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A meta-analytical global comparison of aboveground biomass accumulation between tropical secondary forests and monoculture plantations

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ABSTRACT

Secondary forests and monoculture plantations are widespread in the tropics and are the two most common forms of reforestation. To assess the value of both systems for CO_2 mitigation, we performed a systematic analysis of the two systems comparing growth rates and potential to store carbon. The increasing involvement of these forest types in carbon trading makes a pertinent issue. We used a meta-analytical approach to evaluate relative rates of aboveground growth (biomass accumulation) in secondary forests and monoculture plantations, controlling for climate and site characteristics. We find a general tendency for aboveground biomass accumulation (ABA) to be marginally higher in plantations than secondary forests. Three recorded site factors were significantly associated with ABA, but differed between reforestation types. Plantation growth rates were negatively correlated with precipitation seasonality, while growth rates of secondary forest were positively correlated with surrounding tree cover and negatively correlated with duration of prior land use. It is noteworthy that poor reporting of site history such as prior land-use duration, particularly in monoculture plantations, and a strong bias in studies towards measuring young forest plots obfuscates evaluation of some ecological drivers and long-term processes. We conclude that the difference in ABA between tropical secondary forests and monoculture plantations is smaller than previously assumed, emphasising the potential of secondary forests for low-cost carbon storage and biomass production, particularly in landscapes with high existing tree cover or highly seasonal rainfall.

1. Introduction

The tropical biome is estimated to have seen 476,000 km^2, ca. 2.5%, of its forests cleared between 2000 and 2005 (Hansen et al., 2010). Widespread clearing coupled with frequent subsequent abandonment (Wright, 2005) has enabled regenerating forests to become dominant in many parts of the tropics, with as much as 90,000 km^2 of secondary forest formed in the tropics annually (Brown and Lugo, 1990; Silver et al., 2000), sequestering approximately 60% of gross carbon emissions from tropical deforestation (Pan et al., 2011). The International Tropical Timber Organisation (ITTO) defines secondary forest as: "woody vegetation regrowing on land that was largely cleared of its original forest cover (i.e. carried less than 10% of the original forest cover). Secondary forests commonly develop naturally on land abandoned after shifting cultivation, settled agriculture, pasture, or failed tree plantations." The same source (ITTO, 2002) estimated 50% of tropical forest cover to be degraded or secondary in 2002. A parallel trend associated with tropical deforestation is the extensive establishment of tree plantations, particularly monocultures (FAO, 2009). Monoculture plantations, actively planted and managed, and secondary forests, arising from unmanaged regeneration, represent extremes on a continuum of silvicultural management intensities. These forest types are increasingly widespread and the dominant forms of tropical reforestation, incentivising comparison of their respective values.

Secondary forest growth is often apportioned into three general stages (Corlett, 1995; Finegan, 1996), beginning with a rapid colonisation by fast-growing herbaceous and shrub species, succeeded by short-lived pioneer trees, after which long-lived pioneer trees achieve dominance once short-lived species senesce. In practice, antagonistic site conditions such as intense prior land use, distant seed sources, impoverished soils, or seasonal fire cycles can constrain forest recovery (Holl et al., 2000; Chazdon, 2003; Lamb, 2011). Secondary forests can from a young age perform important services, including stabilising topsoil, improving soil chemistry, reducing nutrient leaching, sequestering carbon, producing timber and non-timber forest products, regulating climate, improving landscape hydrology (Finegan, 1992; Corlett, 1995; Guariguata and Ostertag, 2001; Bonan, 2008) and conserving biodiversity (Chazdon et al., 2009). Wright and Muller-Landau (2006) argue that secondary forests have the capacity to ameliorate or even

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prevent predicted mass-extinctions in the tropics by means of providing large-scale biodiversity refuges (Barlow et al., 2007) that increase in value over time (Chazdon et al., 2009; Letcher and Chazdon, 2009).

The global expansion of plantations (FAO, 2009) is largely attributable to tropical plantings (Cossalter and Pye-Smith, 2003). Approximately 90 million hectares of tropical plantations existed in 2005 (Cossalter and Pye-Smith, 2003; FAO, 2009), the vast majority of which were planted as monocultures (FAO, 2001). Observations of higher primary producer diversity conferring higher productivity in ecosystems (Cardinale et al., 2011) extend to plantations. Compared with monoculture (monospecific) plantations, which are criticised for having poor ecological, edaphic and hydrological credentials (Cossalter and Pye-Smith, 2003; Lamb et al., 2005; Piotto, 2008), polyspecific plantations can exhibit better soil chemistry (Binkley et al., 1992; Richards et al., 2010), faster biomass accumulation (Forrester et al., 2004; Kanowski and Catterall, 2010) and improved timber yields (DeBell et al., 1997; Erskine et al., 2006) due to complementarity of resource use (Kelty, 2006; Manson et al., 2006; Richards and Schmidt, 2010). Tropical plantations with rotation times shorter than 20 years are established predominantly to produce pulpwood and charcoal and longer-rotation plantations are more often dedicated to sawlogs, but both may also cater ecosystem services, including carbon sequestration, habitat provision, soil stabilisation and watershed protection (Cossalter and Pye-Smith, 2003; Richards et al., 2010). As such, it is tempting to hypothesise that all of the services sought from plantations, both economic and ecological, are strengthened by diversity.

