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Infrastructure development and contested forest governance threaten the Leuser Ecosystem, Indonesia

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ABSTRACT

The Leuser Ecosystem in northern Sumatra, Indonesia is a globally-significant landscape for biodiversity conservation and ecosystem services. It is however increasingly threatened by infrastructure development, enabled by discordant forest governance amongst central and regional governments. Here we identify these infrastructure threats and related shortcomings in forest management and conservation planning. Environment-development conflicts were mapped across the Leuser Ecosystem, in addition to unofficial and official roads as well as planned road, electrical generation, and electrical transmission developments. We find that conflicts concentrate in the Leuser Ecosystem, where many protected forests were formerly degraded and are now undergoing *de facto* conversion. Unofficial roads, not observed within government maps, were nearly double the length of official roads within the Leuser Ecosystem (6818 km vs 3597 km). Approximately half of all roads occurred in forests, particularly historically-exploited forests. Consequently, small forest patches and narrow forest corridors comprise 27% of the Leuser Ecosystem, and most are subject to ongoing degradation and conversion. We identify eight conservation priority areas where concentrations of road developments have produced particularly vulnerable forests. Planned infrastructure developments would directly impact these priority areas and bisect the Leuser Ecosystem, contradicting national conservation planning directives. These trends are framed by an assertive decentralisation by regional governments, aggravating the legal-administrative volatility surrounding the Leuser Ecosystem and empowering development interests. Such volatility is poised to become more common in Indonesia at a time of rapidly expanding development pressures within remaining natural environments.

1. Introduction

Deforestation in Sumatra is largely associated with prior forest degradation (Margono et al., 2012; Margono et al., 2014), as by agricultural incursions, forest extraction (Gaveau et al., 2014a; Linkie et al., 2014), and fires (Gaveau et al., 2014b; Sloan et al., 2017), much of which is illegal. Such trends reflect development pressures amidst poor spatial planning and law enforcement (Robertson and Van Schaik, 2001). Recently, Indonesia undertook reforms to 'rationalise' its forest management (Sloan et al., 2012; Sloan, 2014; Samadhi, 2013; Astuti and McGregor, 2015; Wibowo and Giessen, 2015). Yet the implications of these reforms remain uncertain where developmental pressures are acute (Wijedasa et al., in press). A case in point is the Leuser Ecosystem in Sumatra, a globally-significant conservation landscape (Le Saout et al., 2013) and the last habitat wherein orangutans, rhinoceros, elephants, and tigers co-occur (Fig. 1). The Leuser Ecosystem is subject to infrastructure development plans contested amongst central and regional governments while, in its most afflicted areas at least, nearly all forest destruction derives from breaches of environmental and planning laws (Tata et al., 2014). Here we assess current threats to the Leuser Ecosystem and highlight the governance challenges that play a pivotal role in its future.

Current threats to the Leuser Ecosystem (hereafter 'Leuser') center increasingly on infrastructure development. For instance, part of the Leuser is a World Heritage Site[1] (WHS) (Fig. 1) that has been listed as World Heritage in Danger since 2011 due to 'serious and specific' infrastructure threats (GOI, 2017). Indonesia has recently assured the UNESCO World Heritage Committee that there are no new road projects

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[1] The Tropical Rainforest Heritage of Sumatra, which encompasses forests within the Leuser Ecosystem as well as elsewhere in Sumatra.

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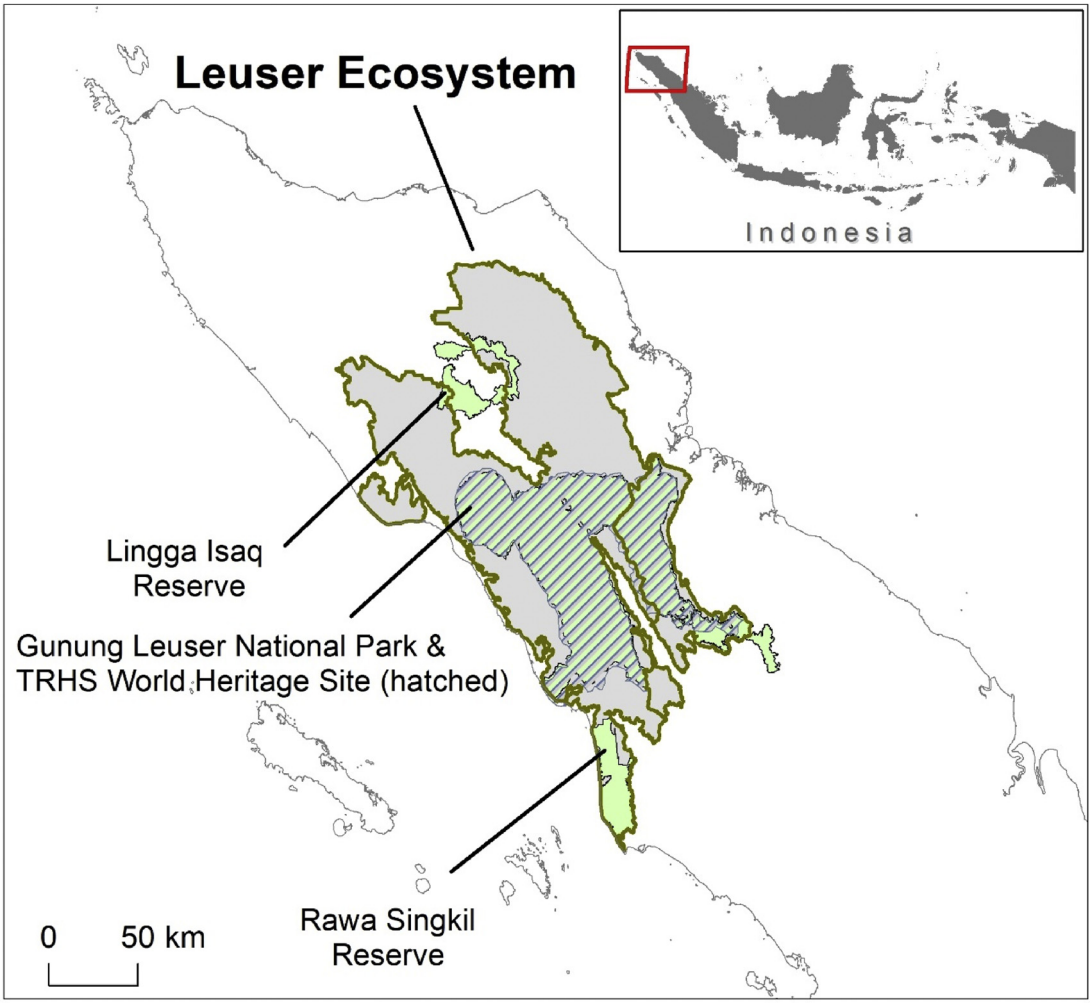

Fig. 1. The Leuser Ecosystem and its Protected Areas, Sumatra.
Note: 'TRHS' means Tropical Rainforest Heritage of Sumatra.

planned for the WHS, but ongoing road developments within the Leuser are still supported (GOI, 2017; Jong, 2017). A road-development proposal to bisect the WHS was recently stayed by the central government, but it is pending imminent reapplication by North Sumatra province. The 400-km Ladia Galaska road-expansion initiative facilitated smallholder agricultural encroachment into the Leuser along recently-built roads (Gaveau et al., 2009a). Meanwhile encroachment along older roads occurred in the adjacent Ulu Masen protected forest (Linkie et al., 2014). As detailed here, the Acehnese provincial government, which is responsible for the vast majority of the Leuser's area, recently planned an array of road and hydroelectric development projects (Hanafiah, 2017) that would fragment and degrade the Leuser Ecosystem.

