *et al.* (2015c). Briefly, these state that production features can only derive benefit from their respective land-use zone (e.g. oil palm production benefits are only seen when a planning unit is allocated to an oil palm zone), while carbon and biodiversity features gain differential benefits across all land-use zones. Primate benefits were derived from expert elicitation, and typically assumed to be highest in forest areas, moderate in smallholder agriculture and least for oil palm (Appendix S1; Law *et al.* 2015c).

Targets were identified for each ecosystem service. Targets reflect the aspirations of stakeholders or current entitlements (Appendix S1; Law *et al.* 2015c). The target for smallholder agricultural production reflects levels of economic development necessary to maintain the target population size at levels above the poverty line. The target for oil palm production reflects the economic value expected if all current oil palm concessions were developed. Similarly, the target for timber production reflects values expected if forestry was developed across all the areas zoned as specified in the legislated zoning plan. The target for carbon emissions mitigation reflects national targets presented to global stakeholders through the UNFCCC, while the biodiversity targets represent goals for biodiversity conservation outlined by the Convention on Biological Diversity.

LAND-SHARING AND LAND-SPARING STRATEGIES

To simulate potential land-sharing and land-sparing strategies we modified the current potential production yield and biodiversity benefits for agricultural areas (i.e. both smallholder agriculture and oil palm land uses; Fig. 2). We specified that:

- In land-sharing, agricultural areas experience equivalent or reduced yields (yield penalties), but higher biodiversity benefits (for primates).
- In land-sparing, agricultural areas experience higher yields through specialization but equivalent or reduced biodiversity benefits.
- Mixed strategies allow for diverse combinations involving both land-sharing and land-sparing of agricultural land throughout the landscape.

In all cases, we allowed the optimization algorithm (within Marxan with Zones, see below) to allocate the amount and location of land in each zone, including the amount of protected area, and the relative area of land-sharing and land-sparing agriculture in mixed strategies. For instance, we did not explicitly link land-sparing agriculture to a respective area of 'spared' (conservation) zone.

Modifiers for the potential impacts on agricultural yields and biodiversity (Fig. 2) were drawn from a literature review and locally relevant constraints (Law & Wilson 2015; Law *et al.* 2015c). We specified three levels of relative strength for the land-sharing and land-sparing strategies (levels A–C) with stronger strategies imposing a greater impact on biodiversity and/or yield and accepting penalties to competing objectives, whereas weaker strategies aimed for more moderate benefits with no penalties (Fig. 2). Thus, we examined several dimensions of the land-sharing to land-sparing 'continuum', one in which land-use intensity varies (levels A–C), the other which allows land-use allocations to include both strategies (MIX strategies). We assessed 10 land-use strategies (Fig. 2): the reference level of benefits (BASE), three land-sparing strategies ($SPARE_{A–C}$), three land-sharing strategies ($SHARE_{A–C}$) and three mixed strategies ($MIX_{A–C}$).

TRADE-OFF ANALYSES

Marxan is a commonly used conservation-planning tool that poses a spatial minimum-set problem that is solved using simulated annealing (SA) (Watts *et al.* 2009). Here, we use a recently developed modification of Marxan with Zones, which replaces the SA algorithm with IP by linearizing the classic nonlinear

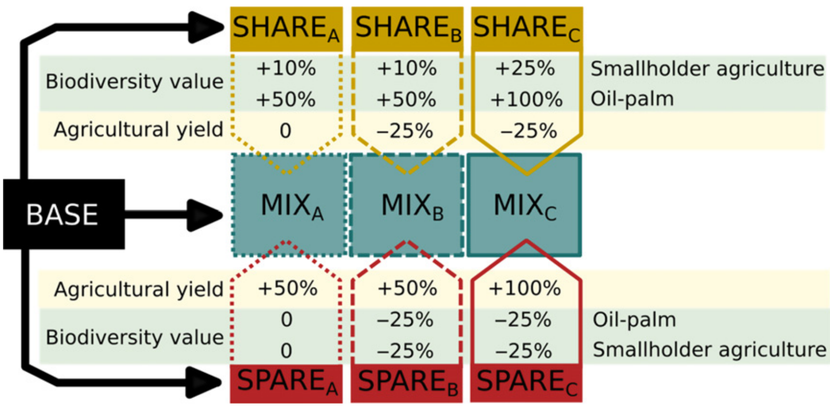

Fig. 2. Three levels of strength (A, B and C) of the expected impacts of each land-use strategy on biodiversity and yield. Starting from a reference level baseline, level A has improvement for one objective and no impact on the other; B has improvement for one objective and a negative impact on the other; and C has a large improvement for one objective and a negative impact on the other. Mixed strategies allow both land-sharing and land-sparing agriculture. Values were derived from a literature review (Law & Wilson 2015; Law *et al.* 2015c).

