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Assessing relatedness and redundancy of forest monitoring and change indicators

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Information on changes in forest structure and composition is required for informed, adaptive management and conservation. As the collection of such information requires field studies that are expensive, difficult, and time consuming, the prioritization of metrics can be of significant value. This study evaluates a number of metrics used to assess changes in forest structure and composition for a set of 59 forests in five countries – Kenya, India, Nepal, Uganda and USA. Changes in tree density are significantly positively correlated with changes in species richness, and changes in sapling/shrub density are significantly positively correlated with changes in species richness. Thus, rapid assessments of tree density change can be used to prioritize locations where there may be rapid deterioration in tree diversity, where the collection of detailed information on changes in species composition may be prioritized. Changes in tree density do not reflect changes in shrub and sapling density. The shrub and sapling layer appears to respond differently to human or natural disturbances compared to the tree layer, and may require separate assessment. Changes in tree DBH and tree height are not completely congruent, indicating that measurements of DBH and height may be required to accurately estimate changes in above ground carbon storage over time, for programs such as REDD that provide payment for carbon sequestration services.

1. Introduction

Effective knowledge of where and how forests are changing is essential for management and conservation. In contrast to forest clearing, now routinely assessed using remote sensing (Achard et al., 2002; Nagendra and Rocchini, 2008), changes in forest structure and composition are difficult to detect without in depth field studies, repeated over time (Peres et al., 2006; Sasaki and Putz, 2009; Southworth and Nagendra, 2010). Generating such data is time consuming, expensive, and often challenging in the field, yet monitoring fine scale changes in forest structure and composition is critical in order to assess forest management strategies (Folke et al., 2002; Ostrom, 2005; Karna et al., 2010).

For efficient assessment, it is important to carefully select a set of metrics that provide information about different aspects of forest change that can provide insights for forest management (Tucker et al., 2008; DeFries et al., 2010). Permanent plots are ideally suited to the study of changes in forest biodiversity, density and biomass (Phillips et al., 2008), but establishing permanent plots is expensive, time consuming and requires the availability of trained personnel (Hoolck, 2008). Thus, there are relatively few locations worldwide where permanent forest plots have been established. Many studies of forest change instead rely on random forest plots within the same forest, yet distributed across different locations at different points in time (Ostrom and Nagendra, 2006; Tucker et al., 2008).

What do these assessments measure? Despite the substantial body of literature on ecological measurement of forest structure and composition, the goals of conservation change from location to location, and the indices to use remain in debate (Nordling, 2009). Changes in forest structure and composition can occur due to natural causes, or be induced by humans or indeed, a combination of the two, but such changes need to be recognized and adequately addressed with the overall purpose of forest conservation and management. Much recent research has focused on carbon, but some scholars caution that this can lead to changes in biodiversity being overlooked or ignored (Harvey et al., 2010; Sasaki and Putz, 2009; Strassburg et al., 2010). Other research demonstrates that our understanding of how forest disturbance impacts forest structure and composition can change depending on the metric of forest change that is used. For instance, Prasad (2009) finds that proximity to roads influences the amount of dead trees in a dry tropical forest, but there are no significant differences in tree

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Table 1
Description of study forests.

Country	India	Kenya	Nepal	Uganda	USA
Number of forests	7	7	20	21	4
Forest size (ha) – average and standard deviation	458 ± 250	80 ± 76	89 ± 65	297 ± 220	163 ± 218
Sampling intensity (plots/ha)	0.15	0.63	0.61	0.27	0.53
Standing tree density (/ha) – average and standard deviation	263 ± 160	217 ± 167	345 ± 316	216 ± 168	371 ± 163
Tree species richness (per plot) – average and standard deviation	4.4 ± 2.4	3 ± 2.1	2.9 ± 2.3	4.3 ± 3.3	4.7 ± 1.8
Plant species richness – tree, shrub and sapling (per plot) – average and standard deviation	6 ± 2.8	4.1 ± 2.4	4.8 ± 3.3	6.1 ± 4.1	5.5 ± 2.1
Time between visits	5 years	3–9 years	3–9 years	3–8 years	4–6 years
Forest types	Dry tropical deciduous	Tropical evergreen, deciduous, dry deciduous	Tropical evergreen, deciduous	Tropical evergreen, deciduous, dry deciduous	Temperate forests
Management regimes	Government Forests and co-managed Joint Forest Management areas	Government Forests and Protected Areas	Government Forests, Community Forests, and Protected Areas	Government Forests, Protected Areas, and Private Forests	Intentional community forests[a]

