Opportunities and Challenges for an Indonesian Forest Monitoring Network

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Key Message:

Permanent Sampling Plots (PSPs) are a powerful and reliable methodology to help our understanding of the diversity and dynamics of tropical forests. Based on the current inventory of PSPs in Indonesia, there is high potential to establish a long-term collaborative forest monitoring network. Whilst there are challenges to initiating such a network there are also innumerable benefits to help us understand and better conserve these exceptionally diverse ecosystems.

Keywords: tropical forests, carbon, data-sharing, dynamics, monitoring

List of abbreviations: NFI = (Indonesian) National Forest Inventory, PSP = permanent sampling plot, REDD+ = Reducing Emissions from Deforestation and forest Degradation

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1. Why monitoring tropical forests is important

Tropical forests are arguably the most important terrestrial ecosystems. Whilst occupying around 15 % of the global land area, tropical forests store two-thirds of all the carbon in terrestrial vegetation (Pan et al. 2013) and are the most important above-ground terrestrial carbon sink (Beer et al. 2010; Pan et al. 2011; Soepadmo 1993). They house half the world's biodiversity and provide a wide range of goods, including sources of new medicines, and ecosystem services including clean and sustained water supplies, climate regulation and pollinators for crops (Cámara-Leret et al. 2016; Ghazoul 2015; Peters et al. 1989; Ricketts et al. 2004). If suitably managed, tropical forests can provide economic benefits through ecotourism, non-timber forest products, a sustainable source of timber, and through carbon financing mechanisms for developing tropical countries such as REDD+. Therefore, understanding where, how and why the world's tropical forests are changing is a key question of global importance (Hansen et al. 2013; Pan et al. 2011).

The periods over which trees establish, grow and die (tens to hundreds of years) do not make for rapid experimental tests of forest functioning. Instead, direct measurements of stands of trees over long time periods are essential to truly understand forest processes and dynamics (Lutz 2015). Permanent sample plots (PSPs) in which all trees are marked, identified and repeatedly measured provide a series of direct observations on forest condition, dynamics and change over time. As longitudinal data sets, PSPs offer an excellent opportunity to study forest dynamics, and to separate short-term environmental impacts, such as drought, from long-term trends (Condit 1998). A forest monitoring network is a series of PSPs using a consistent protocol - such networks allow an assessment of numerous aspects of forest ecology, including biodiversity, biomass (analogous to carbon stocks), regeneration, dynamics (including succession) and 'health'. Furthermore, forest monitoring networks distributed along large geographical and environmental gradients allow testing for the generality of factors controlling ecosystem functioning with increased statistical power (Craine et al. 2007) and allow space-for-time analyses to project potential impacts of global changes on forests.

Numerous high-impact studies based on PSPs as the fundamental measurement unit have greatly advanced our understanding of the function, biodiversity and evolution of tropical forests. For example, PSPs have provided clear evidence that the tropical forest above-ground carbon stock has been increasing over time (Lewis et al. 2009; Pan et al. 2011; Qie et al. 2017) but that the sink strength into this stock appears to be declining, at least in Amazonia (Breinen et al. 2015). The above studies were conducted in 'undisturbed', i.e. primary, forests but a major proportion of tropical forests have been disturbed by human activities. Fewer PSP networks have been established to study forest recovery from logging (Rutishauser et al. 2015; Sist et al. 2014) or from shifting cultivation (Chazdon et al. 2016) yet they are also providing valuable data. Furthermore, PSPs contribute vital datasets to improve our still poor understanding of patterns in tropical tree species richness (Slik et al. 2015; ter Steege et al. 2013), biogeography (Slik et al. 2018) and evolution (Baker et al. 2014) at multiple scales. Field data collected on the ground from biogeographically well-replicated PSPs is also a prerequisite to calibrate remotely-sensed biomass mapping (e.g. Asner et al. 2010; Avitabile et al. 2016; Réjou-Méchain et al. 2014).

Permanent Sample Plots are a standard method but can be supplemented by biodiversity observing networks such as the transect approach of the Asia-Pacific Biodiversity Observation Network (Yahara et al. 2012, 2014). Larger PSPs (~50 ha), such as those established by the Centre for Tropical Forest Science (CTFS, now ForestGEO), play an important role in furthering our understanding of community ecological patterns as they monitor a larger number of smaller (≥1 cm dbh) trees over bigger areas. In contrast, smaller PSPs (usually 1 ha), such as those established by the Amazon Forest Inventory Network (RAINFOR) and the Indonesian National Forest Inventory (see section 2) offer extensive coverage that is more appropriate for a regional-scale forest monitoring network.

