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LETTER

Spatially explicit estimates of forest carbon emissions, mitigation costs and REDD+ opportunities in Indonesia

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Abstract

Carbon emissions from the conversion and degradation of tropical forests contribute to anthropogenic climate change. Implementing programs to reduce emissions from tropical forest loss in Southeast Asia are perceived to be expensive due to high opportunity costs of avoided deforestation. However, these costs are not representative of all REDD+ opportunities as they are typically based on average costs across large land areas and are primarily for reducing deforestation from oil palm or pulp concessions. As mitigation costs and carbon benefits can vary according to site characteristics, spatially-explicit information should be used to assess cost-effectiveness and to guide the allocation of scarce REDD+ resources. We analyzed the cost-effectiveness of the following REDD+ strategies in Indonesia, one of the world's largest sources of carbon emissions from deforestation: halting additional deforestation in protected areas, timber and oil palm concessions, reforesting degraded land and employing reduced-impact logging techniques in logging concessions. We discover that when spatial variation in costs and benefits is considered, low-cost options emerged even for the two most expensive strategies: protecting forests from conversion to oil palm and timber plantations. To achieve a low emissions reduction target of 25%, we suggest funding should target deforestation in protected areas, and oil palm and timber concessions to maximize emissions reductions at the lowest cumulative cost. Low-cost opportunities for reducing emissions from oil palm are where concessions have been granted on deep peat deposits or unproductive land. To achieve a high emissions reduction target of 75%, funding is allocated across all strategies, emphasizing that no single strategy can reduce emissions cost-effectively across all of Indonesia. These findings demonstrate that by using a spatially-targeted approach to identify high priority locations for reducing emissions from deforestation and forest degradation, REDD+ resources can be allocated cost-effectively across Indonesia.

1. Introduction

Tropical forests are important reservoirs of carbon, containing around half (55%) of the carbon stored in forests worldwide (Pan *et al* 2011). Globally, tropical forests declined at a rate of ~0.5% pa for the period 1990–2010 which equated to ~120 million ha (Achard *et al* 2014) and contributed to ~15% of anthropogenic carbon emissions (Houghton 2013). Indonesia is one of the largest contributors of carbon emissions from tropical deforestation and degradation (Baccini *et al* 2012). The Indonesian government have pledged to curb the conversion of tropical lowland forests and one of the initiatives they are supporting to achieve this goal is REDD+ (for Reducing Emissions from Deforestation and forest Degradation plus conserving, sustainably managing forests and enhancing forest carbon stocks). REDD+ payments are intended to provide the economic incentives needed to conserve forests by linking financial rewards to emissions reduced or carbon sequestered (Agrawal *et al* 2011). When REDD+ was first conceived in 2005 it sought to Reduce Emissions from Deforestation (RED; see den Besten *et al* 2014) at which point it was chiefly concerned with limiting tropical deforestation. During early-stage discussions, the scope of REDD+ was broadened to include reducing degradation (REDD) as well as conserving and sustainably managing forests and enhancing forest carbon stocks (REDD+). This development opened up a range of new opportunities for addressing forest carbon loss, including activities that sequester carbon, such as reforestation, and that reduce degradation, such as reduced-impact logging (RIL; Putz *et al* 2008, Alexander *et al* 2011).

Through its range of strategies, REDD+ has the potential to reduce carbon dioxide (CO_2) concentrations in the atmosphere, which will aid in the transition to a low fossil fuel global economy (Houghton *et al* 2015). Since its inception, REDD+ has attracted over US$7.3 billion in funding, including pledges of over US$2 billion to Indonesia alone (Forest Trends Association 2016). A key issue hindering the implementation of REDD+ is how well cost-effective climate mitigation activities align with the rights of local forest users, with concerns raised that the priorities of international investors will be privileged over those of local communities (Howson and Kindon 2015). Additionally, economic concerns have been centred on the unlikelihood that REDD+ will generate sufficient finance to off-set lost revenues from alternative land-use activities, drawing comparisons against the moderate level of funding directed towards REDD+ relative to the high profits generated from deforestation-dependent activities such as timber and oil palm production (Venter and Koh 2011). The literature shows that projects aimed at limiting deforestation from large-scale oil palm production are expensive due to the high forgone revenues (i.e. opportunity cost) from converting forest into oil palm (e.g. Butler *et al* 2009, Venter *et al* 2009, Fisher *et al* 2011a, Irawan *et al* 2011, Ruslandi *et al* 2011).

An alternative and potentially cheaper pathway for REDD+ to contribute towards carbon mitigation is via reforestation, reducing illegal deforestation in protected areas (PAs) and reducing forest degradation. The optimal approach to allocating REDD+ resources will be influenced by the spatial context in which each project is applied, as costs and carbon benefits can vary spatially (Pagiola and Bosquet 2009). Site-specific factors that influence costs and benefits include terrain, distance to markets and soil type (Gibbs *et al* 2007, Pagiola and Bosquet 2009). Recent studies undertaken in Indonesia highlight how applying a spatially-targeted approach to regional development plans can reduce the trade-offs of agricultural or timber expansion and forest protection (Koh and Ghazoul 2010, Venter *et al* 2012). A key question therefore is how does spatial variation influence the effectiveness of REDD+ strategies to mitigate forest-based carbon emissions at low-cost across Indonesia.

