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Missing the wood for the trees? New ideas on defining forests and forest degradation

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Abstract

The forest ecology literature is rife with debate about how to: (i) define a 'forest' and distinguish it from similar systems, such as woodlands, savannas, parklands or plantations; (ii) identify transitions from 'forested' to 'non-forested' states and, most challengingly; (iii) quantify intensities of degradation. Here we argue that past attempts to define forests and forest degradation, focusing on attributes of living trees (e.g., height, canopy cover), combined with regenerating processes such as recruitment and succession, whilst useful, are ecologically incomplete. These approaches do not adequately represent processes that, operating over long time scales, determine whether a forest system is structurally healthy (as opposed to degraded), functional and persistent. We support our case using a conceptual model to illustrate how deeper-time processes, as well as instantaneous or chronic disturbances that cause degradation, might be revealed through analysis of the patterns of size structure and density of the fallen wood, in relation to the living trees and standing dead. We propose practical ways in which researchers can incorporate dynamic, long-term processes into definitions of forests and forest degradation, using measurements of dead and fallen trees. Doing so will improve our ability to manage and monitor forest health under global change.

Keywords

deforestation, forest structure, ecological processes, ecosystem dynamics, disturbance, restoration

Introduction

The forest biome provides vital global ecosystem services like nutrient cycling and carbon storage, and is the habitat for an immense diversity of terrestrial species (Gentry 1992). Forests also deliver important economic benefits through commercial forestry and tourism, and economic disservices through fire-risk management. As threats to global biodiversity from land-use and other anthropogenic influences such as climate change mount, the future of the world's forests has become progressively more uncertain. As a consequence, many studies focussing on the impact and sustainability of activities associated with human development on forest biomes (e.g. logging and cultivation), and their interaction with the agents of global change (e.g. climatic shifts, altered fire regimes and invasion of non-native species) have been done over the last two decades (e.g. Clark et al. 2011; Lindenmayer and Franklin 2002; Noss 1999). These studies typically use plot-based surveys as 'snap shots' of standing pattern, time series of marked individuals, and remote-sensed imagery. Such information can then be used to characterise the ecological status of the forest, and to categorise and quantify both forest health and forest degradation over space and time. However, assessing the extent of degradation or loss of forest cover, and conversely, measuring the success of actions that seek to protect existing forests or ameliorate past damage, remains a fundamental challenge. This is, in part, because the definition of 'forest' and 'forest degradation' is still elusive (Putz and Redford 2010).

Is that a forest, or is *that* a forest?

There are many different forest types worldwide, some cosmopolitan (e.g. boreal coniferous forests across Eurasia and North America) and others regionally restricted (e.g. mixed Nothofagaceae/Podocarpaceae forests in New Zealand). The forest biome is often sub-categorized according to variation in the structure and dynamics—covering a wide span of climatic and latitudinal gradients. These cross-continental differences make it quixotic to define a generic 'forest' (Chazdon et al. 2016). Indeed, the meaning of the term 'forest' can strongly depend on who is doing the defining (e.g. politicians, environmentalists, scientists), and the underlying motivations or concerns for both the forest and the landscape (e.g. maintenance and restoration of ecosystem services, biodiversity conservation, economic gain, land control, recreation and ecological research) (Lund 2002; Perz 2007).

In the era of international conventions and other efforts to enhance forested-landscape restoration and recovery from human-induced impacts, new targeted definitions and concepts of forests are required to help resource managers and academics navigate the complex mosaics that are modern forest landscapes. A scientific working definition '*…land with tree crown cover of >10 per cent, area of >0.5 ha, and a minimum height of 5 metres at maturity*' has been adopted and is used by the United Nations Food and Agriculture Organization (http://www.fao.org/forestry). Yet a direct interpretation of this definition also captures a variety of anthropogenic landscapes, such as parklands or monoculture plantations. From an ecological standpoint, it is desirable to demarcate 'natural' systems, and to exclude certain wooded ecosystems that are underpinned by different forest processes and/or are dominated by distinct biophysical features such as grazing or fire (e.g. savanna and/or woodland compared to a boreal forest). But how?

Of planets and streetlights

It is helpful to acknowledge at this point that the problem of vague definitions in science is not isolated to forest ecology. To illustrate, see Box 1 for a classic example. The analogy here with classifying or excluding a land unit as a forest is obvious. What the FAO and similar definitions of forest lack is the equivalent of the planetary 'clearing the orbit' clause (Box 1) – it is missing a *dynamic* component that captures both the ecological vibrancy and time-dependent nature of a functioning forest ecosystem. This is partially a pragmatic choice, because such events are difficult to measure in remote-sensed imagery or field surveys. Philosophically, this is a poor excuse: it is the ecological equivalent of the 'streetlight effect' (the old joke of searching for dropped keys in an illuminated street where it is easy to see, despite dropping them in a nearby dark alley). We argue that including dynamic elements in the definition of forest (such as the presence of treefalls and associated logs and coarse-woody debris), would not only contribute to a better description of what a forest is or is not, but also could provide valuable diagnostic tools to assess forest health.

