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Altered stand structure and tree allometry reduce carbon storage in evergreen forest fragments in India's Western Ghats

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ABSTRACT

Tropical forests are among the largest terrestrial reservoirs of carbon, and play an important role in regulating global climate. However, as a result of historic and ongoing deforestation, carbon storage in this biome is increasingly dependent on forests that are fragmented and used by humans, with considerable uncertainty about how such disturbance alters carbon storage potential and cycling. Here, we evaluate differences in above-ground carbon stocks between fragmented and contiguous evergreen forests in the central Western Ghats, India. We also assess differences in the structure, tree allometry and functional composition of forest stands between contiguous and fragmented forests, and explore how these differences influence carbon storage in fragmented forests. Relatively large, well-protected forest fragments currently store 40% less carbon per hectare above ground than contiguous forests. These differences in carbon are related to (i) lower tree density and basal area in fragments, (ii) lower average stand height in fragments, and (iii) compositional shifts favoring species with lower wood densities. Reduced stand height in fragments was associated with intra-specific variation in tree allometry, with trees in fragments being relatively shorter at any given diameter than conspecifics in contiguous forests. Further, the relatively skewed distribution of carbon storage within a few large trees in current-day fragments is added cause for concern: carbon stocks in fragments are likely to decline further in the future, following the eventual death of large trees. Active management and restoration to mitigate ecologically driven changes in habitat structure and species composition might be as important as improved management of resource use and protection from exploitation in order to sustain carbon storage ecosystem services provided by these tropical forest fragments.

1. Introduction

Carbon storage by tropical forest vegetation, currently estimated at nearly 250 Gt, strongly influences the global carbon cycle and plays a crucial role in regulating the concentrations of greenhouse gases in the atmosphere (Lewis et al., 2009; Malhi and Grace, 2000; Pan et al., 2011; Saatchi et al., 2011). However, deforestation and fragmentation continue to be widespread in the tropics, with resultant carbon emissions and loss of sequestration potential a cause for global concern (Achard et al., 2002; Harris et al., 2012). While deforestation clearly has negative impacts on carbon storage, there is considerable uncertainty surrounding ecosystem and carbon dynamics within tropical forests that are fragmented or otherwise disturbed.

While, in the absence of disturbance, intact tropical forests likely act as carbon sinks (Lewis, 2006; Phillips et al., 2009), fragmented forests may be vulnerable to carbon losses and accelerated carbon cycling (Nascimento and Laurance, 2004). These losses may be brought about by changes in habitat structure and tree species composition (Laurance et al., 2006a). In central and southern America, major biomass losses occur in the immediate aftermath of fragmentation, resulting from the death of large, old-growth trees, especially close to fragment edges that are exposed to wind and fire (Laurance et al., 2000; Laurance et al., 1997; Laurance et al., 2006a). As fragments age, aboveground biomass can decline further due to the proliferation of relatively softer-wooded, shorter-statured pioneer species (Laurance et al., 2006b). Wind and other abiotic stresses can also change tree allometry, with trees in fragments being shorter for a given basal diameter (Dantas de Paula et al., 2011; Oliveira et al., 2008). Through these multiple processes, some with immediate effect and others acting more slowly over the timescales of species turnover and forest succes-

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sion, carbon stocks and sequestration potential in fragmented forests may be depleted over time.

While forest fragmentation is ubiquitous across the tropics, scientific insights into fragmentation impacts on carbon dynamics are largely derived from work in central and southern America. Whether taxonomically different tree communities elsewhere in the tropics show functionally similar responses to fragmentation is unknown. In south Asia, and the Western Ghats in peninsular India in particular, a large proportion of the remaining forest cover is fragmented and otherwise affected by humans (Bawa et al., 2007; Menon and Bawa, 1997). A substantial extent of these forests, particularly in the wet evergreen zone, fall outside the current network of strictly protected areas, with many biologically rich and unique forests persisting as isolated fragments with varying levels of protection in agro-forestry landscapes (Anand et al., 2010; Bhagwat et al., 2005b; Das et al., 2006). With payments for forest carbon emerging as an important strategy to facilitate biodiversity conservation in the densely-populated tropics (Schroth et al., 2011), understanding the impacts of fragmentation on aspects of forest carbon storage in these landscapes becomes essential both for the conservation of biodiversity and for the sustained provisioning of ecosystem services. Here, we estimate the carbon storage ecosystem services provided by tree communities in fragmented evergreen forests in the Western Ghats, in comparison with contiguous forests. We evaluate differences in the structural properties of tree stands (stand density, basal area, stand height and carbon storage) and functional traits of tree species (wood density) in response to fragmentation across a gradient of mean annual precipitation. We compare tree height to diameter (tree *H*:*D*) relationships between contiguous and fragmented forests in terms of variation within and across species and size-classes. Finally, we evaluate differences in the distribution of carbon storage across trees of different sizes within contiguous and fragmented forests and draw insights into the stability and future potential for carbon storage in fragmented forests based on the skewedness of these distributions.