problem formulations (Beyer *et al.* 2016). The use of IP in this context allows for more rapid development of PPF curves with known levels of departure from the optimal solution. Preliminary analysis identified three main trade-off axes: biodiversity, oil palm and smallholder agriculture. We specified the biodiversity, carbon and timber production targets as constraints, and assessed the trade-off between smallholder agriculture and oil palm by varying the requirement to achieve the target of one while maximizing the achievement of the other. Alternative formulations (e.g. examining the trade-off between biodiversity conservation and agricultural production) are possible; however, targeting the trade-off between smallholder agriculture and oil palm focuses the analysis on the policy relevant trade-off between these largely substitutable goods, and allows the determination of minimum required areas for effective conservation. We calculated a separate PPF for each of the 10 land-use strategies. Further details of problem specification and parameterization are provided in Appendix S2.

All analyses and programming were conducted in the R statistical package (v3.1.2; R Core Team 2014), with IP solved with Gurobi (v6.0; Gurobi Optimizer Inc. 2015). Analysis units were based on a 100-ha hexagonal grid. Results are presented for the PPF curves overall, highlighting those that produce expansions in the PPF (and thus increase the flexibility for achieving all targets simultaneously) and those that cause contractions in the PPF (reducing flexibility to achieve all targets). We also report on detailed zoning outcomes for the points on these frontiers that maximize the production of either oil palm or smallholder agriculture, subject to the constraints of achieving all other feature targets (Fig. 3). We caution that these applied results should not be viewed as land-use plans *per se*, rather as illustrations of potential outcomes and requirements given the assumptions outlined in the model, including land-use zone optimization and full implementation.

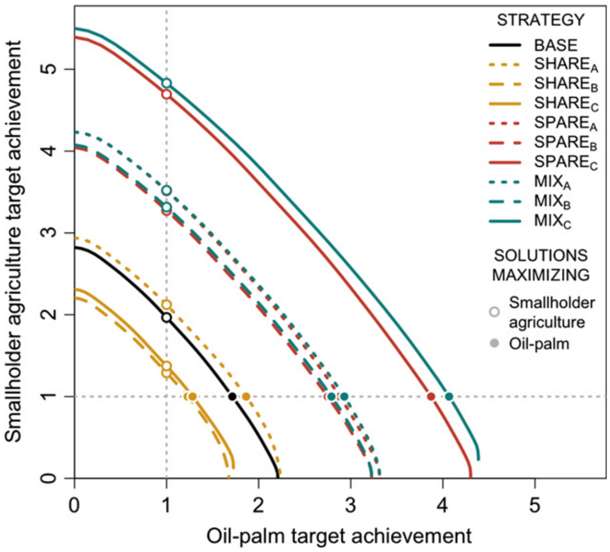

Fig. 3. Production possibility frontiers show maximum smallholder agriculture and oil palm target achievement, subject to achievement of biodiversity, forestry and carbon emissions mitigation targets. Scale is proportional to the target derived to satisfy stakeholder needs (smallholder agriculture) or current concessions (oil palm) (dashed line at 100% of target achieved). Scenarios: baseline (BASE), land-sharing (SHARE$_{A–C}$), land-sparing (SPARE$_{A–C}$) and mixed strategies (MIX$_{A–C}$), with weak benefits (A), weak benefits and penalties (B), and strong benefits and penalties (C). Further analysis of zone composition is given for the solutions that, subject to the achievement of all other targets, maximize smallholder production (open circles) or maximize oil palm production (closed circles).

Results

The PPF analysis revealed that all 10 strategies had the potential to achieve all targets simultaneously (Fig. 3). The best performing strategy was the strongest mixed strategy (MIX$_C$), closely followed by the strongest land-sparing strategy that had a large improvement in yield in agricultural areas (SPARE$_C$). The weak mixed strategy and land-sparing strategies without any penalties imposed to biodiversity (MIX$_A$, SPARE$_A$) performed slightly better than those that incurred penalties but had only moderate increases in yield (MIX$_B$, SPARE$_B$). Land-sharing only performed better than the baseline when no yield penalties were incurred (SHARE$_A$; Fig. 3), because in other cases the additional benefits to biodiversity were limited due to the specification of this as a threshold-based constraint, and outweighed by the yield penalties imposed on the production (maximization) objectives.