The 2.6-million-hectare Leuser Ecosystem falls under two legal umbrellas for conservation, the role of which are increasingly uncertain for development planning in northern Sumatra. First, as in Indonesia generally, forests within the Leuser are designated for either conservation, protection, production, or conversion, affording decreasing degrees of protection (Brockhaus et al., 2012). These designations are often loosely enforced in Indonesia (Fuller et al., 2004), or have appeared as such where different levels of government have interpreted them differently (Samadhi, 2013). Production forest designations may protect against deforestation effectively where they are relatively inaccessible (Gaveau et al., 2009b; Gaveau et al., 2012; Gaveau et al., 2013; Santika and Meijaard, 2015), but they have also served as an 'overflow' designation for expansive cultivation and settlement (Potter and Lee, 1998), including within the Leuser (Eddy, 2015). Second, the Leuser is also relatively unique as a 'national strategic area' (NSA) for the protection of ecosystem services. NSAs broadly restrict infrastructure development and agricultural expansion to ensure ecological integrity. While clearly articulated in national legislation, the NSA status of the Leuser is increasingly ambiguous. In its latest spatial development plan, the Aceh provincial government failed to recognise the Leuser as a NSA and outlined countervailing infrastructure development plans. This has raised unresolved questions regarding the conservation status of the Leuser and the coherence of decentralised Indonesian forest governance.

The development pressures and challenges faced by the Leuser Ecosystem reflect those across Indonesia generally. Indonesia is pursuing six major road-development corridors to expand and consolidate estate agriculture (e.g. oil palm), timber extraction, mining, and international trade. These corridors are a priority for the central government and would traverse relatively remote, forested regions of Kalimantan, Papua, Sumatra, and Sulawesi, with investments of $14 billion USD (187 trillion Rp) for roadways alone in the former three regions (CMEA, 2011). The environmentally-judicious development of these corridors is contingent on the coherence of national and regional land-use plans and corresponding laws. The case of the Leuser suggests that this coherence remains elusive, while the history of Indonesian development suggests that the corridors may proceed in some form regardless.

This article observes conflicts between infrastructure development and environmental conservation across the Leuser in the context of contested forest governance. We present exhaustive maps of current

and planned infrastructure in the region, including many roads not included in official road maps, and consider these relative to forest-management plans. We also identify several conservation priority regions where planned developments will entail significant environmental impacts. The following preface summarises the history of contested forest governance within the Leuser. The article concludes with a discussion of implications for the broader development agenda in Indonesia.

2. The shifting management of the Leuser Ecosystem

The history of the Leuser is exemplary of how inconsistent forest management amongst central and regional governments has undermined conservation planning and enabled infrastructure development. The Leuser NSA arose from disparate conservation-and-development projects later consolidated by the central government. In the early 1990 s, the Leuser Development Programme (LDP) of the European Union commenced conservation-and-development activities to integrate multiple environmental protections enacted by previous Dutch and Indonesian governments. Initially focused on the Gunung Leuser National Park (Fig. 1), the LDP expanded to surrounding forests critical to sustaining endangered orangutan, elephant, tiger, and rhino populations (Rijksen and Meijaard, 1999: 137). By the late 1990 s, the central government, keen to protect LDP investments and assert its influence within the then-separatist Aceh province, consolidated the LDP expansion as watershed catchments. At the same time, the Leuser was legally recognised as the charge of both the central government and the LDP managing body[2] (Eddy, 2015) (Ministry of Forest Decree 227/KPTS-II/1995, Presidential Decree No. 33/1998).

With the cessation of separatist hostilities in over 2005, the Leuser became central to reformed, decentralised conservation planning. The central and Acehnese governments accorded the Law on the Governance of Aceh (LOGA, Law 11/2006) to establish norms of post-conflict governance. This law stipulated a protected, conserved, and sustainably-used Leuser as a condition of decentralised governance in Aceh (Article 150[1]). Aceh was tasked with the protection of the Leuser, while the central government was obliged to provide funding and facilities (Article 150[4]), though neither government would fully comply with its responsibilities. Immediately following the LOGA, the central government legally enacted NSAs as environmental planning priorities, and it counted the Leuser amongst them (law 26/2007, PP. 26/2008). Key to this legislation was its stipulation of *broad*, *holistic* landscape management practices to protect NSAs and subject developments therein to strict conditions. For example, Article 9[2] requires not only the cessation of 'spatial uses' (i.e., road development, agriculture) where these may reduce ecological function within the NSA, but also the minimisation of other spatial uses around NSAs that could have the same effect. For instance, it necessitates the limitation of infrastructure development within and around NSAs where such development might facilitate agricultural expansion. The central government retained the authority and obligation to formulate NSA management plans, though none were issued for the Leuser, opening the door to similar abdications by provincial authorities.

The role, if not the practical existence, of the Leuser NSA has come in question with the second Acehnese government since the 2006 Peace Accords. At the outset of its tenure, which spanned 2012-2017, this government disbanded the official provincial body overseeing the Leuser (BPKEL), sought the deferral of an anticipated Leuser spatial plan from the Indonesian Ministry of Public Works,[3] and pursued geothermal development within the WHS of the Leuser. Most significantly, the Acehnese government decreed a provincial spatial plan (Qanun 19/2013) that failed to recognise the Leuser as a NSA. Indeed, this plan pointedly references the 'adjustment of NSAs according to the needs and conditions of Aceh', and though it observes various economic or cultural NSAs in Aceh pursuant to national planning legislation, the Leuser does not count amongst them (Article 47[2]). The Indonesian Ministry of Home Affairs rejected the Acehnese plan on grounds that it violated the national planning laws on 28 counts, including its omission of the Leuser NSA, and demanded its revision within a specified period. The Acehnese government instead adopted its development plan *de jure*, aggravating the legal-administrative ambiguity surrounding the Leuser NSA. Meanwhile, the Ministry of Environment and Forestry approved redesignations of the Acehnese forest estate corresponding to the provincial spatial plan (e.g., MoEF, 2015a), seemingly in conflict with the Ministry of Home Affairs, further aggravating ambiguities. In this volatile context, an array of development proposals was put forth.

3. Methods

3.1. Environment-agriculture conflicts

The contested nature of developments within Aceh and North Sumatra provinces (northern Sumatra hereafter) reflects competition between development pressures and high-conservation value forests. It therefore follows that opportunities for rational planning depend on the consideration of both these factors. We identified 'conflict areas' in northern Sumatra where development would be relatively beneficial but entail relatively significant environmental losses. This was done by observing the areas with a coincidence of high environmental values and potential agro-economic benefits given further road infrastructure development, following the approach of Laurance et al. (2014). Our unique index of environmental values incorporates multiple regional factors pertaining to both ecological integrity and conservation urgency (Table 1), such that higher environmental values describe areas where ecological integrity supports conservation. Our index of agro-economic benefits reflects potential increased agricultural productivity facilitated by road development, specifically where productivity is low but agricultural activity and market access are high (Table 1).