2. Opportunities from permanent sample plots in Indonesia

Indonesia has the third largest area of tropical forest globally (following Brazil and D.R. Congo; FAO 2015) including some of the largest extents of carbon-dense peat swamp forests. However, as with other regions of the world, Indonesia's forests are undergoing rapid change and anthropogenic disturbance (Abood et al. 2014; Gaveau et al. 2014) and around half the country's land area currently supports primary forest (Kementerian Lingkungan Hidup dan Kehutanan 2015b; Margono et al. 2014). The forests of western Indonesia are highly productive and the dominant trees, the dipterocarps (Brearley et al. 2016), have been favoured as commercial timber trees for many years leading to the majority of accessible forests being brought into timber production. By contrast, the forests of eastern Indonesia (especially Papua) contain few dipterocarps and remain more intact owing to the rugged topography and isolation. More recent challenges include droughts and fires associated with El Niño that have had marked impacts upon forest functioning (Page & Hooijer 2016; Slik 2004) and increasing forest fragmentation (Qie et al. 2017), yet large-scale analyses that test for such impacts across Indonesian forests are largely absent.

Numerous PSPs have been established across Indonesia over the last c. 60 years but not all have been maintained continuously. The earliest PSPs were established during the late Dutch colonial era, but they were mostly in plantation forests to study tree growth and timber yield (Hart 1928; Von

Wulfing 1938). Among the first PSPs established in primary forest was the 1-ha plot set-up by Willem Meijer (1959) to study the ecology of Gunung Gede's montane forests. Since then, PSPs have played an important role in silvicultural research such as the STREK (Silvicultural Techniques for the Regeneration of Logged-over Forest in East Kalimantan) project (Bertault & Kadir 1998). The Indonesian National Forest Inventory (NFI) is a national program initiated by the Indonesia Ministry of Forestry in 1989 (and implemented by the Directorate General of Forestry Planning) utilizing PSPs. Through this program, PSPs were established systematically with a 20 x 20 km grid across forested areas in Indonesia (< 1000 m above sea level) with the primary objective to monitor the growth of timber stocks. In total, 2735 1-ha PSPs were established, although not all have been monitored on more than one occasion (Kementerian Kehutanan 1996). Depending on the location, the NFI plots were not necessarily located in logging concessions but all logging companies were required to establish PSPs for monitoring growth and yield. In addition to monitoring timber growth and yield, data from these PSPs has provided a basis for estimating carbon stocks and changes associated with land-use change and forest management activities (Kementerian Lingkungan Hidup dan Kehutanan 2016; Krisnawati et al. 2014, 2015).

Despite the large-scale coverage of Indonesia's NFI, the limited scientific access NFI offers to its data and the few large-scale analyses that have resulted from the NFI's dataset limit our understanding of the composition and functioning of Indonesia's tropical forests. Given the current threats to Indonesia's forests, it is important that Indonesian and foreign scientists collaborate, with a consolidated scientist-led forest monitoring network having the flexibility to address ecological questions in a democratised and collaborative fashion, to jointly establish PSPs and analyse large datasets spanning Indonesia's forests. To date, at least 150 ha of PSPs (besides those in the NFI) have been established in primary forest, and are still maintained, in Indonesia (Table 1; Figures 1a & 2). Although these PSPs have different sizes, re-measurement intervals and measurement protocols making direct comparisons challenging, they offer a starting point for developing an Indonesian forest monitoring network with a standardised protocol. The density of sampling across the whole of Indonesia is only about 3.4 ha of plots per 10^6 ha of primary forest and there are clear differences in sampling density between different geographical regions (Table 1). The highest density (ratio of plot area to primary forest area) of PSPs, by an order of magnitude, is found in Java and Bali (Table 1). Although the total area of PSPs is modest, the area of primary forest remaining is particularly low on these islands leading to an overall very high sampling density. Of the outer islands, Kalimantan has a high density of sampling – likely due to this being the centre of production forest logging activity coupled with interest in its exceptional biodiversity since the times of early colonial explorers. Sumatra has a similar sampling density and has also been heavily exploited for timber in the past. Maluku also has a high sampling density but this is largely confined to Seram only. Sulawesi and Nusa Tenggara have sampling densities comparable to the mean for the whole of Indonesia (although note that there are only 2.5 ha of plots in Nusa Tenggara). Sampling density for Papua is, by far, the lowest among the Indonesian islands; this is partly due to the large remaining area of forest combined with difficulties in establishing PSPs in areas with challenging access. Of these PSPs, nearly half have been measured on more than one occasion, thereby markedly increasing their value for assessing forest functioning, with the median monitoring period for those measured more than once being 8 years and the longest being 50 years (Fig. 2b). About half of the plots that have been measured on more than one occasion are in Kalimantan (e.g. Qie et al. 2017) so the total monitoring effort (plot area x monitoring length) at around 1300 ha years is an order of magnitude greater than Java + Bali, Maluku, Sulawesi or Sumatra; none of the PSPs in Nusa Tenggara or Papua have been re-measured (Fig. 2c). In addition, there are over 100 ha of PSPs in disturbed forest (Fig. 1b); many of these are forests that have been logged; in this case, the geographical foci are Kalimantan and Sumatra that have historically been important for timber and, secondarily, in Papua where logging activities are currently expanding.