To address this question, we used spatial analyses to assess the variation in costs and carbon benefits of various REDD+ strategies in Indonesia and identified the factors that drive cost-effectiveness. We used maps of carbon stocks, forest cover, peatlands and crop suitability to estimate the potential for REDD+ to slow or reverse carbon emissions from oil palm, timber and logging permits, PAs and on degraded land. We explored the cost-effectiveness of REDD+ strategies for reducing one tonne of carbon and for achieving a range of emissions targets. We compared the results from this spatial analysis to estimates from a cost-benefit analysis of REDD+ that used average costs and benefits (Graham *et al* 2016). This paper is designed to deliver fine-scale information to policy makers on spatially-targeted opportunities for mitigating carbon emissions from deforestation and forest degradation in Indonesia.

2. Materials and methods

In this paper, we estimated the 30 yr carbon emissions and financial costs from anticipated land conversion and determined the carbon sequestered from restoring land that is not slated for urban development or agriculture across Indonesia. The term 'permits' refers to land use rights issued to companies for logging, oil palm or timber concessions. We ranked all permits, PAs and reforestation sites by the cost of reducing one tonne of carbon (from low to high), to determine the combination of strategies that achieve emissions targets (25%, 50%, 75%, 100%) most cost-effectively. All carbon values are in tonnes (1 tonne = 1 Mg) of carbon (C). Carbon dioxide (CO_2) was converted to carbon by dividing by 3.67 (van Kooten *et al* 2004). Biomass was converted to carbon by multiplying by 0.492 (Pinard and Putz 1996). All financial figures are in 2010 US dollars. Here we present a summarized version of the steps involved in calculating the spatially explicit emissions and costs individually for each permit, PA or reforestation site. See appendix S1 (available at https://stacks.iop.org/ERL/12/044017/mmedia) in supporting information for details on the input data and detailed methods.

2.1. Estimating carbon benefits of REDD+ strategies

Spatial analysis was performed in ArcGIS v10.3 (ESRI 2014). We used 250 m spatial resolution land cover maps for 2000 and 2010 that were produced using Moderate Resolution Imaging Spectroradiometer (MODIS) images and Daichi-Advanced Land Observing Satellite data (Miettinen *et al* 2012b). We created binary maps of 2000 and 2010 natural forest cover (figure 1(*a*)) by classifying: mangrove forest, peat

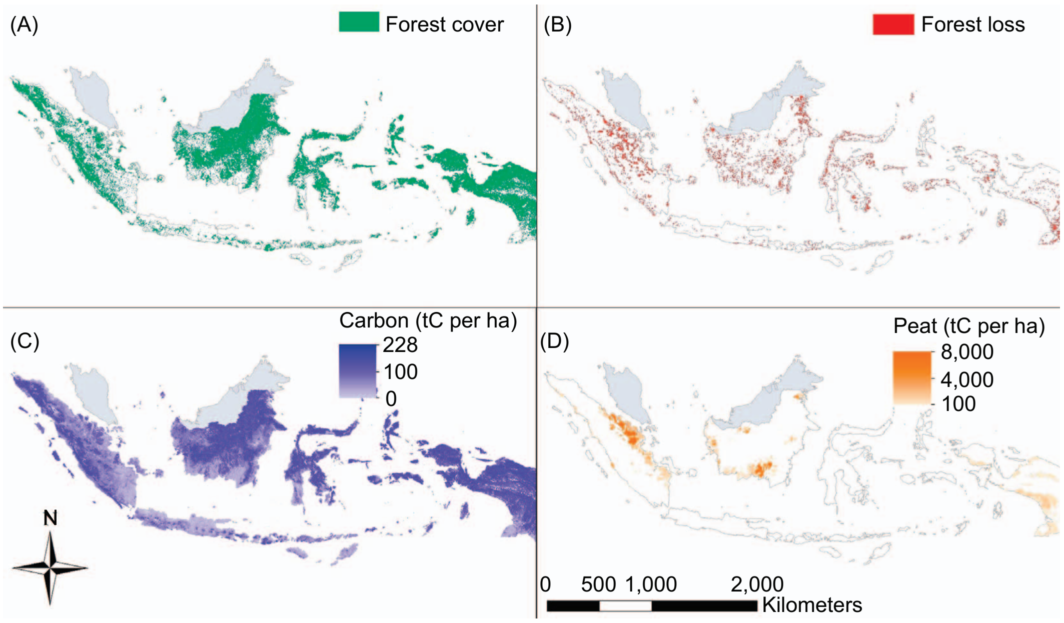

Figure 1. Forest and carbon data used in the spatial analysis: (*a*) 2010 forest cover (Miettinen *et al* 2012b); (*b*) forest loss between 2000 and 2010; (*c*) terrestrial above-ground carbon for the period 2007–2008 (Baccini *et al* 2012); and (*d*) carbon stored in peat swamps for 2002 (Minnemeyer *et al* 2009).