Dead wood is key to forest dynamics

Treefall and its consequences (e.g. decaying logs, coarse woody debris, canopy gaps, mortality) are a characteristic marker of turnover in forests, illustrating that even forests considered to be 'in equilibrium' are not just static stands of growing trees, but dynamic ecosystems (Buettel et al. 2017). The spatial pattern and physical structure of living,

Box 1: A classic example of definitional vagueness in science

Consider a well-known recent example in astronomy, where arguments raged on what constituted a 'real' planet, rather than some other solar-system object. In this case, a majority of planetary scientists felt that with the burgeoning number of large Kuiper-belt objects being discovered, the concept of a planet risked being diluted to meaninglessness (Brown 2010). This led the International Astronomical Union (www.iau.org) to formulate a more precise (and arguably scientific) definition of a planet, which included reference to physical dimensions (e.g. a body with sufficient mass for gravity to form a spheroid) and dynamical outcomes (e.g. large enough to have cleared the neighbourhood around its orbit). While not free from some controversial outcomes (most famously, the demotion of Pluto to dwarf-planet status), this new definition excluded many 'unwanted' icy objects and captured all of the 'traditional' rocky worlds and the gas giants. A more scientific, testable and 'future-proofed' concept of what it means to be a 'planet' was established.

standing-dead and fallen trees can also serve as time capsules, because they integrate information on past ecological processes, like climatic variation and fire events (e.g. via examination of tree rings, or positions of large fallen logs that create persistent gaps and leave a legacy of physical displacement on growing trees) (Bassett et al. 2015; Swetnam 1993). Yet the presence or consequence of treefall is often not measured in ecological studies, and is not included in contemporary 'operational' definitions of forests; such as the structurally-focused FAO classification based on crown cover and tree height. The measurement of treefalls might also provide a powerful tool for quantifying a forest's carbon stocks (including the living and the dead) and detecting degradation of forested landscapes. The idea here is that alterations in treefall pattern, dynamics and tree mortality (across many different forest types), may be early-warning flags of trends (gains and losses) in forest structure and function (see below).

Reading the forest leaves: what patterns in the coupled living-dead dynamics can reveal

A deforested landscape; one that was once covered with large trees but later converted into agricultural crops, pasture, urban areas, clear fell, or similar is obvious to recognise and uncontroversial to define. However, a degraded forest, as measured against a reference 'pristine' state (which is highly context-specific!), can be far more difficult to quantify. The reasons are twofold:

i. The baseline for non-disturbance is contextual and dynamic; are any forests truly in equilibrium or untouched by anthropogenic disturbance (Josefsson et al. 2009; van Gemerden et al. 2003)?
ii. There are many possible ways to describe degradation (e.g. tree death, canopy thinning, fire scars) (Ghazoul et al. 2015).

To the field ecologist or forester, the earliest stages of degradation are likely to be imperceptible, whereas the final phase will approach a state of degradation where large trees might still remain, but the 'forest' has ceased to support a diverse biota or supply basic ecological services like energy and nutrient flows (Foley et al. 2007). For practical and ecological purposes, it is therefore the 'intermediate zone' of degradation, where changes in structure and ecological processes are visibly obvious/detectable, but the forest is still a functional system, that is of most relevance when thinking about forest definitions, management interventions, and state transitions.

One obvious feature of the loss of forest health is that the mortality rate of the trees rises. Irrespective of whether this occurs due to direct harvest of the larger trees, a drying trend, disease, or fire, a forest suffering from degradation will usually become more open, with larger and more frequent canopy gaps and fewer living trees. Depending on the nature of the degrading processes, this might lead to a higher proportion of standing dead trees, more logs accumulating on the forest floor, or both.