To determine each index, the input factors (Table 1) were mapped for Sumatra, rescaled (0–1), and summed. Each index was subsequently categorised into deciles so that, when combined spatially, 100 'conflict' levels were delineated. Many input factors were complementary, and any localised collinearity amongst them served to highlight priority areas for regional planning. Since each index defines a conceptually broad or potential value, validations against an empirical reference were not possible, and conflicts are thus intuitive planning guides. Consultations with regional conservation organisations ensured that the indices recognised local planning and conservation priorities. All spatial data had spatial resolution of ~1 km. See the online supplement for further details.

3.2. Unofficial roads and forest segmentation

To identify infrastructure threats to the Leuser, we compared official maps of existing road infrastructure against road infrastructure independently mapped across the Leuser. Independent mapping identified 'unofficial' roads of ca. 2012–2016 via the visual interpretation and manual digitisation of high-resolution imagery in Google Earth. Unofficial roads are those not already mapped by the best-available, recently-updated 1:25,000 and 1:50,000 scale official road maps for the region (BIG, 2014). Unofficial roads frequently occurred in areas of forest incursion and agricultural activity, much of which is typically beyond the realm of (legal) official road planning and approval. A small fraction of unofficial occur within plantations that, where legal, are locally sanctioned yet privately developed. Logging roads in legal concessions are considered to occur rarely within the unofficial-road dataset because legal logging is not common within the Leuser, logging

[2] Namely, the Indonesia Leuser Institute.

[3] As stipulated in letter 650/42461 from Acehnese Governor Zaini Abdullah to the Indonesian Ministry of Public Works, dated 1 August 2013.

Table 1
Factors of Indices of Environmental Values and Potential Agro-Ecological Benefits.

Factor	*Description*	*Source*
Environmental Values		
Tree coverage	Percent canopy closure	MODIS imagery vegetation continuous fields product (Townshead et al., 2011)
Primary forest patch area	Proxy for intact forest contiguity	MODIS land-cover classification of Miettinen et al. (2016)
Biomass	Live vegetative aboveground biomass density	MODIS imagery calibrated with plot measures (Baccini et al., 2012)
Number of threatened species	Frequency of local intersection of species ranges for critically endangered, endangered, or vulnerable mammals and amphibians	Ranges according to IUCN (2016)
Rare-habitat extent	Local extensiveness of spatially-confined or locally-rare habitats. Given as the area of peatland, mangrove, or forest as a proportion of 20-km radial area centered on a pixel containing these habitats.	Land-cover classification of Miettinen et al. (2016).
Topographic slope	Proxy for watershed recharge and runoff mitigation	GMTED digital elevation model (Danielson and Gesch, 2011).
Protected-area status	Protected areas assume maximal values, reflecting their long-standing forest integrity and rare refuge for wildlife	IUCN and UNEP-WCMC (2015), and GFW (2017c)
Agro-Economic Benefit		
Agricultural yield gap	Difference between current agricultural production and the upper 75th percentile of potential production given local agro-ecological conditions	Laurance et al. (2014)
Local agricultural extent	Percentage area of pixels dedicated to agricultural or grazing	Foley et al. (2011)
Accessibility of urban markets	Travel time to urban centres of > 50,000 residents by road and/or water transport	Nelson (2008)

See the Supplementary Information for a discussion of these factors.

roads are quickly recovered by forest (where allowed), and some legal logging roads were observed in the official-road dataset. Nonetheless, the possibility that some unofficial roads are those merely omitted from the official dataset cannot be discounted entirely. Unofficial roads encompass all road types but exclude roads within settlements. A validation of the unofficial road data confirmed them to be both exhaustive and highly accurate (Text S2).

Regions increasingly separated from the contiguous extent of the Leuser were identified by prominent coincidences of road infrastructure (unofficial and official) and official non-forest or 'secondary' degraded/exploited forest covers (MoEF, 2015b). Non-forest land covers indicate where agricultural or infrastructure development has occurred and could be further sanctioned in the absence of NSA status. These non-forest land covers define the realm outside of the official Forest Estate and its corresponding forest-use designations. Areas of secondary forests indicate where road incursions have facilitated degradation and where forest redesignation or further developments leading to more intensive exploitation is most likely. These land use/covers were visually interpreted using Landsat 8 imagery at 1:25,000 and 1:50,000 scales (MoEF, 2015b). While a proportion of the official secondary-forest extent may contain primary forests, these two forest classes are also confused by independent satellite observations to varying degrees (Gaveau et al., 2014a; Miettinen et al., 2016). As such, the use of official forest classes, integral to the spatial planning in northern Sumatra, was considered the most insightful of all possibilities. The latest forest-use provincial zoning maps (MoEF, 2014, 2015a) were consulted to affirm non-forest covers as well as relatively restrictive conservation, protection, and production forest-use designations. (Conservation and protection forests prohibit exploitation and conversion, whereas production forests allow limited exploitation but not conversion). Landsat-derived maps of deforestation for 2000–2015 (Hansen et al. 2013; GFW, 2017b) were also consulted for the extents of these forest-use designations.

A morphological spatial pattern analysis (MSPA) was used to describe the spatial configurations of forest cover in the Leuser Ecosystem. This was achieved by segmenting Leuser forests into 'core' forest patches (≥ 1 km from patch edge), 'edge' forest (< 1 km from edge), 'fragment' forests (disjointed non-core patches), as well as forest corridors connecting either two core patches ('bridges'), a core patch to itself ('loops'), or a core patch to nothing ('branches'). Prominent concentrations of bridge and branch corridors flagged vulnerable areas of the Leuser, particularly when coincident with smaller core patches. For the MSPA, forest was defined as official primary and secondary dryland (mineral soil), peatland, and mangrove forest classes (MoEF, 2015b) at 250 m pixel resolution, excluding roaded pixels as well as oil-palm and pulp/paper plantations mapped by Transparent World and published by Global Forest Watch (GFW, 2017a). Soille and Vogt (2009) describe MSPA in detail.

3.3. Planned infrastructure development

To examine interactions between past and future developments that may compound threats to the integrity of the Leuser, plans for infrastructure developments were obtained from the Acehnese provincial planning office (*Bappedal*). Plans for various classes of roadways, electricity generation plants, hydro-electric flood zones, and electricity transmission lines were observed according to the 1:50,000 'structure maps' of the current provincial spatial plan (Qanun 19/2013). This spatial plan has been approved by the Acehnese parliament, and its features are variously scheduled or anticipated for near-term development or, in some instances, already under construction. Features were digitised directly into a GIS with a locational error of < 200 m relative to the structure maps. Planned roads were identified as those observed in the structure maps but not in the aforementioned official and unofficial road maps. Extensive discussions were also held with *Bappedal* officers to appreciate the ambitions, constraints, and precautions surrounding the planned developments.