swamp forest, lowland forest, lower montane forest and upper montane forest as natural forest (hereafter referred to as '*forest*'). To create a layer of deforestation, we used the erase function to estimate net forest loss for the decade 2000 to 2010 (figure 1(*b*)). We resampled all layers to a ~250 m resolution to match the Miettinen *et al* (2012b) land cover dataset and projected all spatial data into Asia South Albers Equal Area Conic. We measured carbon emissions from loss of above- and below-ground carbon (AGC; BGC; figures 1(*c*) and (*d*)). Baccini *et al* (2012) used field data and remote sensing to estimate and map AGC for all of Indonesia. We used a root:shoot ratio of 21:100 to convert the AGC estimates from the Baccini map to total carbon in natural forests and timber plantations (Saatchi *et al* 2011, Kotowska *et al* 2015) and 32:100 in oil palm concessions and mixed-crops (Kotowska *et al* 2015). We tested the sensitivity of our results to changes in the forest cover and carbon input data by analyzing all of the scenarios using high spatial resolution (30 m) land cover maps for 2000 and 2010 (Hansen *et al* 2013) and a map of above- and below-ground biomass produced circa 2000 (Saatchi *et al* 2011)—refer to supporting information for details. Carbon benefits refer to emissions reduced from avoided deforestation and degradation, as well as carbon accrued from reforestation.

2.1.1. *Oil palm and timber concessions*

We overlayed maps of timber (Minnemeyer *et al* 2009, figure 2(*a*)) and oil palm concessions (Greenpeace 2011, figure 2(*b*)) with our 2010 forest cover and AGC maps to estimate the total carbon contained within the forested part of each permit and estimate the emissions that would result from clearing the forest and replacing it with plantations (see appendix S1). If a permit was highly suitable for growing oil palm, we accounted for carbon stocks in the replacement vegetation (a carbon benefit), whereas if a permit was unsuitable for oil palm, we accounted for no carbon benefit following deforestation if oil palm could not be grown. Prior to the establishment of oil palm and timber plantations, peat swamps are firstly drained (FAO 2014) which leads to additional carbon emissions from the oxidation and increased probability of fires after draining. We calculated the extent of peat emissions by intersecting the map of forest threatened by oil palm and timber with a map of carbon stored in peat swamps (Minnemeyer *et al* 2009, figure 1(*d*)).

2.1.2. *Reduced-impact logging*

Employing RIL techniques to logging operations saves an additional 19% of the pre-harvest biomass compared to conventional logging (CL; Healey *et al* 2000, Pinard and Cropper 2000, Putz *et al* 2008). We estimated the emissions that could be reduced from minimizing forest degradation during log-harvesting under RIL practices, by multiplying the 30 yr carbon benefit of RIL (19%) by the carbon stored in each existing logging concession (Minnemeyer *et al* 2009, figure 2(*c*)). Selective logging of forests can be conducted without major disturbances to peat hydrology (FAO 2014) and therefore we did not account for emissions from peat drainage in logging permits.

2.1.3. *Illegal deforestation within protected areas*

For each terrestrial PA (IUCN and UNEP-WCMC 2016, figure 2(*d*)), we projected 30 years of future

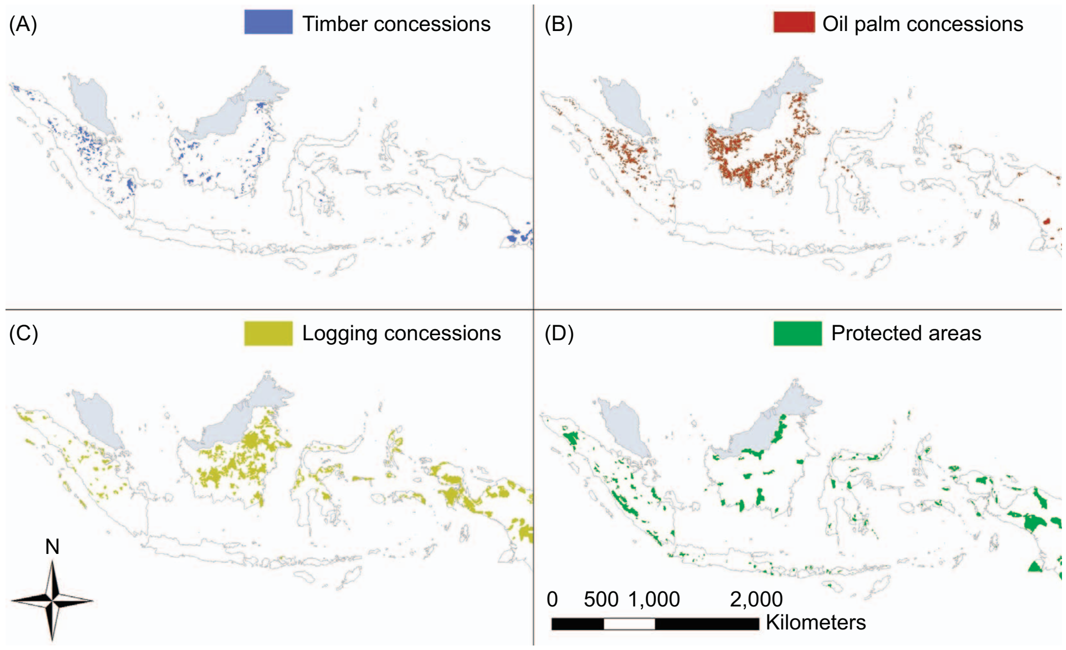

Figure 2. Cadastral data layers used in the spatial analysis: (*a*) timber concessions (Minnemeyer *et al* 2009); (*b*) oil palm concessions (Greenpeace 2011); (*c*) logging concessions (Minnemeyer *et al* 2009); and (*d*) protected areas (IUCN and UNEP-WCMC 2016).

emissions from illegal activities using a linear extrapolation of deforestation observed over the period 2000–2010 (Miettinen *et al* 2012b). It is common in Indonesia to plant cacao, oil palm, rubber and coffee (hereafter 'mixed-crops') in PAs following deforestation (Swallow *et al* 2007). We estimated the carbon lost by converting natural forests to mixed-crops (accounting for carbon stocks in replacement vegetation) and multiplied it by the deforestation rate to project the carbon emissions from illegal deforestation. We assumed that half of the deforestation activities that occur on peat soils in PAs require drainage while the other half do not (FAO 2014). We calculated the extent of peat emissions by intersecting the map of forest threatened by agriculture in PAs with a map of peat soil and multiplied this by 0.5 and by the deforestation rate.