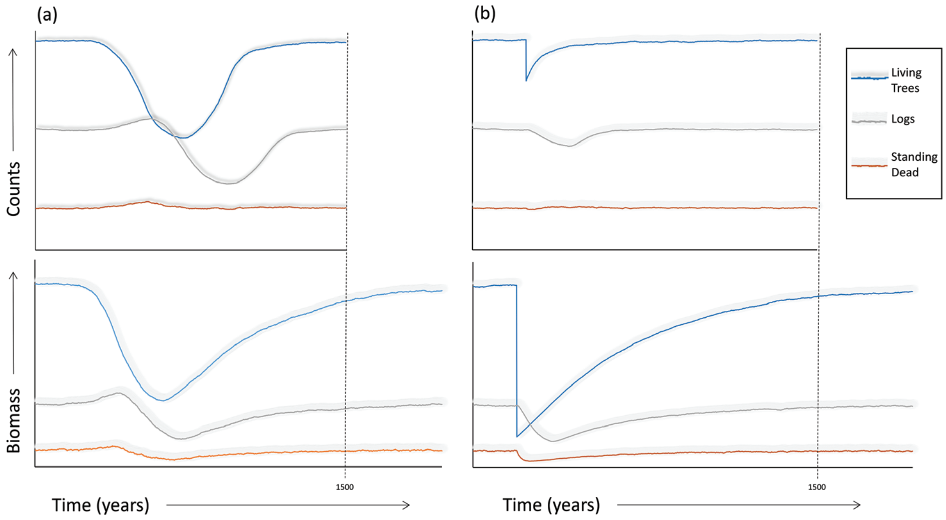

Figure 1. Conceptual model for a hypothetical forest showing: **a** a gradual loss of 50 % of the original biomass, followed by a slow recovery, and **b** an instantaneous selective harvest of all large trees, followed by an unfettered period of recovery. In the former case, there is likely to be a period during which living trees are regenerating but the supply of newly fallen logs continues to reduce, leading to a temporary uncoupling of their dynamics (with likely consequences of reduced turnover of nutrients). In the latter situation, the unstable size structure of the post-harvest forest will result in rapid re-establishment of tree abundance, but a slower recovery of biomass, and again, a period of decoupling between the living and dead forest components.

Thus, the interplay between the dynamics of the number and biomass of living trees, standing dead and logs would, as a corollary, provide a *key signature* to the type and rate of the degradation process and recovery rates (Fig. 1). Degradation is not always followed by regeneration. Depending on type, frequency, and duration of disturbance events, forests might cross a critical threshold beyond which they are not capable of regeneration (see Reyer et al., 2015), due to sustained levels of disturbance over time (Fig. 2a), or permanent anthropogenic changes in land use (Fig. 2b). Additionally, these conceptual models (if optimised, and field-verified) could be used for scenario testing and agent-based modelling that would allow for predictions of when forest health is declining (e.g., mortality is increasing) across both space and time (e.g. by taking a snap-shot survey of a forest to quantify the relative ratio and size structure of living, standing dead and fallen trees). Furthermore, important questions such as "*is the transition from healthy to un-healthy an abrupt threshold?*", "*does degradation occur across a continuum from 'normal' (<10% degraded) to deforested (>90% degraded)?*", "*how can we optimise these conceptual models to detect and predict the early signs of a forest transition passing an abrupt 'tipping point' threshold?*", or "*how many trees can be harvested from a forest stand, and of what size class, whilst avoiding approaching a forest transition that sets the trajectory of declining forest health*" can be conceptualised and then tested using this approach.

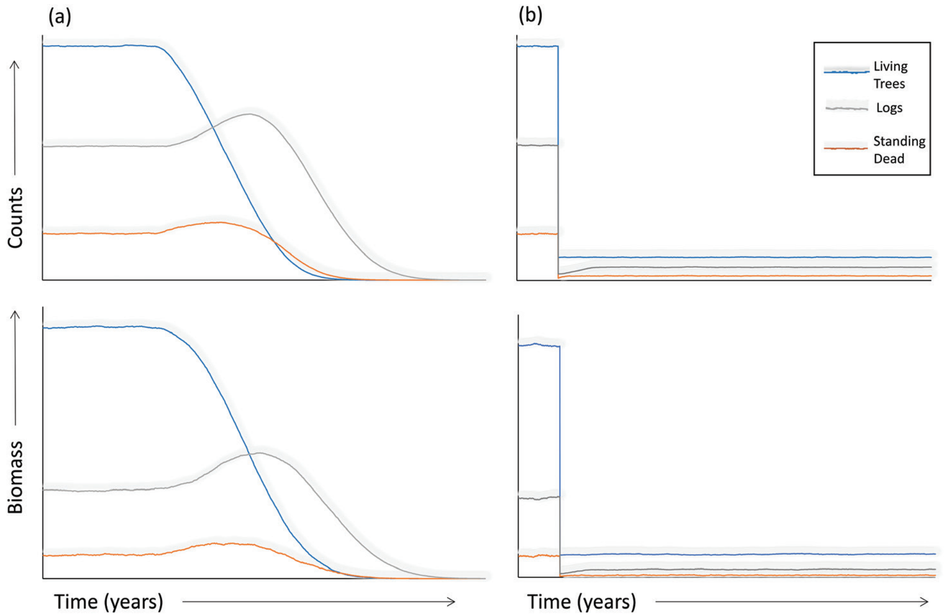

Figure 2. Conceptual model for a hypothetical forest that: **a** degrades systematically over time (e.g., through disease or drying), until the region is completely deforested, and **b** experiences a rapid (but not total) deforestation event (e.g., conversion to agriculture), in both cases with no subsequent recovery. In the first case, we would expect to see a lagged rise in the relative proportion of the woody biomass found in standing dead trees and a subsequent lag towards logs—which would peak at some time during the phase of decline of the number and biomass of the living trees. In the latter case, the character of the forest might be quite similar (unless heavily fragmented), but reduced substantially in areal extent.