4. Results

4.1. Planning conflicts and the Leuser Ecosystem

The Leuser Ecosystem area hosts the vast majority (80%) of the high environmental values (environmental value decile ≥ 8) observed in northern Sumatra. It also contains the areas of greatest conflict between high environmental values and high potential agricultural benefits (Fig. 2). These conflict areas concentrate in the northern Leuser, adjacent to Takengon City, a local epicentre of small-scale oil-palm production. High-conflict areas within the northern Leuser encompass the Lingga Isaq Game Reserve (~800 km^2) (Fig. 1) but largely occur

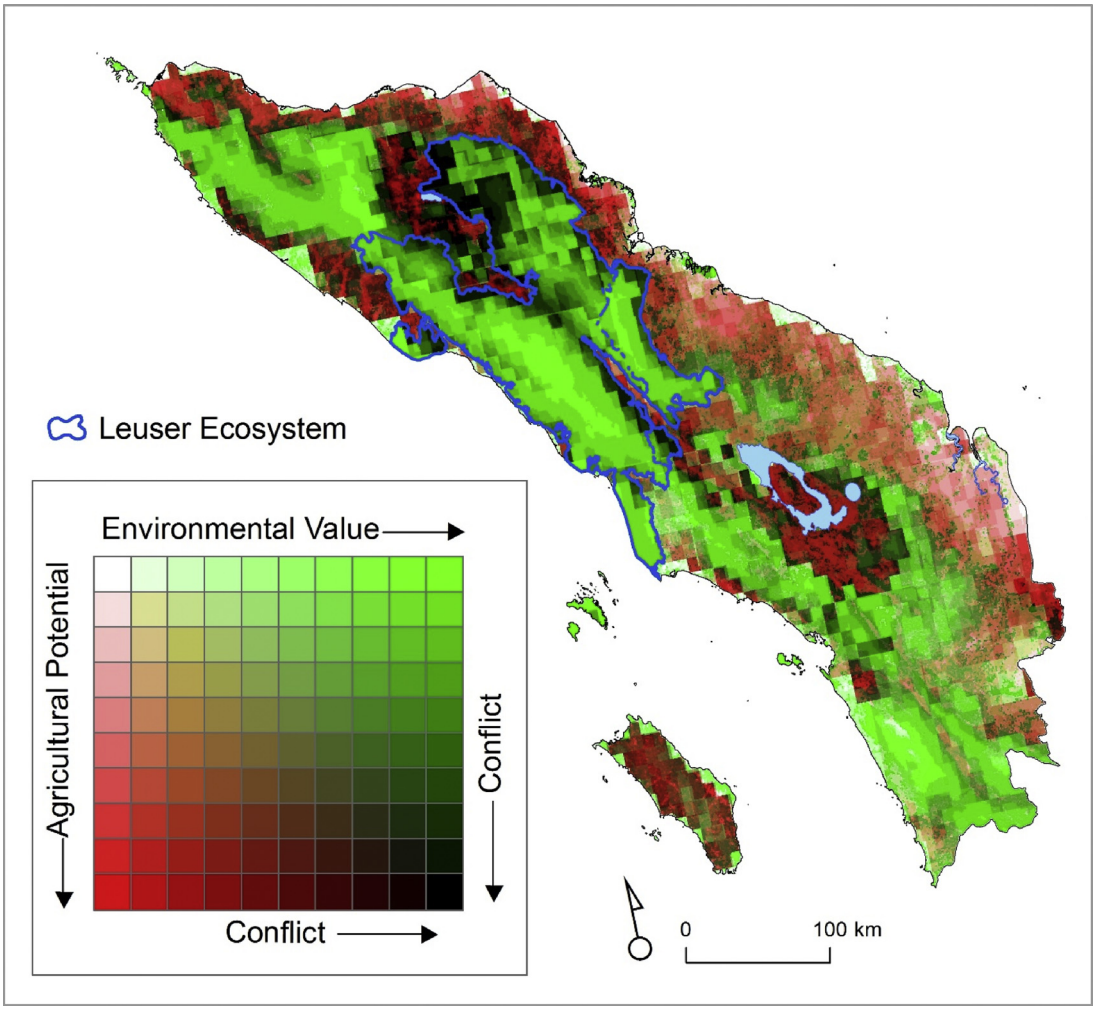

Fig. 2. Conflict between Environmental Values and Potential Agricultural Benefits Given Road Infrastructure Development in Northern Sumatra.

outside the reserve. High-conflict areas have comparable frequency in primary (intact) and secondary (exploited/degraded) forests zoned for permanent protection. Areas with the highest potential agricultural benefit and lower environmental value (where planned developments would ideally concentrate) are overwhelmingly mixed smallholder/oil-palm agricultural mosaic areas. In contrast, the more extensive zones of industrial oil-palm production along the Malacca Strait have far lower environmental values, and thus lower conflict values (Fig. 2).

The concentration of high-conflict areas within the Leuser is contrasted by the relative rarity of such conflicts regionally. Areas of greatest conflict – defined as the co-occurrence of environmental and potential-benefit index deciles of ≥9 – accounted for 9% of the Leuser but only 3% of northern Sumatra. In the Leuser and northern Sumatra, these areas of greatest conflict accounted for comparable proportions of the extent of environmental values with deciles ≥9, at 9% and 8%, respectively, reflecting the concentration of high environmental values in the Leuser. In these respects, the northern Sumatra region displays commonalities but also critical differences with the wider Sumatran context. Whereas northern Sumatra and the rest of Sumatra have comparable relative frequencies of conflict levels (Fig. 3), northern Sumatra is unique in that most of its conflict is concentrated within the Leuser.

The uneven distributions of conflict levels in northern Sumatra highlight a continuum of development pressures within degraded and relatively intact forest areas. the highest environmental values (deciles ≥9) across northern Sumatra coincide overwhelmingly with lower potential agricultural benefits given further road development, notwithstanding high levels of conflict inside the Leuser. Hence, the frequency distribution of conflict levels exhibits a strong negative skew at higher environmental values (Fig. 4 (grey bars)). This skew suggests that many areas with the highest environmental values enjoy passive protection due to inaccessibility or ruggedness. However, it also reflects the tendency for factors elevating potential agricultural benefits (Table 1) to gradually degrade environmental values. Accordingly, as greater potential agricultural benefits become relatively more frequent in an area, environmental values decline to moderate (deciles 7, 8) and lower (deciles 3–6) values and the frequency distribution of conflict levels becomes increasingly uniform and, ultimately, positively skewed (Fig. 4**)**. Partially degraded landscapes according to our environmental index are therefore relatively subject to further degradation and conversion according to our agricultural-benefit index. This is in keeping with tendencies for degraded forests to be progressively redesignated and converted, as has been observed in Indonesia (Margono et al., 2012; Margono et al., 2014).

The legal forest-function designations central to landscape planning in the Leuser do not reflect the distribution of conflicts. The relative frequencies of conflicts within production forests and protection/conservation forests[4] are virtually identical to each other for environmental values greater than the median (5) (Fig. 4). Higher environmental values in either designation are therefore equally subject to forces for

[4] Here we exclude the conversion-forest designation, since it accounts for only 1.4% of Northern Sumatra's forest cover. Protection and conservation designations are combined here because they equally prohibit forest use and conversion.