2.1.4. *Reforesting abandoned land*

We overlayed a map of biomes (Olson *et al* 2001) with our 2010 forest cover map to find sites where forests previously existed but had been cleared. We disregarded 'afforestation' activities (planting forests in historically non-forest locations). We classified the World Wildlife Fund for Nature (WWF) biomes 'tropical and subtropical moist broadleaf forests', 'tropical and subtropical dry broadleaf forests' and 'mangroves' as '*forest*'. We then refined our area to 'highly degraded land' which we identified as areas with less than 35 $tC{\cdot}ha^{-1}$ (Baccini *et al* 2012), which is a recommended practice for identifying degraded forest lands in Indonesia (Gingold *et al* 2012). We excluded areas that overlapped with oil palm, timber or logging concessions and all areas classified as 'APL', which is outside of the national forest estate (Minnemeyer *et al* 2009). We created 2214 'hypothetical management units' for reforestation in areas of 900 ha in size to compare against permits and PAs. We estimated the potential carbon benefit of reforestation projects in Indonesia based on the 30 yr sequestration rate (appendix S1) of regenerating tropical forests.

2.2. Cost of reducing emissions

The financial costs of employing each REDD+ strategy as calculated by Graham *et al* (2016; see appendix S1 for details) included opportunity, management and transaction costs. Most costs were presented as net present values, which are the discounted value of the sum of projected future cash flows expected under the business as usual scenario (Stone 1988), that were extrapolated over 30 years at a discount rate of 10% pa. In this paper, we modified the average per hectare costs based on spatially-explicit site characteristics. Spatially-explicit opportunity costs of oil palm were estimated by overlaying a suitability map for oil palm (FAO 2012) to determine where oil palm is profitable. Opportunity costs of land that is unsuitable for oil palm are restricted to the profits from timber extraction. Conversely, sites that have high suitability for oil palm will generate larger revenues from its production and sale, as well as from timber extraction, than sites that have low or no suitability. Depending on a plantation's suitability, we applied different costs to permits (see appendix S1). Costs for oil palm, timber, PAs and logging permits were calculated based on the forested part of the permit only.

We calculated the cost of reducing emissions ($\${\cdot}tC^{-1}$) by dividing the total cost by the total carbon

Table 1. Summary information on the total area (ha), cost (US$) and carbon benefit (C) of the following REDD+ strategies: targeting deforestation within timber and oil palm concessions, halting illegal forest clearing in protected areas, reforesting degraded land and employing reduced-impact logging techniques at logging concessions. Total figures are for all of Indonesia and means are the average across all permits, protected areas or reforestation sites. The cost of reducing emissions ($ tC^{-1}) at each site is displayed in figure 4. Reforestation has no forest area because the target area for forest restoration is where forest has been cleared and no variance because of the flat rate of carbon accrual used.

REDD+ strategy	(a) Timber	(b) Palm oil	(c) RIL	(d) Protected areas	(e) Reforestation
Number of sites	429	1845	557	289	2214
Total area (ha)	8586 711	15 200 084	29 575 904	18 425 301	5002 200
Total forested area (ha)	2053 338	3003 896	17 775 332	13 831 004	—
Average forest area (ha)	8181	3530	33 922	62 584	—
Total cost (US$ millions)	8978	18 028	14 791	7306	8717
Total carbon emissions (tC millions)	831	836	638	414	965
Mean carbon benefit ($\text{tC}\cdot\text{ha}^{-1}$) including peat	308	234	35	54	193
Mean cost (and range) of reducing emissions ($\text{US}\cdot\text{tC}^{-1}$)	56.36 (5–972)	73.14 (6–8272)	23.77 (21–30)	39.27 (2–1725)	9.03 9.03–9.03

benefit for each permit, PA and reforestation site, using the formula below.

$$\text{Cost of reducing emissions } (\$\cdot\text{tc}^{-1}) = \frac{\text{Total cost}(\$)}{\text{Total carbon benefit}(\text{tC})}$$

3. Results

Across Indonesia, ~85.3 Mha of forest cover remained as of 2010, of which logging concessions represented the largest area (~17.8 Mha; 21%; table 1), followed by: PAs (~13.8 Mha; 16%), oil palm concessions (~3.00 Mha; 4%) and timber concessions (~2.05 Mha; 2%). Sites suitable for reforestation covered ~5.00 Mha of degraded land. We estimated the maximum potential 30 yr carbon benefit of employing five REDD+ strategies: (1) reforesting degraded land could sequester 965 MtC; (2) limiting the expansion of oil palm into forests could reduce 836 MtC; (3) limiting the expansion of timber plantations into forests could reduce 831 MtC;(4) employing RIL techniques in logging concessions could reduce 638 MtC; and (5) halting illegal forest loss in PAs could reduce 414 MtC. On an annual basis, the combined carbon benefit of applying these strategies across Indonesia is 123 MtC (3684 MtC over 30 years) at a cost of $1.9 billion, or $15.7 tC^{-1}.