Conservation zones were allocated to roughly a third of the study region in all strategies (Fig. 4a). This represents the minimum area required for conservation in this region and is driven by the importance of forest protection for the conservation of ecosystems and species. The strongest land-sharing strategy (SHARE$_C$) provided the most opportunity for biodiversity in agricultural areas and thus required the least area allocated to the conservation zone (28·9–30·1%; Fig. 4a). The land-sparing strategies required the greatest extent allocated to the conservation zone (33·2–37·4%). On average, maximizing oil palm production increased the required area in the conservation zone by 4% over the equivalent policy maximizing smallholder agriculture to compensate for the relatively low biodiversity within oil palm plantations (Fig. 4a). Conservation zones were predominantly derived from existing forested land (89·4–96·1%; Fig. 4b), but more of the extant forest was protected under land-sparing, mixed policies and the baseline than land-sharing strategies (Fig. 4b). For all strategies, conservation zones removed very little from the area currently under smallholder agriculture production (1·4–3·8%; Fig. 4b). All policies required some area of reforestation within conservation zones, with land-sparing policies requiring 30% more, and land-sharing and mixed policies requiring respectively 39% and 34% less reforestation compared to the baseline. However, across all strategies, at most, only 4% of the total region required reforestation (in SPARE$_C$; Fig. 4b).

In the mixed strategies, no areas of oil palm production were allocated to land-sharing. In the mixed strategies, the area of smallholder agriculture allocated to land-sharing was greatest (54·7% equating to 8·2% of the study area) under the strongest mixed strategy (MIX$_C$)

when oil palm production was maximized (subject to constraints; Fig. 4d). This result arises because land-sharing strategies are able to capitalize on the contribution of smallholder agricultural production lands for the conservation of certain species that prefer areas of low-intensity agriculture over intact forest cover. When smallholder agricultural production was maximized, land-sharing of smallholder agriculture was less prominent (1·7–5·6% of the study area; Fig. 4d), because a greater area was allocated to smallholder agriculture overall (47·2–52·9%; Fig. 4a,d), mitigating the need to seek the benefits to biodiversity (and accept yield losses) from land-sharing.

To achieve oil palm targets (when maximizing smallholder agriculture production), oil palm zones were required to cover 12·7–16·9% of the region in mixed and land-sparing scenarios, and 24·6–32·7% in baseline and land-sharing scenarios (Fig. 4a,c). Oil palm zones were predominantly derived from degraded areas in all scenarios (57·6–71·6%; Fig. 4c). Roughly proportional to the increasing area allocated to oil palm, which was highest when oil palm production was maximized in the strongest mixed strategy (50·6% of the total area in MIX_C), oil palm zones would repurpose 15·0–72·9% of the currently degraded area, but also remove 33·2–78·0% of the existing agricultural area and replace 2·4–12·5% of the extant forest area (Fig. 4c).

Discussion

This is the first study that directly compares a range of land-sharing, land-sparing and mixed policy strategies for achieving multiple ecosystem services targets in an extensive, heterogeneous, tropical forest landscape. Our results emphasize that land-management trade-offs in complex landscapes require consideration of landscape heterogeneity, the relative importance of achieving competing targets, and how objectives are specified. Our evaluation of PPFs has allowed the combination of these factors to be considered simultaneously and trade-offs to be explored and elucidated. Such methods are of particular importance to exploring complex, mixed land-use strategies in multifunctional landscapes, and developing viable and effective land-management strategies for biodiverse forest frontiers that are likely to experience high development pressure and biodiversity loss in the near future (Newbold *et al.* 2015).

We found that mixed strategies that allow for both land-sharing and land-sparing have the greatest potential to satisfy all stakeholders, closely followed by land-sparing. This preference for mixed strategies is intuitive in environmentally and socio-economically heterogeneous regions such as our case study site, and confirms in a real-world context the results from simplified optimizations (Butsic & Kuemmerle 2015). It also provides empirical support for the increasing calls for land-use policies to contain elements of both land-sharing and land-sparing strategies (e.g. Fischer *et al.* 2014; Kremen 2015).