[a] Intentional community forests include a wide diversity of self-organized local forests in the United States, some organized as condominiums with part of the land jointly managed with common access and use, others as cooperatives, or as developments with homes on private land and joint ownership of and responsibility for the surrounding forest.

composition of the surviving trees, while Nagendra et al. (2010) find that proximity to settlements inside a tiger reserve impacts regeneration, while mature trees seem relatively unaffected. Similarly, Ghate et al. (2009), while assessing differences in three community-managed forest locations, find that the forest with the greatest tree density is quite low in sapling density, indicating that human impacts have taken a particularly severe toll on regeneration in this forest.

It is expensive and challenging to measure all parameters in all forests. The objective of this paper is to evaluate whether there is redundancy in assessments of change provided by different metrics of forest structure and composition for a number of forests in different ecological regimes. This will provide inputs for efficient design of forest monitoring protocols, in order to collect data required for conservation planning and forest management while maximizing returns on investment (Grantham et al., 2008).

In this paper, I draw on a dataset of 59 forests in five countries, collected by the International Forestry Resources and Institutions (IFRI) Research Program. The IFRI program is a unique long term multicountry study of institutions and forests, using a standardized set of data collection protocols across multiple countries (Ostrom and Nagendra, 2006; Tucker et al., 2008; Persha et al., 2011). This program provides one of the largest available datasets on forests and users from different parts of the world, and provides a unique opportunity to conduct such comparative, cross-forest research in a variety of human-impacted forests located in different institutional, ecological and socio-economic conditions (Persha et al., 2011).

2. Methods

The International Forestry Resources and Institutions Research Program is a multicountry effort to assess how human institutions impact forest change, initiated in 1992 at Indiana University, and now coordinated by the University of Michigan. The IFRI program has been applied in diverse forests located in a range of ecosystems and countries (Chhatre and Agrawal, 2008). More details about IFRI are available at www.sitemaker.umich.edu/ifri/.

In order to assess changes in forests for the study discussed in this paper, this analysis focuses on a subset of IFRI forests for which data were available from at least two visits at different points in time. I selected forests from five countries – India, Nepal, Kenya, Uganda, and the USA – for which over time forest plot data was available for multiple forests within a country. Some of these forests had data from more than two visits – I selected the most recent visits for which complete information was available. A total of 59 forests were selected for analysis – 7 forests each in India and Kenya, 20 in Nepal, 21 in Uganda, and 4 in the USA. As Table 1 indicates, these forests cover a range of forest types, forest sizes, and management regimes. All forests are "working" forests (Zarin, 2004), with some level of human use ranging from relatively low impact activities such as recreation, to more intensive uses such as timber and firewood extraction, collection of non-timber forest products, grazing and charcoal production. Management approaches differ widely, from a complete absence of active management in some forests, to tree plantation and protection from grazing, timber and firewood extraction through fencing, monitoring and/or sanctioning. Although these forests were not selected randomly or in a manner representative of different biomes or forest types, they nevertheless represent a variety of locations in five geographically distributed countries, and provide a unique, fairly large dataset that can be very useful to assess common metrics of forest change.

At each time point, aspects of forest structure and composition were assessed using randomly distributed circular plots of 10 m radius, within which plant species' identity, height, and girth were recorded for all trees greater than 10 cm diameter at breast height (DBH). Within this, a central circular plot of 3 m radius was used to collect information on saplings and shrubs between 10 cm and 2.5 cm DBH. Between 20 and 60 random plots were located in each forest, depending on the size of the forest patch being studied and the biodiversity and variation in the patch.