2. Materials and methods

2.1. Study site

The study was conducted in south-western Kodagu district, Karnataka state, in the Western Ghats of peninsular India (12.17°N, 75.8°E; Fig. 1). The study area experiences a gradient of annual precipitation from 2300 mm in the E to around 3800 mm in the W (Hijmans et al., 2005; Kumar et al., 2012). Elevation ranges from 700 to 1000 m above sea level. Ultisol soil formations in the study area are characterized by deep, well-drained clays on plateaus and moderate slopes (Anonymous, 1998; USDA Soil Survey Staff, 1999). Intact, mid-elevation forests in the study area are characterized by old-growth evergreen species *Mesua ferrea* and *Palaquium ellipticum* (Pascal, 1982, 1986).

Over the ~6000 years of human settlement, the landscape has witnessed multiple advances and retreats of forest cover, with present day forests likely to be a mix of primary forests and old (~400 years) regrowth (Bhagwat et al., 2012, in press). At present, the western and southern parts of the study area along the eastern slopes of the Western Ghats contain large areas of evergreen forest (hereafter, contiguous forests) which are protected by the State (Bramhagiri Wildlife Sanctuary, and adjacent Reserved Forests), and form part of a large block of evergreen forests spanning over 2000 sq.km. Immediately adjacent to this forest block, the human-dominated landscape is dotted with evergreen forest remnants (hereafter, fragmented forests), many of which are protected as sacred groves (Bhagwat et al., 2005b; Kalam, 1996). Official records list over 1000 sacred groves in the district, ranging from less than a hectare to tens, and rarely, hundreds of hectares in area (Bhagwat et al., 2005b; Kalam, 1996). The protected areas and reserved forests which contain the contiguous forests are presently under the administrative control of the Karnataka Forest Department, while sacred forest fragments are jointly managed by the Karnataka Forest Department and local village temple committees. Selective logging, which was practiced across all forests in the area during the 1900s, has been banned by Indian law in these forests since the 1980s.

Forest cover maps derived from Survey of India topographic maps indicate that forests, which were widespread and contiguous across the region during the 1920s, were highly reduced and fragmented by the 1990s, except those within State protected areas (Menon and Bawa, 1997). Analyses of land use change using satellite images indicate that while forests were widespread in the study area in the 1970s, there were high rates of forest conversion to shade coffee, agriculture and other human land use during the 1977–1997 period (Garcia et al., 2009). It is therefore likely that

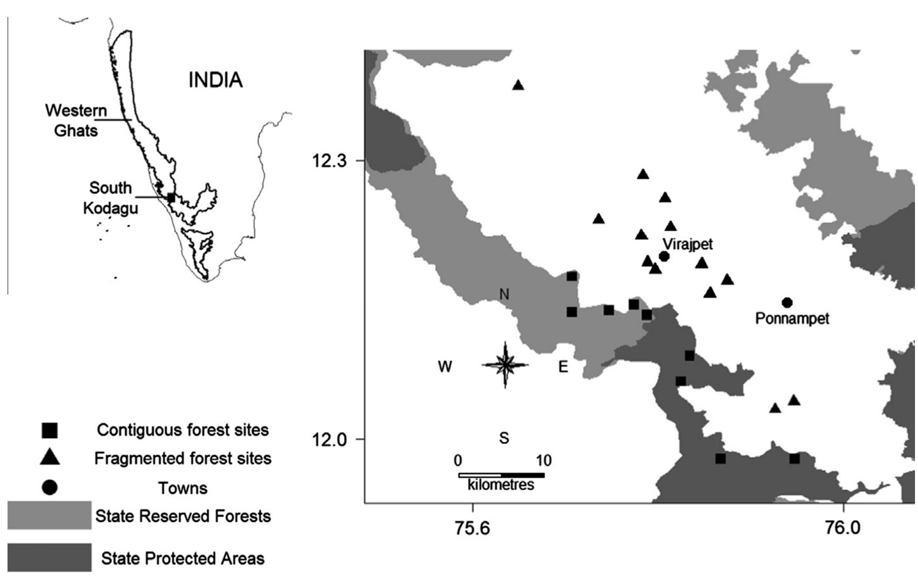

Fig. 1. Study area map: Location of study site (black rectangle) in the Western Ghats of peninsular India (inset), and map of study area showing study sites in south-western Kodagu. Forest cover data sourced from Muthu Sankar (2011) Map of the major forest types of the northern Western Ghats (Mercara-Mysore), through India Biodiversity Portal http://indiabiodiversity.org/.

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