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Vulnerability of tropical forest ecosystems and forest dependent communities to droughts

D.J. Vogt [a,*], K.A. Vogt [a], S.J. Gmur [a], J.J. Scullion [b], A.S. Suntana [c], S. Daryanto [d], R. Sigurðardóttir [e]

[a] School of Environmental and Forest Sciences, College of the Environment, University of Washington, Box 352100, Seattle, WA 98195, USA
[b] McDaniel College, Department of Environmental Studies, 2 College Hill, Westminster, MD 21157, USA
[c] RMI, The Indonesian Institute for Forest and Environment, Perumahan Bogor Baru, Blok C1 No. 12A, Bogor 16127, Jawa Barat, Indonesia
[d] Department of Earth Sciences, Indiana University/Purdue University Indianapolis, 723 W Michigan Street, SL118, Indianapolis, IN 46202, USA
[e] Reykjavik Akademy Thorunnartun 2, 105 Reykjavik, Iceland

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ABSTRACT

Energy captured by and flowing through a forest ecosystem can be indexed by its total Net Primary Productivity (NPP). This forest NPP can also be a reflection of its sensitivity to, and its ability to adapt to, any climate change while also being harvested by humans. However detecting and identifying the vulnerability of forest and human ecosystems to climate change requires information on whether these coupled social and ecological systems are able to maintain functionality while responding to environmental variability.

To better understand what parameters might be representative of environmental variability, we compiled a metadata analysis of 96 tropical forest sites. We found that three soil textural classes (i.e., sand, sandy loam and clay) had significant but different relationships between NPP and precipitation levels. Therefore, assessing the vulnerability of forests and forest dependent communities to drought was carried out using data from those sites that had one of those three soil textural classes. For example, forests growing on soil textures of sand and clay had NPP levels decreasing as precipitation levels increased, in contrast to those forest sites that had sandy loam soils where NPP levels increased. Also, forests growing on sandy loam soil textures appeared better adapted to grow at lower precipitation levels compared to the sand and clay textured soils. In fact in our tropical database the lowest precipitation level found for the sandy loam soils was 821 mm yr^{-1} compared to sand at 1739 mm yr^{-1} and clay at 1771 mm yr^{-1}. Soil texture also determined the level of NPP reached by a forest, i.e., forest growing on sandy loam and clay reached low-medium NPP levels while higher NPP levels (i.e., medium, high) were found on sand-textured soils. Intermediate precipitation levels (> 1800–3000 mm yr^{-1}) were needed to grow forests at the medium and high NPP levels. Low thresholds of NPP were identified at both low (~750 mm) and high precipitation (> 3500 mm) levels.

By combining data on the ratios of precipitation to the amount of biomass produced in a year with how much less precipitation input occurs during a drought year, it is possible to estimate whether productivity levels are sufficient to support forest growth and forest dependent communities following a drought. In this study, the ratios of annual precipitation inputs required to produce 1 Mg ha^{-1} yr^{-1} biomass by soil texture class varied across the three soil textural classes. By using a conservative estimate of 20% of productivity collected or harvested by people and 30% precipitation reduction level as triggering a drought, it was possible to estimate a potential loss of annual productivity due to a drought. In this study, the total NPP unavailable due to drought and harvest by forest dependent communities per year was 10.2 Mg ha^{-1} yr^{-1} for the sandy textured soils (64% of NPP still available), 8.4 Mg ha^{-1} yr^{-1} for the sandy loam textured soils (60% available) and 12.7 Mg ha^{-1} yr^{-1} for the clay textured soils (29% available). Forests growing on clay textured soils would be most vulnerable to drought triggered reductions in productivity so NPP levels would be inadequate to maintain ecosystem functions and would potentially cause a forest-to-savanna shift. Further, these forests would not be able to provide sufficient NPP to satisfy the requirements of forest dependent communities. By predicting the productivity

* Corresponding author.

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responses of different tropical forest ecosystems to changes in precipitation patterns coupled with edaphic data, it could be possible to spatially identify where tropical forests are most vulnerable to climate change impacts and where mitigation efforts should be concentrated.