From the brief analysis above, it is clear that key geographical gaps exist mainly in eastern Indonesia particularly for Maluku (excepting Seram), Nusa Tenggara and Papua. In terms of climate, many areas of drier forest are under-represented (e.g. Timor), as is montane forest and forest over edaphic variants (such as *kerangas* or ultramafic geology). There are some PSPs found in peat swamp forests but many have been burnt or otherwise disturbed in recent years.

3. Challenges facing an Indonesian forest monitoring network

3.1 Methods

Our aim here is not to provide a protocol or critique of methods for PSPs as this has been done in previous work (Alder & Synott 1992; Burslem & Ledo 2015; Condit 1998; Ledo 2015; Phillips et al. 2016; Sheil 1995) but to note concerns with particular relevance to the Indonesian situation.

Plot size: Too many PSPs reported in the Indonesian literature are simply too small to provide a generalisation of the area they study. Small plots (e.g. 0.04 ha) might be useful when installed in a series (e.g. 25) to provide data on forest biodiversity that does not require accurate scaling-up to larger areas. However, for a more in-depth assessment of forest biodiversity, the larger the area sampled, the greater the number of species captured due to a large number of rare species (Plotkin et al. 2000). Of the PSPs noted in our analysis, the median size is 0.25 ha whilst the most frequently sized plot is 1 ha (Figure 2a), which is comparable to forest monitoring networks on other continents

(Brienen et al. 2015; Lewis et al. 2009; Phillips et al. 2009, 2016). Small plots cannot accurately predict forest biomass when scaled-up to a larger area due to a high edge:interior ratio that elevates the relative importance of marginal boundary decisions (Burslem & Ledo 2015), a high coefficient of variation between plots, and the likelihood they will not represent all forest stages (e.g. gap, building and mature, sensu Whitmore 1998). Calibration of remote sensing data for large-scale forest biomass mapping is more accurate if the PSPs can be ground-truthed accurately, which also requires larger plots (Avitabile et al. 2016; Réjou-Méchain et al. 2015). Finally, small plots are also prone to the 'majestic effect' where researchers may unconsciously select pristine forest with 'majestic' large trees and avoid disturbed areas (Sheil 1995).

Frequency of measurement: Whilst the definition of a PSP is that trees will be re-measured at some point in time, re-measurement intervals are not always regular. A typical re-measurement interval is five years as this allows increases in tree size to be seen more easily. Whilst intervals of four to ten years are appropriate for most recording purposes of PSPs (Sheil 1995), an increasing census period leads to a greater likelihood of unobserved growth and therefore an underestimation of forest productivity (Talbot et al. 2014). In cases of annual censuses, this will allow much better predictions of forest dynamics in relation to annual climate fluctuations (Clark et al. 2010). Dendrometer bands are a possible inexpensive alternative to increase measurement frequency (Anemaet & Middleton 2013), but require much greater time investment at installation; such bands can also avoid errors due to changes of the point of measurement. Of course, regularity of re-measurement depends upon plot security and accessibility, and funding is a key determinant of frequency of fieldwork activities (see section 3.3).