Six indicators of forest change were computed for each forest – 1) changes in tree density 2) changes in tree species richness 3) changes in sapling/shrub density 4) changes in sapling/shrub species richness 5) changes in tree DBH and 6) changes in tree height. For each plot, I calculated the number of trees (tree density), number of species of trees (tree species richness), number of shrubs and saplings (shrub/sapling density) and number of species of shrubs and saplings (shrub/sapling species richness). Changes in tree DBH and height were assessed using data on individual trees, and were not based on per plot computations of basal area or volume, in order to enable assessment of changes in tree size independent of density.

As the distribution of these metrics did not fit a standard normal distribution (as noted in other studies as well, Kohyama and Hara,

Table 2
Comparison of pairs of forest change indicators.

Metrics of forest change	Spearman *r*	Significance	Percentage of forests where both metrics provide the same assessment of forest change based	Percentage of forests where there is partial disagreement in assessments of forest change, with only one metric indicating significant change	Percentage of forests where the two metrics provide different assessments of forest change, with one metric indicating a significant increase while the other indicates a significant decrease in the measured parameter
Tree density vs tree species richness	0.84	$p < 0.00001$	83.1%	16.9%	0%
Sapling/shrub density vs sapling/shrub species richness	0.85	$p < 0.00001$	89.8%	10.2%	0%
Tree density vs sapling/shrub density	0.24	$p > 0.10$	44.1%	49.1%	6.8%
Tree species richness vs sapling/shrub species richness	0.39	$p < 0.05$			
Tree density vs tree DBH	−0.35	$p < 0.05$	28.8%	40.7%	30.5%
Tree DBH vs tree height	0.38	$p < 0.05$	52.5%	35.6%	11.9%

1989), a nonparametric one-tailed Mann–Whitney *U* test ($p < 0.10$) was used to identify forests with a significant decrease or increase in parameters of forest structure and composition, and those with no significant discernable change (Sokal and Rohlf, 1981). Similarly, for all trees from each forest, changes in DBH and height over time were evaluated using the Mann–Whitney *U* test to look for significant changes. Cronbach's alpha assessed the degree of internal consistency between assessments of forest change provided by different indicators (Morgan, 2004). A Spearman rank correlation was computed to assess the degree and significance of association between specific pairs of variables.

Pairwise comparisons of assessments of change were used to look for redundancies between assessments provided by different metrics. If two metrics provided identical assessments of change, then these were categorized as "Agreements". If the assessments were diametrically opposite, with one metric indicating a significant decrease (e.g. in tree density), for instance, while another metric indicated a significant increase (e.g. in sapling density), then these were categorized as "Disagreements". In instances where one metric indicated significant change (increase or decrease), while the second metric did not indicate any significant change in forest structure or composition, these were categorized as "Partial Disagreements". Table 2 focuses on 5 pairwise comparisons of indicators of particular interest to studies of forest change, assessing their agreement using a nonparametric Spearman rank correlation, with a Bonferroni adjustment (Sokal and Rohlf, 1981). The Supplementary Table provides the full details of assessments of change based on the set of six metrics of forest structure and composition, separated by country.

3. Results

There is substantial variation between assessments of forest change provided by different indicators of forest structure and composition, with a Cronbach's alpha of 0.46 (Morgan, 2004). Assessments based on changes in tree density, tree species richness and DBH change do not indicate any strong directional trends toward increase or decrease in these parameters, while changes in sapling and shrub density and species richness indicate an overall trend toward decrease (Fig. 1). An overall decrease in tree height is also observed – this could be due to selective felling of tall trees, or due to an increase in the number of young, short trees.

Changes in tree density are highly correlated with changes in tree species richness (Spearman *r* 0.84, $p < 0.00001$). Partial disagreements are observed in only 17% of forests, with no instances of complete disagreement (Fig. 2). Changes in density and richness for shrubs and saplings are also strongly correlated (Spearman *r* 0.85, $p < 0.00001$).

Changes in the density of trees are not significantly correlated with changes in the density of shrubs and saplings (Spearman *r* 0.24, $p > 0.1$). These assessments agree in only 44% of forests (Fig. 3). Changes in tree density are negatively correlated with changes in tree DBH (Spearman *r* −0.35, $p < 0.05$). Assessments of change in tree DBH and tree height are also significantly correlated (Spearman *r* 0.38, $p < 0.05$), but with disagreement in 12% of forest assessments (Fig. 4). This disagreement is not confined to a specific country, but varies across locations from different countries (Supplementary Table). Overall, no consistent patterns of difference in metrics of change were observed for different countries.