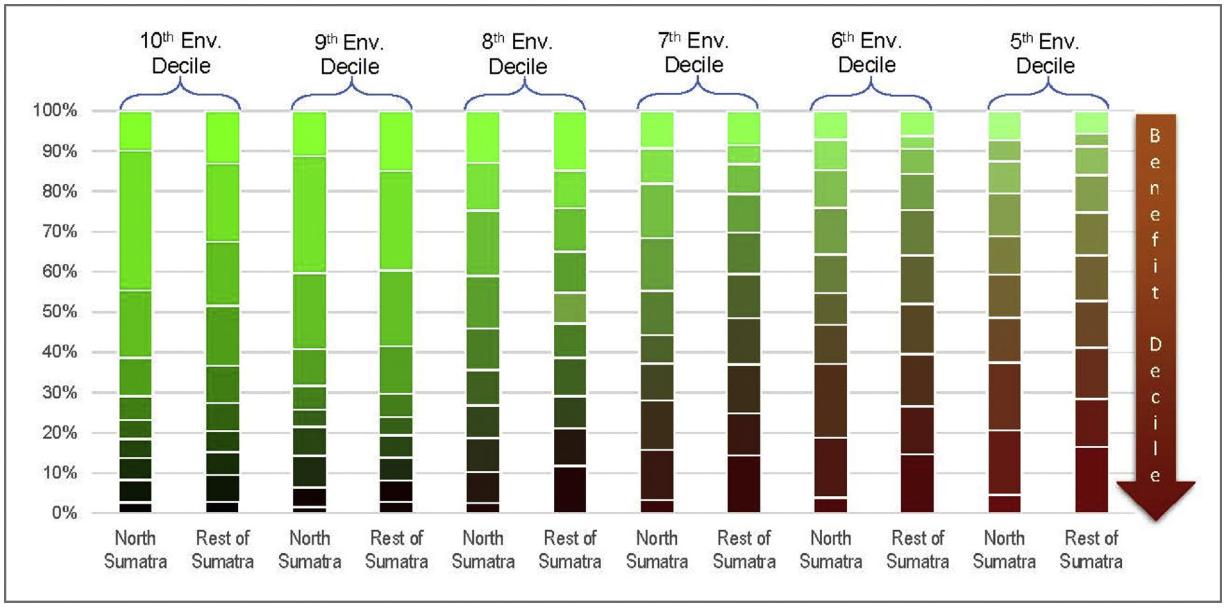

Fig. 3. Relative Frequency of Co-Occurrences of Environmental Values and Potential Agricultural Benefit Values, for Northern Sumatra and the Rest of Sumatra.
Note: Percentage values on the y-axis were calculated with respect to the total area of a given Environmental Value decile, per region.

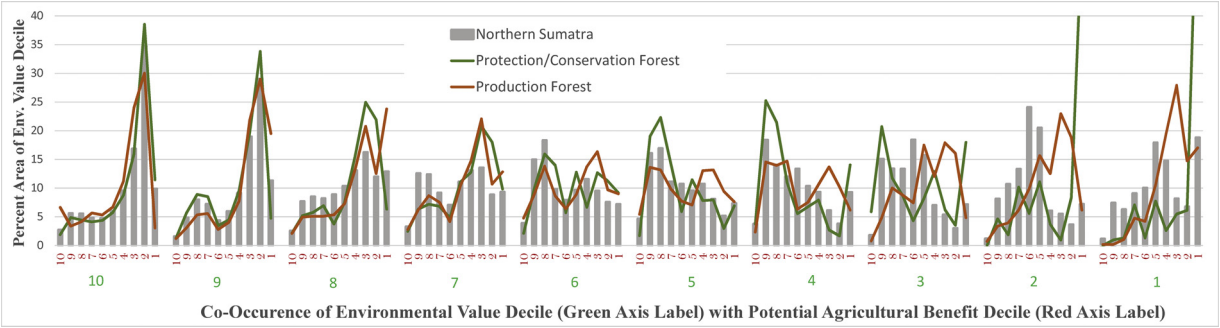

Fig. 4. Frequency Distribution of Environmental Values and Potential Agricultural Benefit, for Northern Sumatra and Forest-Use Designations.
Notes: Percentages on the y-axis are with respect to the total areas of each Environmental Value decile, defined separately for northern Sumatra, Protection/Conservation Forests, and Production Forests.
Source: Legal forest designation according to MoEF (2014, 2015a).

forest destruction, on average. In light of the similarity of deforestation rates between these two forest designations after controlling for accessibility (Gaveau et al., 2009b; Gaveau et al., 2012), this observation affirms the practical equivalence of these designations in terms of ensuring forest integrity where forests are well managed. In practice, however, forest management has not ensured comparable levels of forest integrity amongst these forest designations, as illustrated below.

4.2. Roads and the segmentation of the Leuser Ecosystem

The Leuser is more roaded than indicated by the official data, particularly in secondary forests. The length of unofficial roads within the Leuser is nearly double that of official roads, at 6818 km and 3597 km, respectively. Both unofficial and official roads are largely confined to non-forest covers (65% and 49% of lengths, respectively). As a proportion of total length, each road class occurs comparably between the 'secondary' exploited/degraded forests fringing the Leuser (14%, 26%) and the Leuser's primary-forest 'interior' (20%, 25%) (Fig. 5a). Road densities are however 5–10 fold greater in secondary forests than in primary forests (depending on the road class) with unofficial road densities being also double those of official roads in secondary forests (Table 2). Roads in primary forests have variable and uncertain statuses but resemble incursions in many instances – for example, where spilling over from adjacent secondary-forests designations widely converted to mosaic agriculture in Langkat District, or where emanating from the central agricultural Alas valley bisecting the Leuser. Unofficial roads in the Leuser concentrate where official roads were relatively sparse, suggesting that spatial planning generally under-estimated the scale and the locations of human activities across the Leuser.

Reflecting the above, production forests fringing the Leuser and buffering its interior have not reliably resulted in the intended sustainable forest management. A total of 1119 km^2 of production forests flank ~175 km of the southeast perimeter of the WHS within the Leuser. Of this flanking forest, 30% has been converted to oil palm, rising to 69% for those confined within the official Leuser boundary (356 km^2 total) (Fig. S13). Moreover, this oil palm production and associated deforestation has extended ~65 km^2 into the WHS (Figs. 5a and S13). Within Leuser production forests, nearly 10% of the area within 1 km of this designation's boundary was deforested over the period 2000–2015, compared to 6% and 2% at 1–2 km and 2–3 km distance intervals, respectively (Table S1). These measures increased only marginally upon confining these observations to areas of production forests within three km of roads since virtually all Leuser production forests are already extensively roaded (Table S1). Comparable deforestation intensities also occur along a ~100 km stretch of the WHS and adjacent protection forests, west of the *Kutacane Tigabinaga*