Parameters measured: Trunk diameter at breast height (usually 1.3 m) is the key parameter measured as this can be incorporated into allometric equations to estimate tree and stand biomass (Chave et al. 2014); including tree height and crown size has been shown to increase accuracy of such equations (Goodman et al. 2014). This is especially needed for dipterocarps that show different architectural patterns compared to other tropical trees (i.e. taller for a given diameter: Banin et al. 2012). Forests in Indonesia cover not only a wide range of soil and climatic types both within and across islands, but also represent a great biogeographical range. Due to variable architectures that require local height-diameter models for accurate biomass calculation, tree height data collected within plots are extremely useful to improve biomass estimates (Ledo et al. 2016; Sullivan et al. 2018).

3.2 Taxonomy

For assessment of species distributions and monitoring, accurate taxonomy, comparable among plots, is paramount. Good taxonomy is clearly challenging as PSPs often contain a large proportion of sterile individuals. Indonesia is fortunate in having a large and well-maintained national herbarium (Herbarium Bogoriense; BO) and a number of regional herbaria but many PSP investigators do not routinely collect voucher specimens but rely on vernacular names instead. Taxonomy takes on extra importance in a forest monitoring network where the aim is to make comparisons among plots, but technological advances have a key role to play here (Baker et al. 2017; Webb et al. 2010). While some Indonesian tree genera are reasonably well known, for example the commercially important dipterocarps (Ashton 2004) many large genera such as *Syzygium* (Myrtaceae) and *Diospyros* (Ebenaceae) have not been monographed. Similarly, digitization of herbarium sheets at BO is ongoing but progress remains slow.

Vouchers for morphotypes can be made available across sites permitting analysis of distribution of taxa without any formal species names, but obtaining the species name increases the value of the voucher. Challenges for the taxonomy of PSP trees must be taken seriously, and we recommend the following: i) make physical voucher collections of several specimens for each morphotype especially where variation appears to be high and collect silica gel-dried samples for subsequent DNA barcoding; ii) carry out routine visits to PSPs to collect fertile specimens as they become available; iii) take high-quality photographs of the fresh vouchers (Webb et al. 2010) and share images and metadata online; iv) cross-match vouchers and images across different sites to both validate formal species name and provide distribution information; v) avoid the use of vernacular names, except as an early step in the determination process yet value the experience of parataxonomists in the field and technicians in herbaria; and vi) publish details of how taxon names were acquired, and give a level of confidence in each formal name. Overall, it is far more useful to publish voucher collection codes, images, morphotype codes and matches of morphotypes to images at other sites than to simply list a botanical name with no additional information. Detailed primary data will also greatly assist taxonomic specialists in the future as they work on the large, complex genera of Indonesian trees.

3.3 Funding

Funding presents a perennial challenge for forest ecological work, particularly in developing countries. Within Indonesia, PSP censuses are not considered as applied research, which receive priority for funding, although NFI plots have been allocated governmental funding. Current funding opportunities through the development of the Indonesian Science Fund (DIPI) and via the UK Newton Fund are positive in this regard. There is also the potential for knowledge-exchange partnerships with logging companies who may fund PSPs in their concessions although, as funders, they may consider themselves data owners (see section 3.4). REDD+ programmes bring similar opportunities for knowledge exchange and funding (Gibbs et al. 2007). Longer-term collaborations between Indonesian researchers, companies and NGOs coupled with leading international expertise are needed. Importantly, PSPs need to be locally owned, and international funding should be invested for pump-priming and capacity-building in order to stimulate long-term funding input from Indonesian sources into tropical forest monitoring.

3.4 Data-sharing

Developing an integrated picture on changes in forest functioning and biodiversity across a forest monitoring network requires the willingness to share data among researchers. Nevertheless, data-sharing can present various challenges. There are a number of data-sharing models in tropical ecology, ranging from the informal to the formal with rigid data-sharing arrangements such as ForestPlots (López-González et al. 2011). What is shared can vary from whole plot data to only the numbers required for a particular analysis. Issues over intellectual property are of considerable concern and unwillingness to share data is often linked to concerns about the loss of control over such data and the lack of professional recognition or reward (Enke et al. 2012; Fecher et al. 2015). Furthermore, clarifying who is the 'owner' of data is essential. In some cases, the funder (often a logging company) may claim ownership, in others, such as the Indonesian NFI, public access to the data is limited. Any forest monitoring network needs clear guidelines on the sharing, use and publication of shared data and an obvious reward system for sharing (i.e. co-authorship).