4. Discussion

Changes in tree density are widely used to indicate changes in forest structure and composition locally (Tucker et al., 2008; Karna et al., 2010; Nagendra et al., 2010), and globally (FAO, 2006). Collecting data on forest density is easy to do through approaches ranging from field assessments to high resolution satellite remote

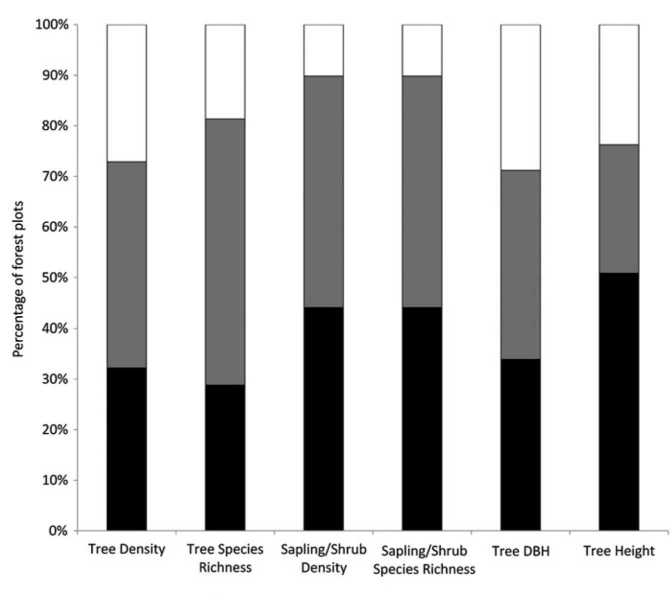

Fig. 1. Variation in assessments of forest change provided by different indicators.

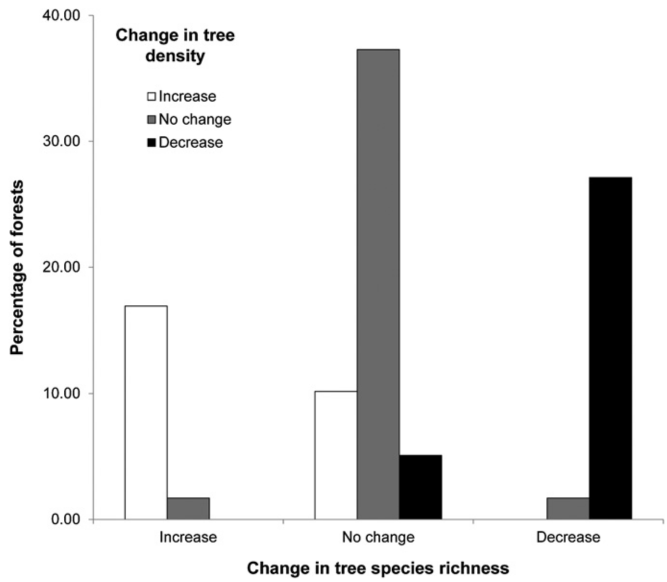

Fig. 2. Assessments of change in tree density vs change in tree species richness.

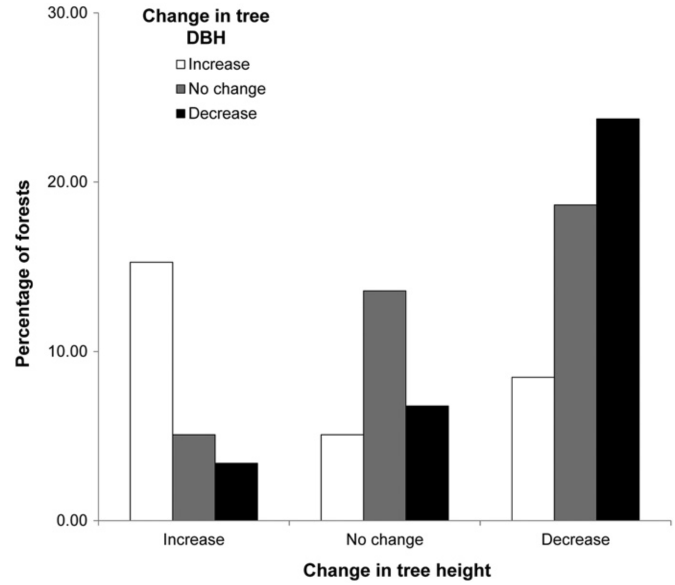

Fig. 4. Assessments of change in tree DBH vs change in tree height.