On average, reforestation is cheaper than the other strategies assessed in terms of cost-effectiveness for reducing emissions ($9·$\text{tC}^{-1}$), but has no variance in costs due to the flat carbon sequestration rate applied here (figure 3). Oil palm and timber concessions and PAs had some of the cheapest (<$7·$\text{tC}^{-1}$) and the most expensive sites (>$200·$\text{tC}^{-1}$) for reducing emissions and the most variation (table 1), indicating site-specific factors strongly influence the cost of reducing emissions at each permit or PA. Cost-effective locations for reducing emissions from timber plantations (figure 4(*a*)) are where carbon-rich forests (e.g. peat forests) remain, while expensive locations have remaining forests of low quality. Approximately 40% of forested timber plantations in Indonesia overlapped with peat soils, predominantly in eastern Sumatra, storing on average twenty times more carbon, and making these permits four times cheaper for reducing emissions than forests on mineral soils.

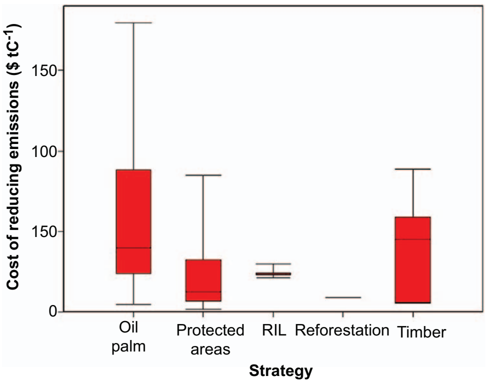

Figure 3. The median cost of reducing emissions for each strategy (US$·$\text{tC}^{-1}$) as shown by the horizontal line in the box. The inter-quartile range, shown by the middle box, represents 50% of the estimates. The whiskers represent the full range of estimates, excluding outliers.

To reduce emissions from oil palm, cost-effective locations are mainly in Borneo (figure 4(*b*)), where remaining forests occur on peat deposits (31% of permits with forest), or where land has climatic and edaphic conditions that is not highly suitable for cultivating oil palm (85% of permits with forest;). The cost of reducing emissions in oil palm permits with low or no suitability (~$39·$\text{tC}^{-1}$) is seven times cheaper than permits with high suitability (~$265·$\text{tC}^{-1}$). Across Indonesia, logging concessions consistently provide low-cost options for reducing emissions from forest degradation through opportunities for employing RIL practices (figure 4(*c*)). Cost-effective opportunities to reduce illegal forest carbon loss in PAs occur on all islands (figure 4(*d*)) and are characterized by high deforestation rates (>3% pa between 2000 and 2010) and dense carbon stores (>500 $\text{tC}\cdot\text{ha}^{-1}$).

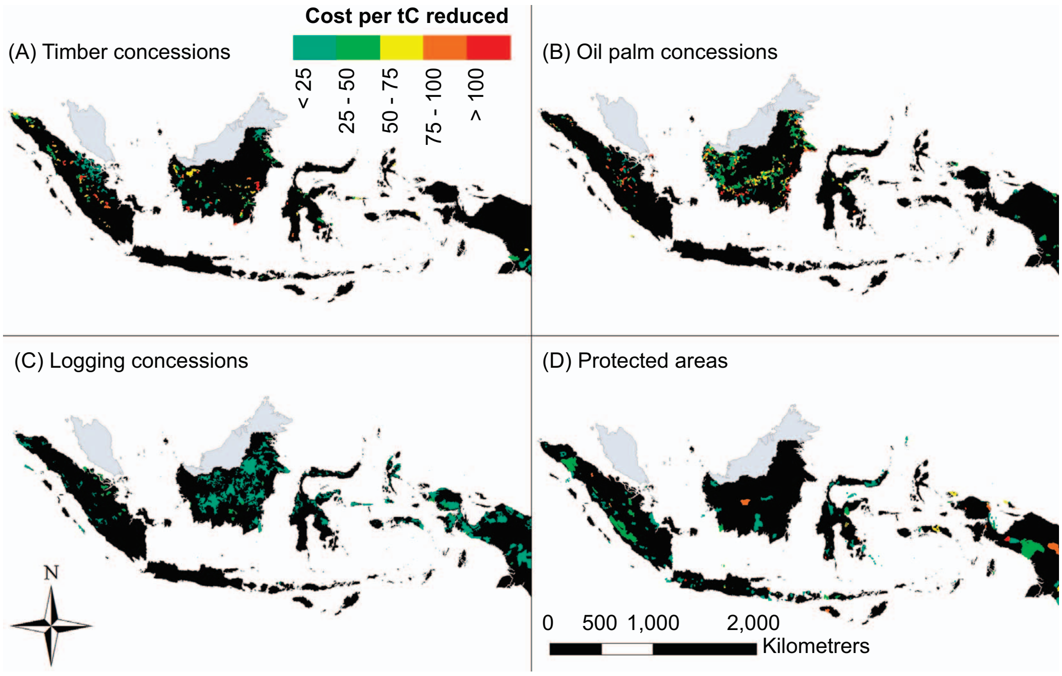

Figure 4. The cost of reducing carbon emissions within: (*a*) timber concessions; (*b*) oil palm concessions; (*c*) logging concessions; and (*d*) protected areas in Indonesia. Costs are per tonne of carbon reduced (US\$·tC^{-1}) for the forested part of the permit or protected area. Only permits and protected areas with forest cover are included in these figures. To improve visibility, the whole permit or protected area has been displayed on the map, regardless of where the remaining forest exists. Reforestation sites are not shown here as they have a fixed cost for all areas.