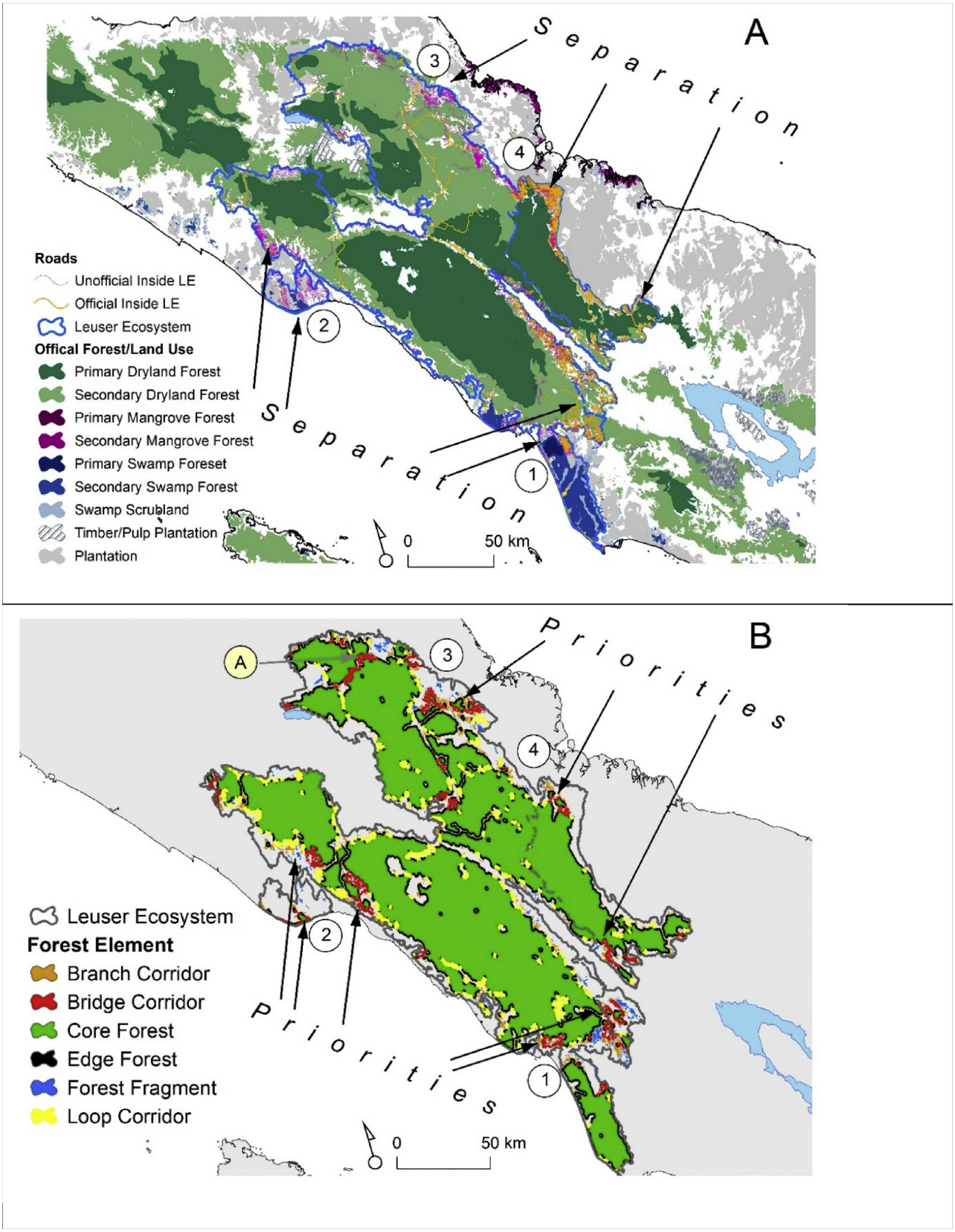

Fig. 5. The Segmentation of Forest Cover in the Leuser Ecosystem as Represented by (a) Concentrations of Roads Coincident with Non-Forest or Secondary-Forest Covers, and (b) Forest Corridors, Patches, and Core Fragments.
Source: Select official forest/land use classes after MoEF (2015b), with supplemental plantations from GFW (2017a). Notes: Readers are encouraged to 'zoom in' to the online version of this figure. Sites: (1) Singkil peatswamp, (2) Tripa peatswamp and nearby mineral-soil forests, (3) East Aceh District, (4) boundary of Aceh Tamiang and North Sumatra districts. Site A in panel B pertains to bridge corridors spanning a major river, not an existing road, and therefore does not constitute a conservation priority per se. However, this site is pending separation from the Leuser due to planned road and hydroelectric developments (Fig. 6).

Table 2
Road Densities in the Leuser Ecosystem by Road Class and Forest Designation.

	Primary Forest		Secondary Forest	
	Official Roads	*Unofficial Roads*	*Official Roads*	*Unofficial Roads*
Road Density (km /100 km^2 Forest)	0.9	1.0	4.5	9.3
Road Length (km)	99.2	111.4	446.2	917.2

access road (Fig. S13). Much of this area was degraded during the early 2000s (Margono et al., 2014) and is now designated as non-forest lands (MoEF, 2015b). Production forests outside the Leuser in northern Sumatra are more extensive and generally less affected but suffer similar incursions.

Four main epicentres of roads coincident with non-forest and/or secondary-forest covers are apparent in the Leuser (Fig. 5a**)**. These epicentres are: (1) the Singkil peat swamp and surrounds; (2) the Tripa peat swamp and surrounds, and; areas currently or recently zoned as 'production forest' in (3) Each Aceh district as well as (4) along the boundary of Aceh Tamiang and North Sumatra districts. The Singkil peat swamp and surrounds are increasingly host to oil palm and non-forest designations, such that roads and agriculture separate extensive peat forests from the greater Leuser area. The Tripa swamp and surrounds have largely been converted to oil palm and zoned as non-forest (Tata et al., 2014), but isolated primary peat forests and orangutans remain. The production forests of East Aceh, Aceh Tamiang and North Sumatra are widely fragmented by oil palm and small-scale agriculture. The epicentres coincide with high-conflict areas (Fig. 2), excepting the Singkil epicentre, which pertains to an acute segmentation of the Leuser rather than a broader overlap of environmental values and agricultural incursions.

A finer-scale fragmentation of Leuser forests by human activities around the epicentres is illustrated by the analysis of forest segmentation. According to the MSPA, only 78% of the total Leuser area is forested (Fig. 5b). Most of this forest occurs within one of eight very large core-forest fragments. The free movement of larger threatened fauna between these fragments is likely to be restricted or precluded in some instances by intervening infrastructure and land uses. Some 27% of the total Leuser forest extent is in the form of non-core forest, e.g., forest corridors and small patches. Eight priority areas for conservation and spatial planning relevant to forest connectivity are identified by prominent concentrations of forest 'bridge' corridors and non-core patches coincident with the epicentres of human activity described above (Fig. 5b). In the worst-case scenario in which all 39 bridge corridors in the Leuser were 'cut' by future developments, 41 newly isolated core-forest fragments totalling 119 km^2 would result. Many of these fragments would lose their 'core' status as the loss of corridors would critically diminish 'buffers' surrounding the fragments. Some 15% of the area of bridge corridors and 46% of patches in the Leuser are zoned as 'non-forest' (Table 3), raising the likelihood of their conversion in the absence of NSA status. The proportions of the areas of forest bridges and patches subject to conversion rise markedly to 68% and 85%, respectively, when considering the extent of both non-forest areas and production forests buffered by 1-km (Table 3), being the extent previously identified as consistent with *de facto* forest incursion and conversion.