Although in-country data owners will regularly be included as co-authors in large-scale data analyses, the lead authors have almost always been researchers from extra-tropical countries. Echoing the sentiments of Ruslandi et al. (2014), we note that simply 'out-sourcing' data analysis to extra-tropical researchers is still far from the goal of building local research capacity. Lack of institutional support and incentive may deter tropical scientists from becoming leading authors, but this appears to be changing lately with Indonesian institutions increasingly rewarding staff publishing in international journals. Investing in capacity-building and knowledge exchange to support Indonesian scientists to take leadership roles in agenda setting is also important in the medium term.

3.5 Land tenure and community engagement

Once a series of PSPs has been established it is important to maintain a commitment to re-measure plots and obtain funding to do so. However, the location and accessibility of plots needs to be considered for long-term measurements. Ideally, plot locations should not be too remote to make accessibility challenging and not too close to settlements put plots at risk from disturbances. If new

PSPs are installed, there should be secure land tenure (Soraya 2011) to offer protection from land-use change and fire risk – particularly in peat swamp forests (Page & Hooijer 2016). Of the PSPs noted (Table 1; Figures 1 & 2), less than half are within formally protected areas (e.g. National Parks or Nature Reserves); of those that are not, the presence of researchers may help in protecting them to some degree (Laurance 2013). In areas where forest land-use classifications may jeopardise studies, it may be possible to re-designate land classifications (e.g. Kawasan Hutan Dengan Tujuan Khusus or 'Special Use Forests'). Local stakeholder engagement is key, and local communities should be considered as valuable collaborators who value the presence of PSPs and can be employed to collect good quality data (Theilade et al. 2015). There are multiple opportunities for synergies between local communities, logging companies and scientists, with NGOs often in a strong position to act as facilitators. Still, unless direct payments to forest owners are established for missed opportunities of economic development, communities may well continue to prefer the economic benefits offered by logging companies over those from researchers or conservationists (Novotny 2010).

4. Translating results from PSPs to forest policy and conservation

Quantification and assessment of carbon stocks in forests underpins international policies to mitigate carbon dioxide emissions such as the REDD+ program (Gibbs et al. 2007) and the recommendations of the Intergovernmental Panel on Climate Change (Watson et al. 2000). For example, Indonesia's forest reference emission level submitted to United Nations Framework Convention on Climate Change (Kementerian Lingkungan Hidup dan Kehutanan 2015a, refined in 2016) utilized NFI data as the primary source to generate information on carbon stocks (and thus emissions from forest change).

It is essential to understand not only carbon stocks in tropical forests through time but also the response of tropical forest to climate change and develop policies accordingly. Information from PSPs will allow us to determine whether Indonesian forests are sinks or sources of carbon and have the potential to help us understand the factors driving carbon stock changes. To derive national policies, information from PSPs needs to be combined with data on land use and land-use change, which is accessible through remote sensing data or national inventories.

In addition, tropical forests are also key repositories of global biodiversity, genetic resources and important ecosystem services for local communities. Reducing biodiversity loss is a target of the United Nations Convention on Biological Diversity (Pereira et al. 2013) which is not only relevant from an aesthetic point of view, but can also threaten ecosystem functioning (Duffy 2009). Permanent sample plot data will foster a better understanding of the autecology, distribution and rarity of tree species and they also have the potential to obtain measures of biodiversity of various taxonomic groups at multiple scales and to link the abundances of each of these with one another. All of the above are needed to enhance Indonesia's conservation planning efforts and manage forests in a way that allows biodiversity to flourish in this exceptionally biodiverse country.

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Table 1. Areas of forested land and sampled by permanent sample plots (PSPs) in primary forest (excluding the National Forest Inventory) on major islands of Indonesia. Data on land and forest area taken from Kementerian Lingkungan Hidup dan Kehutanan (2015b).

Island(s)	**Land area** (10^6 ha)	**Total forested area** (10^6 ha)	**Primary forest area** (10^6 ha)	**Total PSP area** (ha)	**PSP/forest area ratio****
Java (+ Bali)	13.95	3.37	0.08	9.0	113.0
Sumatra	47.16	14.07	4.49	38.0	8.5
Kalimantan	52.96	27.58	9.80	82.1	8.4
Sulawesi	18.53	9.47	3.91	12.3	3.1
Nusa Tenggara*	6.76	2.84	0.68	2.5	3.7
Maluku	7.77	5.11	0.96	12.3	12.8
Papua	40.79	34.06	26.15	2.0	0.1
Total	**187.92**	**96.50**	**46.07**	**158.1**	**3.4**

* Excluding Bali, which is included with Java due to their biogeographical affinity.