1. Introduction

Many studies have focused on measuring the vulnerability of coupled human and natural systems to climate change (e.g., IPCC, 2012) by integrating information from the social and natural sciences (e.g., Chuvieco et al., 2014; Downing et al., 2014; Mumby et al., 2014). Despite the multitude of research, it has been challenging to equate social and ecological resilience with vulnerability to climate change. To fully understand these interconnected systems different approaches and methodologies are needed to address our diverging research objectives (Liu et al., 2007). A lack of knowledge of an ecosystem's pre-novel context (Seastedt et al., 2008) or the interconnectivities of complex social drivers of change (Scullion et al., 2014) means that resilience represents the ability of a system to recover after a disturbance. However does it indicate whether ecological and social systems have recovered within their historical range of conditions? Additional knowledge may be needed to identify system parameters that maintain functionality within the "safe operating space" where a stress or disturbance does not trigger the system to cross a threshold of recovery beyond the historical range of variation (Scheffer et al., 2015). In fact identifying the safe operating space for both the social as well as the ecological systems would probably be even more challenging with the multitude and complexity of connections that exist between them. To help decrease some of those challenges of quantifying the sensitive parameters that reflect movement within and between regimes (Scheffer and Carpenter, 2003), we try to quantify the parameters remotely rather than locally and also at different spatial and temporal scales to minimize unexplained unique results (Vogt et al., 2002; Gmur et al., 2013; Scullion et al., 2014). Further, one cannot focus on a single part of the coupled socio-ecological system (Maxwell, 2014; Silva, 2014) and expect to understand the mechanistic links between them. Even when research has effectively linked the complexity of socio-economic interactions with resources, they have been less able to validate what variables should be managed to reduce the impacts on both people and the environment (e.g., Downing et al., 2014; Görg et al., 2014; but see Scullion et al., 2014).

One metric for detecting mechanistic links between the social and ecological systems is to use an indicator such as total Net Primary Production (NPP). NPP reflects the pools and fluxes of materials and energy flowing through the social and ecological systems (Vitousek et al., 1986; Rojstaczer et al., 2001; Haberl et al., 2007). It is analogous to measuring 'virtual water' which tracks total water consumption by integrating water stored in the materials and track the energy consumed by products across different time and spatial scales and organizational units managing water (Liu et al., 2015). When harvesting forest products are required for survival, those dependent people become vulnerable when a drought affects their forest productivity. Therefore, NPP can potentially reflect whether a forest is competitively fit and whether a species may be more adaptable to a changing environment and stresses (Vogt et al., 1996). NPP could also be used to index plant adaptation and response to a changing environment or physiological adaptation of species to drought, soils, insects and pests (Waring, 1991; Lambers and Poorter, 1992; Davies et al., 2005; Bartlett et al., 2012; Smith, 2015). Thus by determining how much biomass a specific landscape produces each year and obtaining information on the amount of ecosystem services (e.g., habitats, water, nutrient cycles, forest products, biodiversity) collected by a group of people, it becomes possible to estimate whether a landscape is capable of sustainably supporting both activities.

Using NPP data to integrate the social and natural science requires an ability to detect the scale at which these productivity changes occur. For some forests, significant correlations between precipitation and NPP across soil textural-class levels exist suggesting these variable combinations could be used to identify locations where NPP and ecosystem services may be at critical risk to droughts (Slik, 2004; Wooster et al., 2012; Xu et al., 2011). Further, there is considerable research reporting the importance of soil texture in defining the nutrient and water holding capacity of soils – both key factors controlling plant growth rates (Waring and Franklin, 1979; Gentry and Terborgh, 1990; DeWalt and Chave, 2004; Sotta et al., 2007). Soil texture therefore not only influences soil moisture retention capacity and soil available nutrient supplies but they impact how a plant adapts to its growing environment and whether NPP levels will decrease during a drought.

By identifying how a forest maintains functionality for NPP as it is related to its soil texture, it is possible to estimate what levels of NPP are needed to safeguard sustainable harvests of ecosystem services against drought. To demonstrate one possible approach, we used a database populated with metadata from 96 different tropical forest sites to determine if any soil textural class had significant correlates between NPP and precipitation levels. Of 12 soil textural classes, forests growing on three textural classes (i.e., sand, sandy loam and clay) had productivity levels changing in response to precipitation levels. Since these three textural classes are found in over half of the tropical forest sites (Sanchez et al., 1982), relationships between NPP and precipitation (e.g., NPP per precipitation amounts) were examined to search for any potential trends and/or thresholds. A by-product of this exercise generated an estimate of the potential drought impact on productivity as well on the amount of productivity capacity available for harvest by humans. By identifying NPP thresholds, an evidence-based decision-making framework for spatially disparate natural resources could be provided for tropical forests that are potentially vulnerable to drought.

2. Methods

2.1. Database creation and description

This study was based on a compilation of NPP, edaphic and climatic information for 96 published plot-level data entries that had been characterized as natural tropical forests. The geographic distribution of the selected field sites are presented in Fig. 1. The database was populated by information collected in natural tropical forests reported as mature or closed canopy stands. For each site, data were separately recorded by forest region, forest age, climatic variables, elevation and elevation groupings, soil type (i.e., taxonomic soil orders) and soil textural classes according to the USDA soil taxonomy system (Table 1).

We appreciate that many tropical areas may have at least three distinct climatic seasons because of monsoons, but the analyses in this study were limited to the mean annual data since that is what