4.3. Planned developments in the Leuser Ecosystem

Planned infrastructure developments across the Leuser coincide with all high-conflict areas (Fig. 2**)** and six of the eight identified priority conservation areas (Fig. 5b). Foremost amongst these planned developments is a major north-south highway coincident with the aforementioned agricultural incursions west of the *Kutacane Tigabinaga* access road in the central Alas valley (Figs. 6 and S13). This highway would transect areas with the highest environmental index values regionally (Fig. 2). It would also cut the last forest corridors (notably within the WHS) connecting the eastern and western hemispheres of the Leuser. Moreover, if this highway were developed, it would bisect the Leuser and known habitat ranges of threatened tigers (Dinerstein et al., 2007), orangutans (Wich et al., 2008; Wich et al., 2011; Wich et al., 2016), elephants (Leimgruber et al., 2003), and possibly rhinoceros (unknown as range data are restricted to prevent poaching). This planned highway is additional to 99 km of roads planned within the Leuser, just north of epicentres no. 1 and 3 (Fig. 6).

Seven planned hydroelectric generation sites and four planned geothermal sites fall inside or on the border of the Leuser. Of the hydroelectric sites, two have been approved for construction (Tampur [a.k.a. Gayo Lues], at 428 MW; and Kluet, at 141 MW) (Fig. 6). A third hydroelectric site is pending an approval decision (Jamboaye, at 246 MW) and would entail a 9763-ha reservoir providing irrigation for agricultural expansion around Takengon City, a factor contributing to the planning conflicts observed above (Fig. 2). The 76 km of associated electrical lines for the Kluet hydroelectric project that fall within the Leuser would transect the northern 'bottleneck' of the Singkil peat swamp forests at development epicentre 1 and further cut any remaining corridors connecting these peatlands to the contiguous Leuser (Fig. 6). Transmission lines for the Jamboaye hydroelectric project (69 km in Leuser Ecosystem), in conjunction with planned roads just north of epicentre 3, would separate a 590 km^2 core forest area from the contiguous Leuser (Site A in Fig. 5b). Transmission lines extending from a planned diesel electric generation plant (97 km in Leuser Ecosystem), parallel to the proposed highway and existing *Kutacane Tigabinaga* access road, would transect the southern and eastern edges of the WHS coincident with important forest corridors (5b and 6).

The Kappi geothermal project (220 MW potentially) was recently proposed for development within the Gunung Leuser National Park / World Heritage Site, with the support of the previous Aceh government.

Table 3
Occurrence of Forest Elements by Land-Use Zone in the Leuser Ecosystem.

Forest Element	*Area (km^2)*	*% Area Zoned as 'Non-Forest'*	*% Area Zoned as 'Production Forest'*	*% Area Zoned as 'Non-Forest' or 'Production Forest', with 1-km Buffer*
Core Forest	15,130	0.5	6.5	10.8
Fragment	251	47.4	21.0	85.3
Edge Forest	2521	7.4	15.4	46.2
Loop Corridor	1386	12.0	16.6	47.5
Bridge Corridor	855	14.7	35.5	68.0
Branch Corridor	685	29.7	24.5	76.0

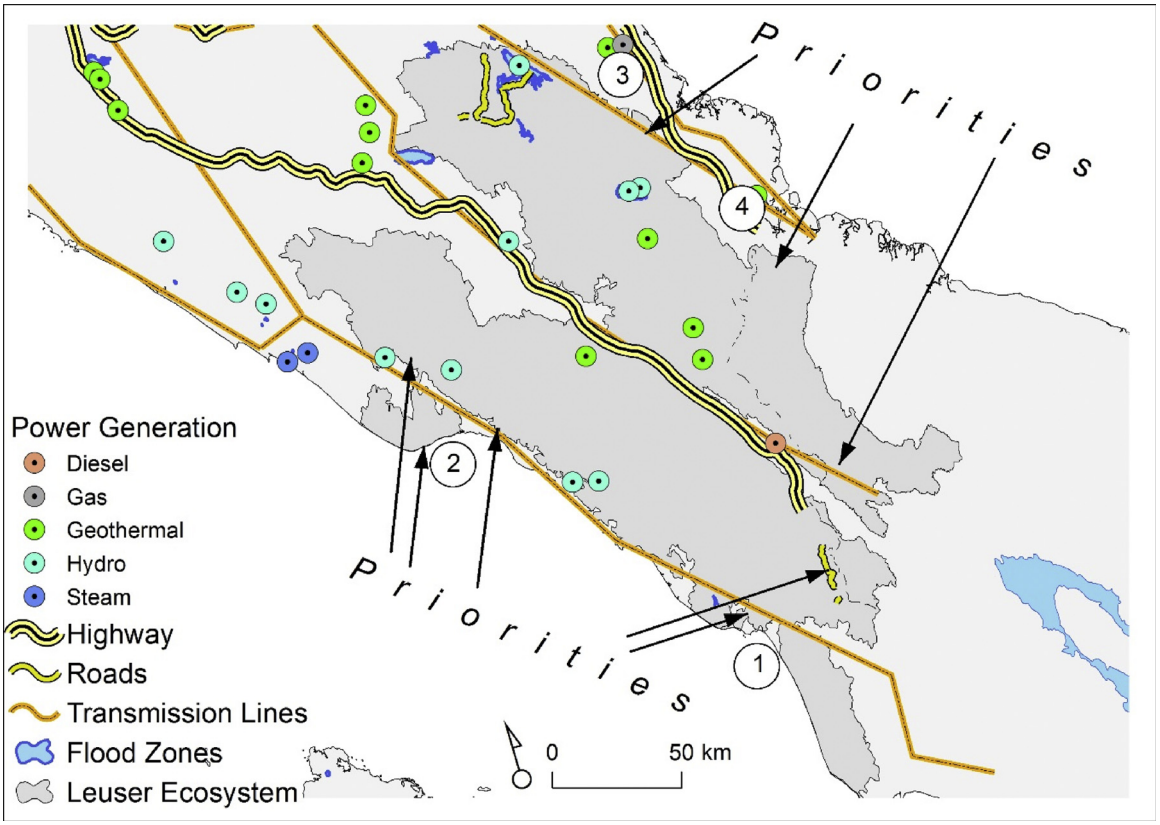

Fig. 6. Planned Infrastructure Developments in the Leuser Ecosystem.

This development would entail the re-designation of 8000 ha of primary forest to 'multi-use' lands. The Ministry of Environment and Forestry, which manages the park, rejected the proposal in late 2016 (Satriastanti, 2016), and the central government later affirmed this position (GOI, 2017), as did Aceh's recently elected governor. The development proponents have since refocused on geothermal sites in Central Aceh and Bener Meriah districts, just beyond the western limits of the Leuser (Fig. 6). Negotiations continue between these proponents and the Government of Aceh, which now supports their request for permits from the Ministry of Energy and Mineral Resources (Richter, 2018).