All 10 strategies however, including the baseline, could produce outcomes that satisfy all stakeholders, given careful attention to land-use allocation. Thus, the choice of policy will ultimately depend on the feasibility and costs of implementation, including moral and ethical implications of pursuing the alternative strategies. Feasibility of implementation (including *inter alia,* social, economic and

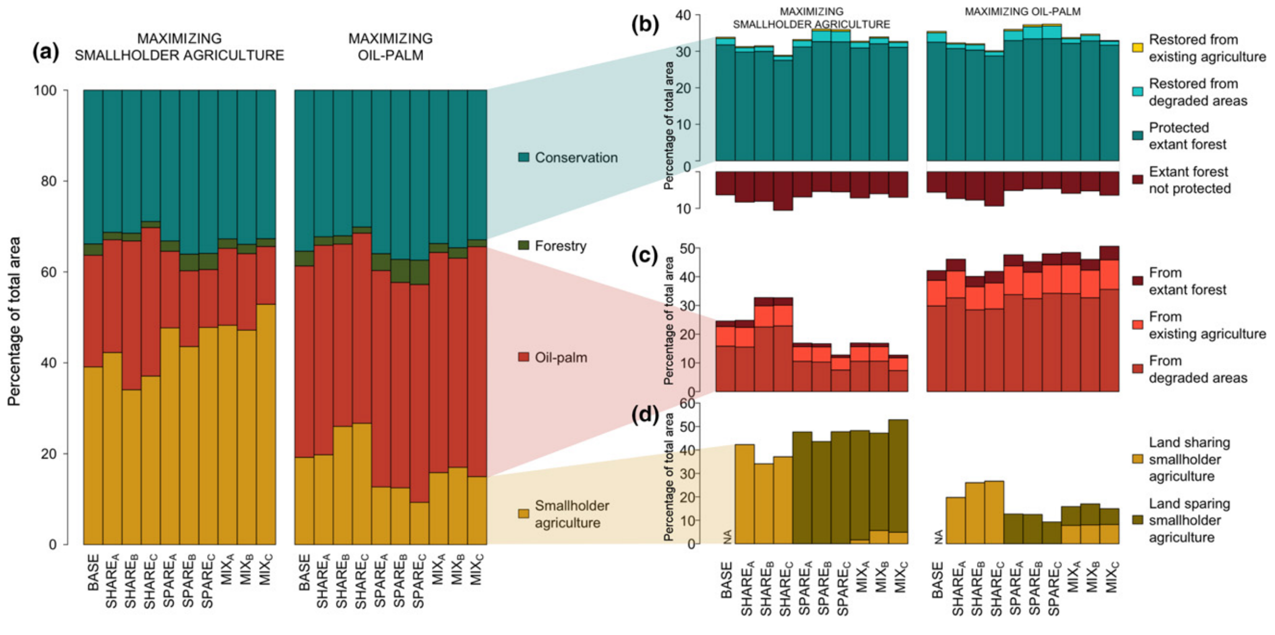

Fig. 4. Zone composition for the solutions of the production possibility frontiers that, subject to achieving all other targets, maximize either smallholder agricultural production or oil palm production. (a) Overall zone composition; (b) derivation of the conservation zone, and outcomes for extant forest; (c) derivation of the oil palm zone; (d) allocation to land-sharing or land-sparing in the smallholder agricultural zone.

legal incentives for policy uptake) is a key variable for determining optimal policy strategies; however, few data are available for this (Ferraro 2012; Polasky *et al.* 2014). Direct costs of implementation could include the costs of reforestation: land-sparing required over twice the area of reforestation than land-sharing in our study (though in all cases this area was <4% of the total region). Other trade-offs are subtler, involving relative benefits and costs between stakeholders. For example, decision-makers need to weigh the benefits and costs of pursuing strong policies (e.g. level C in our analysis, where some stakeholders may incur losses to improve gains overall), against policies where no stakeholders incur losses (otherwise commonly framed as 'win-win' strategies, and represented by level A in our analysis). These choices may not be straightforward: in our case study, strong land-sharing strategies that incur yield penalties result in reduced flexibility to achieve all targets, whereas strong mixed and land-sparing policies provide more opportunity to achieve all targets simultaneously.