** Area of permanent sampling plots (ha) per 10^6 ha of primary forest.

Figure 1. (a) Locations of primary forest and (b) primary and disturbed permanent sampling plots (PSPs) in Indonesia (excluding the National Forest Inventory).

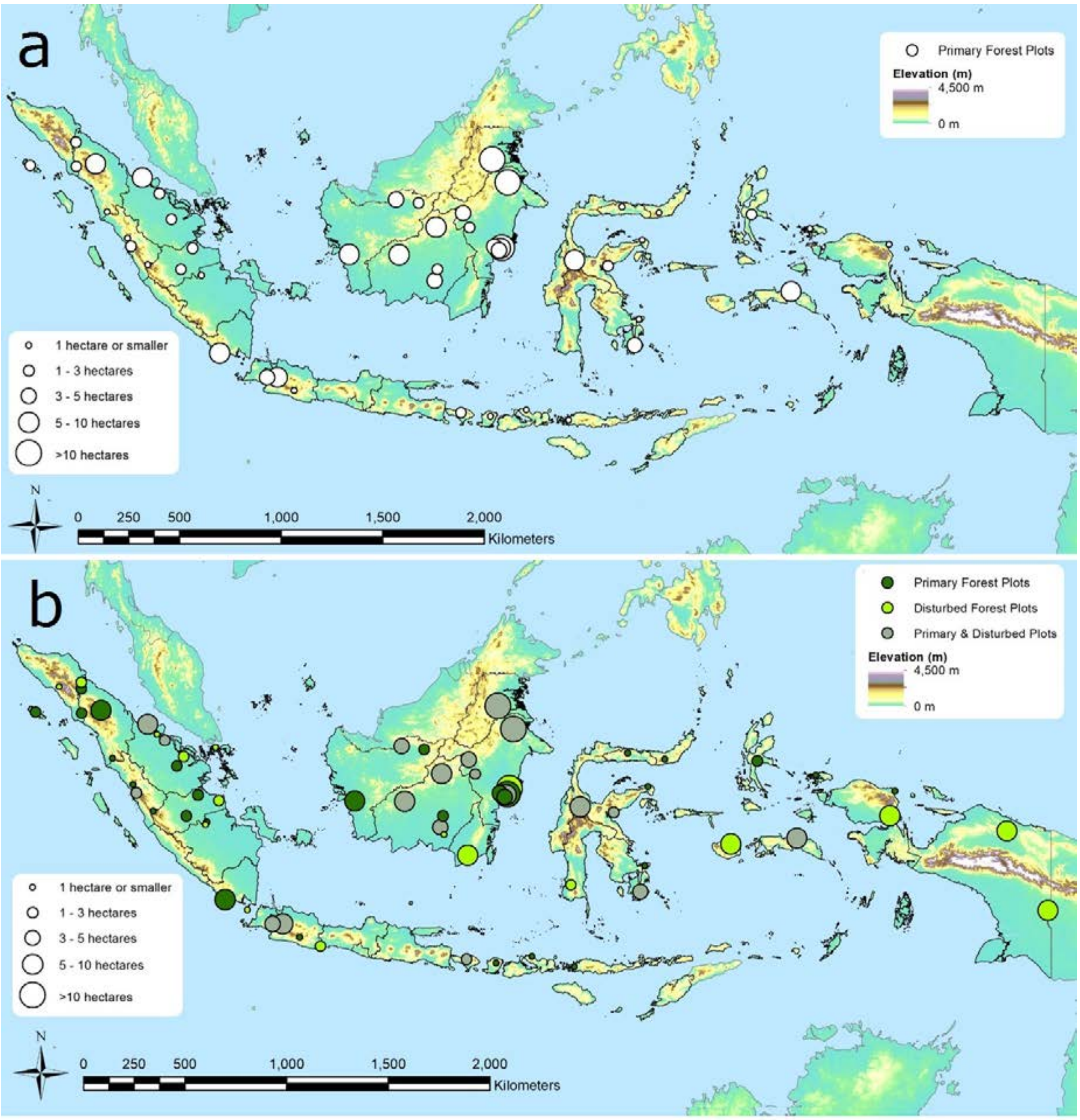

Figure 2. (a) Plot areas, (b) total plot area under different lengths of monitoring and (c) total monitoring effort (i.e. sum of area multiplied by monitoring length for each plot) for permanent sample plots (PSPs) in primary forest (excluding the National Forest Inventory) on major islands of Indonesia. Note that plots only measured once are given a monitoring length of one year and also note the logarithmic scale for panel (c).