sensing (Banana et al., 2007; Greenberg et al., 2008), and rapid field assessments are possible with little specialized training. In contrast, data on species diversity and regeneration are very difficult to gather, requiring specialized skill and training, while information on tree size is time consuming, requiring the physical measurement of a large number of individual trees. Yet, species richness and diversity provide important indicators of ecosystem stability and resilience (Schindler et al., 2010), while tree size coupled with tree density provides an indication of above ground carbon storage, another important parameter of forest structure. Can assessments that focus on tree density provide indicators of other important aspects of forest structure?

4.1. Correspondence between changes in vegetation density and species richness

Assessments of forest change based on tree density and tree species richness are highly correlated, with similar findings at the shrub/sapling level. Since plot based sampling keeps the areal unit of sampling constant, a greater number of stems are likely to support a greater number of species (Gotelli and Colwell, 2001). This correlation will decrease in strength with increase in sampling effort, perhaps reaching a point beyond which further increase in sampling area will not produce substantial increase in biodiversity (Stohlgren, 2007).

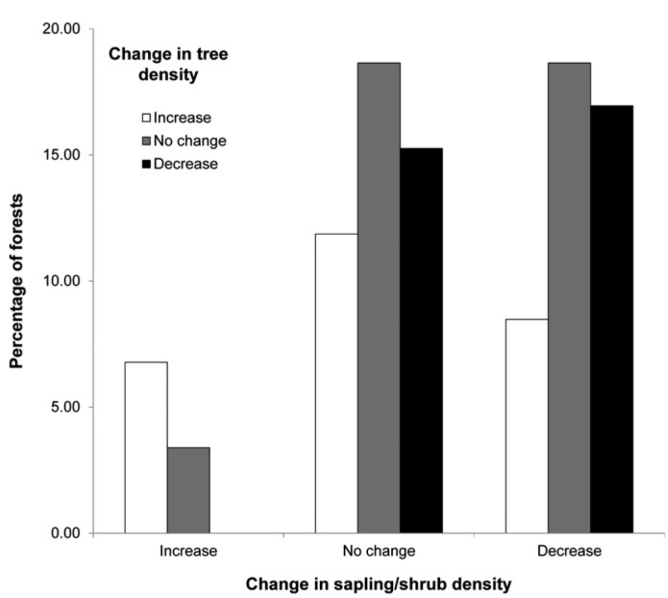

Fig. 3. Assessments of change in tree density vs change in shrub/sapling density.

The results indicated here can aid in the prioritization of locations where rapid changes in plant density are noted, as an indication that field studies of biodiversity studies are especially necessary. Of course, this only applies to plants, as the drivers of forest change are quite different for wildlife and must be assessed separately (Craigie et al., 2010; Datta et al., 2008). Further, it is important to point out that such monitoring of changes in abundance may not provide indicators of change in rare plant species, and should not be so inferred (Margules and Pressey, 2000). Such approaches may also hold greatest applicability relevant in species rich tropical and sub-tropical forests (where the need for monitoring change is critical, Nagendra and Rocchini, 2008). In ecosystems where species diversity is low (such as temperate montane forests and peat swamps) trends in plant density may not be as strongly related to trends in species diversity.

Finally, the proposed relationship may not hold across all forests. For instance, in the case when a native forest is converted to a plantation forest, one could expect tree density to increase, while species richness would decrease substantially. Thus, an additional indicator could be used in addition to tree density, such as the variance or standard deviation of the DBH distribution, which can be expected to be quite low in a plantation, but high in a native tropical forest.