When comparing single strategies in isolation, we find a strong preference for land-sparing over land-sharing. This echoes the results of analyses from other regions (Green *et al.* 2005; Anderson-Teixeira *et al.* 2012; Macchi *et al.* 2013; Macchi, Grau & Phalan 2015), including urban areas (Stott *et al.* 2015), and those reflected in numerous review and perspective articles (e.g. Phalan *et al.* 2011; Cunningham *et al.* 2013; Grau, Kuemmerle & Macchi 2013; Baudron & Giller 2014). Land-sparing is also favoured in our study region when land use is constrained to either current land uses or entitlements, or to prospective land-use plans (Law *et al.* 2015c). Simplified aspatial models also identify preference for land-sparing in the majority of cases and even suggest that land-sharing may deliver worse outcomes than existing management approaches, for example when additional benefits to biodiversity from land-sharing approaches are small and outweighed by losses of yield (Law & Wilson 2015). These outcomes will depend on the level of complementarity in joint land uses.

We find in our largely degraded case study landscape, however, that land-sharing strategies may still deliver acceptable outcomes if land-use allocation is strategically implemented. Also, land-sharing was an important component of mixed policies due to the possible conservation benefits that could be derived from smallholder agricultural areas for species not requiring pristine landscapes. Similar sentiments are proposed in urban areas, where some degree of land-sharing can be beneficial for the maintenance of specific services (Stott *et al.* 2015). In our case study, while optimal allocations in mixed strategies typically highlighted land-sparing (particularly for oil palm agriculture where the potential biodiversity benefits from sharing are minor and are outweighed by potential costs to production, relative to land-sparing), land-sharing was favoured for some areas of smallholder agriculture where highly tolerant primate species were associated more with this land use than the conservation zone. Nevertheless, approximately one-third of the region was allocated to conservation under all assessed land-sharing, land-sparing and mixed policies. Thus, despite the conservation value of agriculture being an important component of conservation strategy (e.g. Wright, Lake & Dolman 2012) and conservation plans (Wilson *et al.* 2010), 'wildlife-friendly farming' alone is likely to be insufficient for maintaining biodiversity in tropical landscapes.

Conversions from extant forest ecosystems to oil palm have a strong evidence base for substantial losses of biodiversity (Savilaakso *et al.* 2014). As expected, allocations to oil palm were mainly transitions from degraded land or existing agriculture in our case study. This provides support for recommendations for oil palm development to occur on already degraded lands (Smit *et al.* 2013). However, we caution that this could displace other potential uses of the landscape and negatively impact associated stakeholders. In our study region, oil palm competes with smallholder agriculture for suitable land (Law *et al.* 2015a). In our analysis, expansion of oil palm occurred at the expense of existing agriculture (up to 78·0% would be repurposed) and extant forest (up to 12·5% would be replaced). Further, in scenarios where oil palm was given preference over smallholder agriculture, conservation areas needed to be increased by up to 8% to compensate for the relative lack of biodiversity supported by oil palm plantations. Care will be required in developing policies that do not simply replace one driver of deforestation with another or displace land uses important for achieving the goals of a subset of stakeholders (Rudel *et al.* 2009; DeFries *et al.* 2010; Hosonuma *et al.* 2012). To achieve this in the case study region, policies developed at larger (e.g. provincial) scales need to recognize and accommodate the particular features of tropical peat swamp forest regions.

In this landscape, both ends of the zoning spectrum have been tested: where land use is completely constrained by existing zoning plans (Law *et al.* 2015c), and in the current analysis where land-use optimization is largely unconstrained, save for the constraints imposed by biophysical and historical land use. In reality, both of these are unrealistic: plans are rarely implemented completely, and 'optimized' solutions often need to consider additional social–political constraints. Land-use allocations are inherently complex and require the coordination of multidisciplinary input (Loch, Adamson & Mallawaarachchi 2014). Many varied options for both land-sharing and land-sparing exist (Kremen & Miles 2012; Phalan *et al.* 2016), each with a distinct distribution of costs, benefits and social acceptability. Yet the comparison of these constrained and unconstrained analyses is informative for further refinement of land-use targets and plans in the region. For example, Law *et al.* (2015c) suggested that while some plans performed better than others, all existing plans failed to achieve all targets simultaneously. Our results demonstrate that with optimization of land-use allocation the simultaneous achievement of all targets is possible. Mixed land-use and land-sparing policies should allow the flexibility required to maintain simultaneous achievement of all targets, even when additional constraints are introduced, such as current regulatory restrictions on deep peat development (Silvius & Suryadiputra 2005; Murdiyarso *et al.* 2011), or if constraints are strengthened, for example increasing the ambition of biodiversity targets. However, strategies that promote land-sharing only, or do not improve biodiversity or yield in agricultural areas, will need to be more strategic in terms of land-use allocation to achieve all targets.