We found that different REDD+ strategies are effective at varying budgets and emissions reduction targets (figures 5(*a*) and (*b*)) and that a combination of strategies should be employed to reduce emissions cost-effectively across Indonesia. For example, to achieve a low emissions reduction target of 25% (920 MtC) through REDD+, funding should be allocated between PAs, timber and oil palm concessions which incurs a total cost of \$5.1 billion (table 2). The least costly approach to reduce 50% of forest carbon emissions (1842 MtC) includes these three strategies as well as reforesting degraded which incurs a combined cost of \$12.9 billion. A reduction of 75% of emissions (2746 MtC) can be achieved at a total cost of \$25.7 billion by employing a combination of all strategies: targeting deforestation within timber and oil palm concessions, investing in better managed PAs, employing RIL techniques in logging concessions and by promoting reforestation. Reducing 100% of emissions from these strategies (3684 MtC) costs \$57.8 billion. The findings of the spatial-targeting approach show that even the strategies that were most expensive on average (limiting oil palm and timber expansion into forests), provided some of the cheapest locations for reducing emissions, while the cheapest strategies on average (reforestation and RIL) were not as competitive for meeting low emissions targets (i.e. had few very low-cost opportunities).

The results from the sensitivity analysis showed that using surrogate forest cover and carbon datasets, or both combined, caused quantitative variances in the proportion of strategies employed to meet emissions reduction targets, but did not change which strategies were employed (appendix S1, table S3). Using a surrogate forest cover map resulted in the average cost of reducing emissions to increase for PAs, and oil palm and timber concessions (appendix S1, table S4), however using a surrogate carbon map caused the cost of reducing emissions to decrease for all strategies, except for reforestation which did not change or RIL which did not change by more than \$1·tC^{-1}.

4. Discussion

This paper reports on the cost-effective allocation of REDD+ resources in Indonesia using a spatially-targeted approach. The maximum potential carbon benefit of applying five REDD+ strategies at all potential locations is 123 MtC·yr^{-1}. This is 17% more than the 105 MtC·yr^{-1} estimated from deforestation for 2000–2005 reported by Harris *et al* (2012), however our approach differed by accounting for carbon losses from degradation (logging) and carbon gains from reforestation and replacement vegetation (where cleared forests were expected to be replaced by other crops). The prevention of emissions of this scale would involve: employing RIL techniques at all logging concessions; stopping further deforestation within all PAs, and oil palm and timber permits; and reforesting all degraded land that has been cleared of forest but was not listed as 'non-forest estate'. Clearly, this is a highly ambitious scenario and unlikely to be implemented in the near term. A more realistic

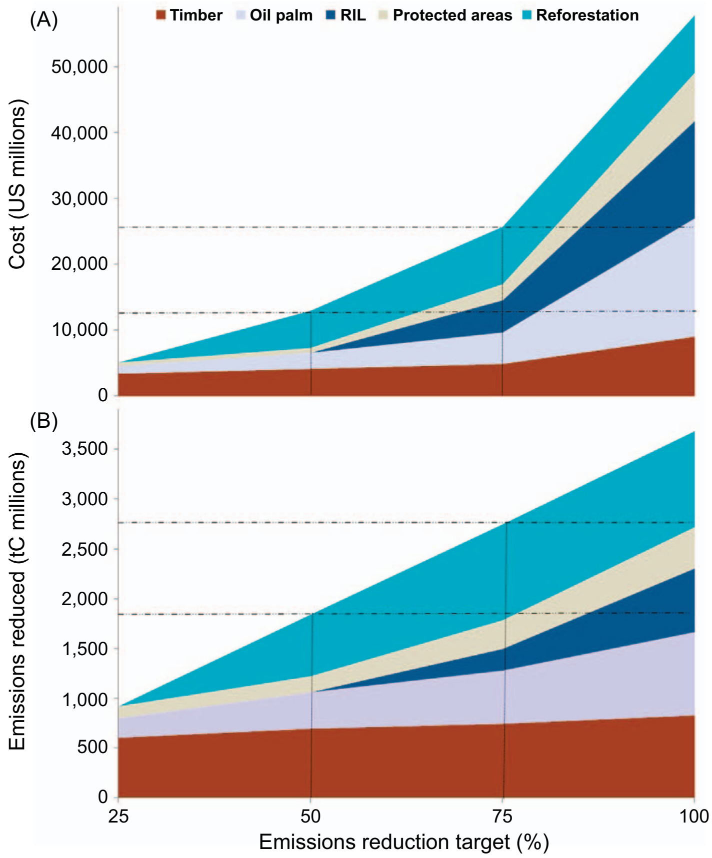

Figure 5. Accumulation curves showing the proportion of each REDD+ strategy employed to reduce emissions at the lowest cost. The *x*-axis represents: the emissions reduction target and the *y*-axis represents: (*a*) the cumulative cost (in US$ millions); and (*b*) the cumulative emissions reduced (tC millions). Strategies are prioritized by the cost of reducing one tonne of carbon, from lowest to highest. Dashed lines display: (*a*) the costs of achieving two emissions reduction targets; and (*b*) the carbon emissions reduced. For example, spending $12 942 million will reduce 1842 MtC (50% of emissions) and spending $25 678 million will reduce 2746 MtC (75% of emissions). RIL = reduced-impact logging.