4.2. Correspondence between changes at the tree and sapling/shrub level

Changes in density at the tree and shrub/sapling level are not significantly related. Thus, trees and shrubs/saplings appear to respond differently to the same drivers of forest change (whether natural, or human-induced), within a forest. Thus, some forests that are protected exclusively for timber can support high levels of human extraction of non-timber forest products, leading to a decrease in density at the shrub/sapling level (e.g. Ghate et al., 2009). Other IFRI research has demonstrated the impact of disturbances such as fire, grazing, charcoaling and collection of non-timber forest products on shrubs and saplings, but not as much on trees, in South Asia and East Africa (Banana et al., 2007; Ghate et al., 2009; Nagendra et al., 2010; Schweik, 2000). Thus, an exclusive focus on monitoring changes in tree density can obscure awareness of other changes that can be important for adaptive forest management (Folke et al., 2002).

4.3. Correspondence between changes in tree density, DBH and height

Changes in tree density and DBH have a significant negative relationship. The causes for this are unknown, and can relate to human influence as well as natural impacts due to changes in stand dynamics. It is important to note, however, that in as many as 12% of the forests studied, significant increase in one of these variables is found associated with significant decrease in the other variable. Why is this important? Many assessments of carbon storage in forests are based on measurements of tree DBH, relying on ecosystem specific regression equations to estimate wood volume and biomass from DBH, largely based on studies carried out in plantations and old growth forests with little human use (Baker et al., 2004; Chave et al., 2004; Chazdon et al., 2007). These results indicate that changes in tree DBH and height are not always related in standardized, computable ways. The forests studied here represent the types of human impacted forests where biomass monitoring protocols can enable payments to communities through programs such as Reducing Emissions from Deforestation and Forest Degradation (REDD), Payment for Ecosystem Services (PES) and the Clean Development Mechanism (CDM) under the Kyoto Protocol (Bond et al., 2009). In such human impacted forests, challenges of monitoring changes in biomass over time can prove particularly problematic (Sandbrook et al., 2010). Measurement of change in both tree DBH and height appear to be essential for monitoring changes in above ground forest biomass, while further research is required to understand how human behavior shapes patterns of planting, thinning, maintenance and harvesting in different forests.

5. Conclusions

We live in an era where impacts on forest change are substantial, ranging from human use, to natural impacts, habitat change and climate change. For effective, adaptive, resilient management of forests, it is essential to have a set of indicators that provide a timely and accurate picture of forest change at a local scale, so that such changes can be managed in forest patches in a cost effective manner. This research finds that changes in tree density can be used to identify areas likely to have experienced significant changes in tree diversity. Thus, rapid assessment of changes in tree density on the ground or using high resolution satellites can be used to prioritize locations to study biodiversity changes in the field. This can be especially useful for large scale, country level or regional scale assessments of forest change. Changes in tree density are however not indicative of changes in density at other strata, especially of the shrub/sapling strata. Most remotely sensed data (apart from LiDAR) is not capable of accurate assessment of plant density at strata below the highest tree canopy (Nagendra and Rocchini, 2008). Thus, large scale monitoring efforts should include field based monitoring of changes in shrubs and saplings, as that can serve as early warning systems that enable forest communities and managers to adaptively manage forest use. This research also points to the need for developing a better understanding of how tree height and DBH are related in allometric models used to estimate above ground carbon storage for REDD, through detailed field studies in a range of ecological and social-institutional contexts.

The analysis presented here suggests a combination of metrics can be deployed, that assess changes in tree density/richness, sapling density/richness, and tree size. While this provides a more comprehensive approach to understanding changes in forest structure and composition, this will not provide an adequate understanding of the type of changes in species and community composition. For instances, increases in biodiversity could be due to disturbance or invasives, or due to restoration, or indeed other types of change that are not due to human influence, such as ecological succession. In order to understand and manage such change, further in depth studies of the type of change in species and community composition will be required. This is expensive and time consuming however – and therefore, in practice, only usually done for selected forest patches. The approach used in this paper, of applying a set of metrics, can be suitable to identify forests where change is occurring – where in depth analysis of species composition can be conducted, thus helping to prioritize valuable sampling effort.

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Appendix. Supplementary material

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.jenvman.2011.10.002.

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