Carbon sequestration performed by forests globally is a service worth hundreds of billions of dollars (Canadell and Raupach, 2008). Tropical deforestation is one of the single largest sources of global carbon emissions (Pan et al., 2011) and may be the component through which the most rapid emissions reductions can be achieved. Frameworks for assigning monetary value to carbon sequestered by tropical forests are presently being negotiated by the UNFCCC: A/R CDM (Afforestation and Reforestation Clean Development Mechanism) and REDD (Reducing Emissions from Deforestation and Forest Degradation in developing countries). At present, the approved A/R CDM framework allows carbon sequestered through reforestation and afforestation in tropical developing countries to be sold in the form of carbon credits, drawing further into focus the question of comparative values of secondary forests and plantations. The case for secondary forests is bolstered by their low cost combined with biodiversity conservation potential (Wright and Muller-Landau, 2006; Barlow et al., 2007; Chazdon et al., 2009; Letcher and Chazdon, 2009; Berry et al., 2010), but only if their capacity for carbon sequestration is not vastly lower. Here we contribute to the debate by exploring the potential values of alternative reforestation types in context of carbon trading. Specifically, we evaluate aboveground biomass accumulation (ABA) rates of tropical secondary forests and monoculture plantations. ABA rate is a precursory measure of the value of reforestation as it provides an approximation of the rate of establishment of aboveground structure.

1.1. A deductive hypothesis

Most internationally appropriated tropical plantation species can be characterised as long-lived pioneer trees in secondary forests in their place of origin, including *Gmelina arborea*, *Eucalyptus deglupta*, *Falcataria molocana*, *Pterocarpus indicus*, *Swietenia macrophylla* and *Cedrela odorata* (Corlett, 1995; Lamb, 2011). Major tree species from secondary forests can typically be used to good effect in plantations (Stanley and Montagnini, 1999; Redondo-Brenes and Montagnini, 2006; Kanowski and Catterall, 2010). Further, plantations with higher tree species diversity appear to have faster ABA, with some studies observing a positive correlation between these two factors (Erskine et al., 2006; Kanowski and Catterall, 2010), and secondary forests host higher floral diversity than plantations under the same conditions (Tsai and Hamzah, 1985; Lugo, 1992). Motivated by their taxonomic similarity, an extrapolation of the species richness trend seen in plantations to secondary forests prompts the hypothesis that ABA should be faster in secondary forests than plantations.

Given the suggestive evidence, we use a meta-analytical approach to quantify relative rates of ABA of tropical secondary forests and monoculture plantations. The initial focus on aboveground biomass reflects a paucity of data on carbon accumulation in belowground biomass across the tropics (Clark et al., 2001a,b). Aboveground biomass constitutes the majority of tree biomass and is far easier to measure (Brown, 1997). Importantly, this focus allows for a larger dataset for a meta-analysis and thereby greater statistical power.

2. Materials and methods

Traditional meta-analysis involves estimating a net effect size of a treatment from a collection of comparisons (Bax et al., 2006). However, this approach has limited utility for comparing global trends in ABA between secondary forests and plantations as there is currently a paucity of studies that compare the two forest types at sites matched for confounding factors other than level of management intervention following land-use change. Studies estimating aboveground biomass in monoculture plantations and secondary forests independently exist in sufficient abundance to permit a meta-analytical approach that compares published studies of one forest type to the studies of the other, controlling for known properties of the measured sites. Performing this type of meta-analysis also has a secondary utility in that it elucidates notable gaps and biases of the published literature. Describing these gaps delineates the research questions most in need of attention, and we treat them in this study as results in their own right.

2.1. Evaluation of existing literature

More than 140 studies were compiled on secondary forests and monoculture plantations in the tropics and subtropics. Studies were derived from an extensive literature search and through communications with scientists practising in the field. We only considered studies that reported on sites located between latitudes −30 to 30° or above mean annual temperature of 19 °C. This criterion excluded cool montane forests occurring at low latitude but high elevation. The inclusion of subtropical sites slightly outside of the strictly tropical region, defined either as within the latitudinal tropics or the 18° isotherm, served to increase our sample size of floristically comparable communities.

We scrutinised all studies for data quality. Specifically, we removed studies that: (i) had inadequate descriptions of the study area (i.e. location, age and type of forest) or methods used to estimate biomass; (ii) only reported on trees above a certain size (e.g. Aide et al., 2000), except where all plots were more than 10 years old (e.g. Saldarriaga et al., 1988) as herbaceous growth can constitute a large portion of biomass in young secondary forests (Naughtontreves and Chapman, 2001); or (iii) reported a single rarefied estimation of aboveground production rate without clearly describing whether it includes litterfall.

Approaches to biomass estimation were not consistent across studies. Some studies used published allometric equations, rather than site-specific calibrations derived from selective harvesting (*sensu* Uhl et al., 1988) or weighing a comprehensive harvest (*sensu* Nykvist, 1996). Values of aboveground biomass in tropical forests