5. Discussion

5.1. Implications for conservation

Infrastructure development in northern Sumatra is increasingly contentious as its flagship conservation landscape – the Leuser NSA – has been implicitly re-negotiated in the context of decentralising governance. This article observed a concentration of planning conflicts between environmental integrity and agricultural development pressures within the Leuser. It further observes a synergy between these conflicts, past forest incursions, and planned infrastructure developments. The segmentation of the Leuser by earlier road incursions and developments defined eight conservation priority areas not identified by earlier surveys of forest degradation (Margono et al., 2014). Most of the priority conservation areas are directly threatened by planned infrastructure developments. If fully realised, these developments would significantly fragment one of Asia's last remaining wildlands and the only habitat in which threatened orangutans, elephants, rhinoceros and tigers co-occur (Leimgruber et al., 2003; Wibisono et al., 2011; Wich et al., 2016). Revised conservation planning is required to prevent such an outcome.

The integrity and standing of the Leuser Ecosystem was undermined by the uneasy co-existence of its NSA status and Indonesia's predominant forest designation regime. Whereas NSAs prioritise whole-of-ecosystem integrity, the forest designation regime is orientated towards piecemeal forest allocation and exploitation (Brockhaus et al., 2012). Environment-agricultural conflicts were comparable between forests designated for conservation/protection and those designated for production, consistent with observations elsewhere in Indonesia (Gaveau et al., 2012; Gaveau et al., 2013; Santika and Meijaard, 2015). Within the Leuser NSA, this comparability recommends an equivalent, conservation-oriented management of these forest designations to ensure enduring forest integrity. In contrast, both past and planned infrastructure developments in the Leuser concentrate disproportionately in historically-exploited 'secondary' forests, as did (apparently) illegal deforestation in production forests. A long-term perspective outlines a sequence of forest incursion, degradation, conversion and, finally, the consolidation of developments around infrastructure at the expense of regional forest integrity.

The lack of recognition of 'ecosystem' as a legal conservation-management unit is a contributing factor to this forest-conversion sequence in the Leuser (Eddy, 2015). An interim measure for the Leuser NSA would be to elevate all forests to conservation or protection status, including forest corridors within 'non-forest' development zones. Such designations would matter little where enforcement is lacking, however. Ecosystem restoration licenses, which are increasingly promoted in Indonesia, may also provide limited support for larger forest ecosystems. Restoration licences are commercial permits to restore degraded production forests to natural states, potentially entailing the sale of ecosystem services, ecotourism, and non-timber forest products (Walsh et al., 2012; Buergin, 2016; Enrici and Hubacek, 2018). While these licenses may unify larger forest areas, they are still based on discrete forest concessions, meaning they must be applied piecemeal across a larger area of production forest. The issuance of restoration

licenses would preclude licensed areas from being elevated to protection/conservation status, but concessionaires would likely prove more effective at preventing further incursions and restoring forests than provincial authorities have to date.

5.2. Conservation, development and decentralised governance

In the Leuser, the convergence of planned developments with earlier forest incursions recalls well-known sequences of forest degradation, redesignation, and conversion (World Bank, 2006: 28). In many respects, such planned developments and forest redesignations often merely 'catch up' with past incursions, consolidating them in the process. The case of the Leuser may foreshadow similar dynamics elsewhere in Indonesia. The Indonesian road network has expanded by 49% over 2000–2014 as central and provincial governments have sought greater economic integration with each other and the world (MoPW, 2017). This rate of expansion is likely greater upon accounting for local roads poorly surveyed by official statistics, as demonstrated here. Indonesia's development 'master plan' for 2011–2025 seeks to support this integration via major transportation/development corridors spanning each of its major islands (CMEA, 2011). For Kalimantan and Papua especially, these corridors would traverse relatively remote, forested regions. Recent movements towards greater decentralisation, typified by the Acehnese posture, raise the spectre of local 'elite capture' of these growth corridors and their associated timber, agricultural, and mineral revenues where the central government is unable to 'check' regional development plans (Persha and Andersson, 2014).

Recent developments in Indonesia's decentralised governance foreshadow a more assertive decentralisation less hindered by national planning and conservation directives. Over 2015–2016, the Ministry of Home Affairs revoked 3134 provincial-level and district-level decrees (including the Acehnese development plan) to reconcile them with national laws and streamline planning and investment (Jakarta Post, 2017; Paath, 2017). This followed the re-centralisation of power in Jakarta regarding provincial land-use plans, budgets, and laws (Ribot et al., 2006; Luttrell et al., 2014; Sahide et al., 2016), as well as regional grievances over arguably politically-motivated charges by the central government concerning 'illegal' forest management (McCarthy, 2010). In this context, these revocations by the Ministry provoked a backlash by the Indonesian Regional Government Association (APKASI) leading to an unprecedented 2017 Constitutional Court decision annulling the Ministry's right to revoke local-level laws (Jakarta Post, 2017; Paath, 2017). In effect, the Acehnese scenario, in which a provincial development plan that violates a legally-sanctioned national conservation landscape was nonetheless retained and implemented as *regionally* valid, may become more common.

The replication of such assertive decentralisation holds significant implications for conservation planning. For instance, the Merauke Integrated Food and Energy Estate (MIFEE) mega-project[5] in semi-autonomous Papua province (MoPW, 2010; Ginting and Pye, 2011) has slowed due to concerns over the ability of provincial spatial planning to target or, indeed, identify 'idle' or 'degraded' frontier lands in an otherwise forested conservation region (Brockhaus et al., 2012; Yulisman, 2015). The MIFEE mega-project is integral to the planned trans-Papuan development corridor (CMEA, 2011; Ito et al., 2014), so much so that it is unlikely that concerns over ineffectual spatial planning alone will halt the mega-project. Ironically, but in keeping with the history of decentralised Indonesian forest management, the ruling by the Constitutional Court to annul the Ministry's right to revoke local-level laws may accentuate, rather than resolve, volatilities surrounding regional planning. Inconsistent laws and plans between Indonesia's central and regional governments are now reconcilable only via legal review by the Supreme Court, which has typically handled only a handful of cases annually. Consequently, as in northern Sumatra, inconsistencies and uncertainties are likely to persist at the ambiguous 'limits of legality' (McCarthy, 2004, 2010), finding resolution through the informal alignments and assertions of powerful interests.

[5] The MIFEEE project would establish 1.6 million hectares of biofuel, oil palm, and food crops in Papua province.

6. Conclusion

Longstanding challenges to forest governance in Indonesia were aggravated by the recent assertive decentralisation by Aceh province, undermining the Leuser's NSA designation. Contradictory positions within, and failures of, the central government exacerbated this situation. Amidst this volatility, an array of legally dubious infrastructure development plans gained *de jure* legitimacy. These plans would consolidate and extend past forest incursions, some of which appear illegal, appreciably degrading the ecological integrity of the Leuser Ecosystem. To avoid this outcome, we urge that (i) the central government promulgate its overdue management plans for the Leuser NSA; (ii) relevant provincial and district-level governments align their own management plans, including by recognising the NSA status of the Leuser Ecosystem, thus precluding or mitigating the planned infrastructure developments; (iii) intervened production forests within the NSA be restored and/or elevated to forest designations ensuring greater protections, accompanied by greater enforcement, potentially entailing the reinstatement of an independent oversight body for the Leuser Ecosystem.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.landusepol.2018.05.043.

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