Table 2. The cost (US$ millions) of reducing 25%, 50%, 75% and 100% of carbon emissions from five REDD+ strategies. The mix of strategies that contributes to achieving the emissions target is prioritized by the cost of reducing one tonne of carbon at each site (concession, protected area or reforestation site), from lowest to highest.

	Emissions reduction target			
	25%	50%	75%	100%
Cost (millions) of achieving emissions reduction targets:				
(a) Timber	3377	4137	4913	8978
(b) Oil palm	1219	2462	4757	18 028
(c) RIL	—	—	4917	14 791
(d) Protected areas	467	763	2374	7306
(e) Reforestation	—	5579	8717	8717
(f) All strategies	5063	12 942	25 678	57 820
Average cost per tonne of avoided emissions ($ tC^{-1})	5.50	7.03	9.35	15.70

emissions reduction target for Indonesia, in the range of 25%–50%, would reduce 920–1842 MtC respectively over 30 years (31–61 $MtC \cdot yr^{-1}$). When compared to the average cost estimates from Graham *et al* (2016) that did not consider spatial heterogeneity, the inclusion of spatially-discrete cost-benefit estimates caused large changes in the average cost of reducing emissions for the timber, oil palm and PA strategies. This is partly because for these three strategies, carbon stored in natural forests is lost when cleared and converted to agriculture, whereas the RIL strategy assesses the proportional carbon benefit from reduced degradation and the reforestation strategy uses a flat rate of carbon accrual. Our results highlight that at lower emissions targets, it is crucial to choose the most cost-effective strategies in the most cost-effective locations, as costs and benefits of REDD+ vary spatially in Indonesia.

Our spatial analysis revealed that because of the variability in cost-effectiveness, low-cost opportunities exist for all of the strategies we reviewed, depending on emissions target and budget. To reduce the first 25% of emissions through REDD+, only three strategies offered very low-cost opportunities—reducing deforestation from oil palm, timber and PAs. A factor driving this result is that ~82% of oil palm permits have been granted on land with partial suitability and 3% on land that has no agricultural potential for oil palm, mostly in Borneo, resulting in costs that are seven times cheaper than sites with high potential. For PAs, priority areas for REDD+ projects are spread across all major Indonesian islands and are driven by high deforestation rates coupled with dense carbon stores. A significant opportunity for carbon mitigation and biodiversity conservation lies in abating the high level of illegal forest loss (Spracklen *et al* 2015) and the carbon emissions predicted to occur in the future (414 MtC) if the current pace (~2% pa) of illegal deforestation in Indonesia continues. Within individual PAs, the allocation of resources should be prioritized by accessibility factors, as some areas within parks are protected 'de facto' due to inaccessibility, while lowland forests that are close to roads or urban areas are exposed to greater risk of forest conversion (Gaveau *et al* 2009, Laurance *et al* 2012).

At a 50% emissions target, reforesting degraded land becomes the most important strategy, alongside lowering forest carbon loss in PAs and oil palm and timber concessions. Employing RIL in logging concessions is not cost-effective until targeting a 75% emissions reduction. Although some strategies are more expensive on average (e.g. limiting timber and oil palm expansion), these strategies are still very important for achieving even the lowest of emissions reduction targets (25%–50%) through REDD+, when spatially-explicit costs and benefits are considered. Conversely, some strategies with low average costs (e.g. reforestation and RIL) are less important for meeting low emissions targets, highlighting the importance of spatial-targeting when prioritizing the allocation of REDD+ resources.

The most widespread spatial pattern observed in our analysis was the importance of protecting forests on lowland peat swamps, which cover peat deposits of up to 10 metres in depth (Page *et al* 1999). Peatlands in Borneo have been declining by 2.9% pa and by 4.6% pa in Sumatra over the last two decades (Miettinen *et al* 2012a), presenting an increased challenge for Indonesia to meet their climate mitigation targets, as once cleared, peatlands are highly fire-prone (IPCC 2007) and their emissions have contributed substantially to the high level of national emissions (Baccini *et al* 2012). Approximately 21% of PAs, 40% of timber permits and 31% of oil palm permits with remnant forest cover in Sumatra, Borneo and Papua occur on peatlands (mainly in eastern Sumatra and southern Borneo); representing high priority areas for forest protection through REDD+. In terms of size, peat forests account for 9% of forested area in PAs, 26% of forested area in oil palm concessions and 62% of forested area in timber plantations.