Pending the availability of data, future analyses for the study region could account for these additional legislative land-use constraints, or other complexities that act as caveats to the current analysis. These may include further spatial and temporal dynamics of species and ecosystem services, particularly hydrology (Barraquand & Martinet 2011; Hooijer *et al.* 2012; Bagstad *et al.* 2013; Wich *et al.* 2015), desirable spatial configurations such as buffering protected areas with complementary low-intensity land uses (Sayer *et al.* 2013), or other spatial interdependencies that may better account for the joint benefits or trade-offs involved in, for example, locating reforestation in proximity to farmland or contiguous forest (Mitchell *et al.* 2015). Future analyses could also incorporate additional elements and facets of biodiversity (Newbold *et al.* 2015; Struebig *et al.* 2015), and more specific management actions, including their biophysical and social implications and implementation challenges (Martinet & Barraquand 2012; Ferraro & Hanauer 2014; Barral *et al.* 2015). Given the sensitivity of the results to the assumptions regarding the relative benefits and costs of land uses, as well as the targets and objectives specified, further refinement of strategies and exploring alternative objective function formulations may be useful. However, results such as the requirement for a minimum of one-third of the region to be maintained and reforested for conservation in order to achieve biodiversity targets should hold regardless, and this analysis as it stands should be helpful to direct further policy refinement and development into the most beneficial avenues.

Land-use planning for multiple stakeholders in the case study region will require careful design in order to satisfy the needs and desires of all. Our study provides evidence to support environmental and agricultural policy reform in the EMRP region with insights that are transferable to other tropical landscapes under pressure for both development and restoration, and multifunctional landscapes more widely. In the case study area, land zoning is primarily the responsibility of the provincial government. However, implementation of these plans is influenced by many factors, including international, national and provincial support and incentive for agricultural development or for restoration and reforestation, and the reactions of industry and local communities to these. International, multistakeholder fora such as REDD+, SEApeat (http://www.aseanpeat.net/), and the Roundtable on Sustainable Palm Oil (http://www.rspo.org/) may provide facilitation of stakeholder deliberations, for example by identifying shared visions, resolving conflicts, providing knowledge and support for stakeholders to achieve their respective goals, conveying best-practice management approaches and standards, and monitoring of policy implementation and impacts. Provincial-level land-use plans for Central Kalimantan have only recently been finalized (May 2015), and while further rezoning of the region is now unlikely, the results of this study and further analyses of the trade-offs involved in land-use allocation and achievement of stakeholder objectives may be used to fine-tune both government and non-government land-use policy to optimize land management in the region.

CONCLUSION

We present a novel method to examine the nature of trade-offs under alternative land-use strategies for multiple ecosystem service objectives across a heterogeneous, tropical forest region. An ecosystem services framework incorporating stakeholder-based targets encourages the consideration of a range of values that contribute to social welfare and for these values to be accounted for in ways that allow for meaningful comparisons of divergent land-use policies. The identification of PPFs using IP enables clearer interpretation of potential trade-offs, revealing in this case that mixed policies are likely to offer the most flexibility and potential to satisfy a diverse array of stakeholders, but that land-sharing and land-sparing may offer acceptable solutions also. Choice of land-use policy will thus ultimately depend on the feasibility of implementation, including associated costs, required social capital and the moral and ethical consequences.

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Data accessibility

Baseline data including the following are available through The University of Queensland eSpace data repository (http://espace.library.uq.edu.au/view/UQ:382357), doi:10.14264/uql.2016.113 (Law 2016):

- A shapefile of planning units
- An index of zones

- An index of features and their targets
- An index of planning units and maximum feature contributions
- Baseline zone contribution fractions for each planning unit
- Land use classes for planning units (as of 2008)

Marxan with Zones is available through http://www.uq.edu.au/marxan/.

Details of ecosystem services benefits and targets, as well as Marxan with Zones problem specification and parameterization, are available as online supporting information.

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Supporting Information

Additional Supporting Information may be found in the online version of this article.

Appendix S1. Ecosystem service benefits and targets.

Appendix S2. Problem specification and parameterization.