The key to making use of this information is robust measurement and *calibration*. For example, if baselines of the proportion of living trees, standing dead and logs in 'healthy' forests can be ascertained using comprehensive plot-based data (such as from the Center for Tropical Forest Science, Forest Global Earth Observatory network), then a study of snap-shots of standing pattern in degrading forests would yield valuable insights into the likely nature and extent of degrading and recovery processes (Buettel et al. 2017). Ideally, such studies would be coupled with short-term monitoring of the direction of change in accumulation or loss of trees and dead wood components.

Expected proportions of living and dead trees would probably depend strongly on factors like climate, fire frequency, and decay rates. For instance, in warmer, drier forests, the frequency of fire and activity of termites will typically be high, thereby rapidly removing any lasting legacy of the fallen trees. By contrast, cool-wet rain forests (where ancient logs strewn on the forest floor are among the most persistent feature of the ecosystem), will have a high biomass of dead wood, acting to shape its dynamics over periods much longer than a typical plant lifespan (Vanderwel et al. 2006). Such stochasticity in climate and extreme events might make it difficult to determine the 'normal window' of variation in treefall dynamics. In these instances, calibration could be attempted using information 'stored' in the old logs. The age of already fallen trees can be estimated through, for example, the study of the invertebrate and fungal communities they harbour (e.g. Boulanger and Sirois 2007). This also means that past treefall dynamics might be estimated and baseline data collected in a single survey, which would facilitate the application of a modelling and forecasting approach.

In open landscapes like woody savannas, rates and patterns of treefall can often be identified and quantified through remote sensing (Levick and Asner 2013). However, in forests, aerial signs of degradation may disappear within 1-2 years (due to rapid canopy closure and understory re-vegetation), resulting in spectral characteristics not dissimilar from intact forests and consequently poorly distinguishable using conventional space-born remote-sensing techniques (Frolking et al. 2009). Forest health may therefore be difficult to assess using current remote-sensing techniques in certain circumstances. However, technological solutions are emerging – for example, downed logs can be mapped using LiDAR in some instances (Blanchard et al. 2011). Consequently, in the absence of plot networks already established, field-based calibration and regular monitoring of treefall dynamics is a challenging task.

Recent work using more detailed plot information and improved interpretation of remote-sensed imagery has led to substantial revisions in our understanding of forest cover (Bastin et al. 2017). However, we argue that the additional benefits arising from monitoring treefall dynamics (i.e. mortality via the frequency distribution of living, standing dead and fallen logs) will provide crucial information that would support forest classification and management. Early assessment of deviations from a healthy state, detected through the observation of signs like treefall and dead wood patterns (that might go overlooked if not specifically targeted), would allow managers to intervene before forest resilience is substantially compromised or positive feedbacks kick in (Trumbore et al. 2015). For example, extensive logging can increase fire frequency, which in turn further contributes to forest degradation, particularly when combined with drought events such as El Niño-La Niña (Siegert et al. 2001). A forest that cannot recover is on a path to becoming something else, given that degradation can alter and potentially interrupt successional trajectories (Ghazoul et al. 2015). At its end point, this can trigger a cascade of events affecting the entire local ecosystem, with potential loss of both animal and plant biodiversity (Gardner et al. 2009).

Conclusion

We argue that the definition of a forest ought to incorporate *both* attributes of the living trees *and* turnover in the dead-wood component. Together, this combined approach would more effectively characterize an ecosystem that is dynamic. This would allow us to infer whether a tree-covered land unit is likely to be in a static, degrading, or unstable state, and potentially vulnerable to tipping into a 'non-forest' (Reyer et al. 2015). Definitions based simply on living structural features like height and canopy cover, for instance, *are not* sufficiently ecological because they ignore this crucial dynamism. Recent papers have pointed out that differences in how a forest is defined is due, in large part, to its relevance to a given scientific, economic, or social sciences issue (e.g. Chazdon et al. 2016). Definitions that reflect a forest's ecological health, by focussing on attributes like regeneration and succession, are vital for identifying degradation (Ghazoul et al. 2015). It is time to move away from making suggestions. Instead, we propose that the dead-wood component of a forest should be used to define what a forest is – and is not.

Author contribution

JCB and BWB conceived the manuscript concept and JCB led the writing. All authors contributed to the writing.

Authors	Contribution	ACI
JCB	0.50	2.000
BWB	0.30	0.854
SO	0.20	0.500

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