Our paper has focused on carbon and financial elements of REDD+, however other social and ecological dimensions of these strategies are also important determinants of which strategies should be employed and where. While scholars are debating the non-carbon benefits and risks, little attention has been directed to how the outcomes vary between project type. For example, projects that focus on avoided deforestation have the greatest opportunity for delivering biodiversity co-benefits (Stickler *et al* 2009). Conversely, projects tacking illegal deforestation in PAs have high social risks to forest-dependent communities whereby communities can be displaced or deprived of access to livelihood resources (Brockington *et al* 2006), yet they can also create employment opportunities for communities associated with implementation (Mustalahti *et al* 2012) and can lead to enhancements in ecosystem service function (Mullan 2014). Biodiversity benefits from reforestation can be large where regrowth is promoted on degraded forest, but one of the most serious risks to biodiversity is afforestation, which could lead to carbon-rich plantation forests being valued over biodiverse, low-carbon grasslands (Veldman *et al* 2015). Logging concessions provide a significant opportunity to achieve biodiversity benefits in tropical Asia (Fisher *et al* 2011b, Gaveau *et al* 2013, Abood *et al* 2014) because they contain more forests (~17.8 Mha; 21%) than PAs (~13.8 Mha; 16%) in Indonesia and are advocated alongside PAs for their role in biodiversity conservation (Fisher *et al* 2011b, Gaveau *et al* 2013). For example, concessions that operate well-managed RIL policies and protect forests from agricultural encroachment can maintain a comparable amount of forest cover as PAs (Putz *et al* 2012, Gaveau *et al* 2013). Also, approximately 76% of carbon and 85%–100% of species of mammals, birds, invertebrates and plants are retained in once-logged forests (Edwards *et al* 2010, Fisher *et al* 2011b, Putz *et al* 2012). Directing REDD+ finance towards logging operations could assist the industry to expand RIL practices and achieve these environmental benefits.

While reducing greenhouse gas emissions cost-effectively was the original motivation for REDD+, it is widely agreed that projects need to achieve broader social and environmental objectives, such as enhancing the livelihoods of local people and conserving biodiversity (Vijge *et al* 2016). These are referred to as 'non-carbon outcomes' (Agrawal *et al* 2011). The majority of projects in Indonesia are implemented in highly biodiverse areas and show no consistent spatial correlation with carbon stocks (Murray *et al* 2015), demonstrating that factors other than carbon are driving REDD+ project implementation. Although they are clearly important outcomes, most nations are yet to develop capacities for monitoring non-carbon outcomes (Vijge *et al* 2016), though they should be considered nonetheless.

This analysis could be enhanced with the addition of spatial information on the potential rate of carbon accrual during forest regeneration. Remote sensing forest cover data can confound natural forest with forest plantations resulting in overestimating forested areas (Sexton *et al* 2016). To address this issue, we imposed a minimum carbon requirement on forest cover, which is an accepted approach to reduce ambiguity in global forest classification (Sexton *et al* 2016). In the supporting information (appendix S1) we discuss these issues and disclose the carbon threshold applied for each strategy. In this study, we did not assess emissions from the 57% of remaining forest cover that occurs outside of PAs or logging, timber and oil palm concession areas. Roughly 55% of deforestation in Indonesia is estimated to occur outside concession areas driven by logging, oil palm, smallholder agriculture, rubber, coffee, mining, urban development and fire (Abood *et al* 2014, Stibig *et al* 2014). This analysis did not incorporate fluctuations in opportunity costs in response to supply and demand conditions—an effect picked up in dynamic models (Wertz-Kanounnikoff 2008, Lu and Liu 2015). For example, limiting production at an oil palm concession that could have been profitable, can increase the opportunity costs at another location as decreased land supply causes costs to rise. Our measurements do not include the recovery state of forest carbon stocks following deforestation and degradation for rotational farming in PAs because spatial data on the proportional area of rotational farming, as well as the state of recovery, is not available for all of Indonesia. Future research should investigate spatial patterns of deforestation in Indonesian PAs and rates of carbon accrual in forest regrowth, as this information will more accurately inform spatial-targeting of REDD+ finance.

By substituting the primary forest layer with surrogate data, we found the average cost of reducing emissions was much higher for timber and oil palm concessions and PAs, because the secondary forest map confounds plantation forests with natural forests causing the projected carbon emissions to decrease and the cost of reducing emissions to increase. There are two reasons for this. First, natural forests that are cleared and replaced with plantation forests may be still classified as forests in this map and therefore the carbon emissions resulting from this type of deforestation may not be included. Second, plantation forests with higher than average carbon levels could be mistaken for natural forests which would drag down the average carbon stored in natural forests at that site.

5. Conclusions

The optimal allocation of REDD+ resources should consider the spatial heterogeneity of landscapes and use this information to apply spatially-targeted strategies (Venter *et al* 2012). Our analysis demonstrates that when fine-scale variation in costs and carbon benefits is considered, there is no single-strategy for curbing future forest carbon loss cost-effectively at all potential REDD+ locations. Rather, adopting a spatially-targeted approach to resource allocation reduces carbon emissions most effectively. This approach involves identifying the cheapest locations for reducing carbon emissions for each REDD+ strategy and targeting these as priority areas for investment. Across Indonesia, avoiding additional deforestation on peat soils and minimizing forest degradation caused during log-harvesting (by employing RIL) are highly cost-effective opportunities for reducing emissions. This type of spatial analysis marks a crucial step forward in multi-disciplinary land-use planning in Indonesia. The outcomes of our analysis can guide the implementation of national and regional plans towards priority areas for combatting forest carbon loss cost-effectively through REDD+.

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