Forest Degradation and Governance in Central India: Evidence from Ecology, Remote Sensing and Political Ecology

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Submitted in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy
In the Graduate School of the Arts and Sciences

COLUMBIA UNIVERSITY

2015

ABSTRACT

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There is no clear consensus on the impact of local communities on the resources they manage, primarily due to a shortage of studies with large sample sizes that incorporate multiple causal factors. As governments decentralize resource management to local communities, it is important to identify factors that prevent resource degradation, to inform more effective decentralization, and help the development of institutional characteristics that prevent resource degradation.

This study used remote sensing techniques to quantify forest biomass in tropical deciduous forests in Kanha-Pench landscape of Central India, and used these metrics to identify factors associated with changes in forest biomass. Kanha-Pench landscape was chosen because of its variation in forest use, and because forests were transferred over a period where satellite imagery was available to track changes. To verify that remote-sensing measured changes indeed constitute degradation, I conducted ecological studies in six villages, to understand changes in biomass, understory, canopy, species diversity and long-term forest composition in intensively used forests. To understand the impact of institutional variables on changes in forest, I interviewed members of forest management committees in fifty villages in the landscape, and tested which institutional variables were associated with changes in forest canopy since 2002, when the forests were decentralized to local communities. The empirical results are of particular conservation significance in

India, where further decentralization of forests to local communities in scheduled under the Forest (Dwellers) Rights Act, 2006.

Results indicate that local forest use is associated with decreases in forest biomass, understory, canopy cover, and changes in vegetation structure, species richness and diversity. Most importantly, I found that human use has the potential to alter long-term forest composition as transition of some species to higher size classes is altered where humans use forest more intensively. Particularly, species that are fire and trampling resistant are more likely to become mature trees in intensely used forests. Thus, local forest use is associated with forest degradation as the long-term trajectory of the forest is altered, and forests may not be able to provide ecosystem services including livelihood needs such as fuelwood, construction, and non-timber forest products in the future.

At a broader scale, remote sensing techniques (optical imagery Landsat and RADAR imagery ALOS-PALSAR FBD) were able to quantify forest biomass at an acceptable accuracy (~67%), while more easily operatable MODIS based EVI was not. Landscape analysis showed that changes in forest biomass from 2007 to 2010 were associated with high population density, high fire radiative power and greater distance to towns. Since people only travel ~2 kilometers for subsistence forest use, the significance of greater changes further from towns suggests that, at a broader landscape scale, forest degradation is not primarily due to local use, but may be a result of other factors.

Action taken to exclude outsiders and lower meeting frequency of committees (never) were identified as institutional variables associated with remotely-sensed positive change in canopy over the period when forest management was transferred (2002-2010).

Villages with no meetings were also associated with higher incumbency of committee Chairpersons and lower incumbency of other committee members. Simultaneously, while economic payments increased awareness and participation in forest management committees, economic payments were not associated with any action to exclude outsiders from forest use. This suggests that managers need to focus on factors besides economic payments to incentivize committees to exclude outsiders, especially as it is associated with positive changes in the forest. Further, while elite capture of resources (as indicated by incumbency and lack of inclusiveness in decision-making) is not helpful for social equity, it does not appear to be detrimental for forests.

Overall, this study suggests a number of management strategies to reduce forest degradation. Managers could focus on forests at a distance from towns and roads, as this is where most negative change in forests appears to occur. They could also work with local communities so that their use of forests does not prevent regeneration of species important for ecosystem services. Managers could also work with committees to find strategies other than economic payments for incentivizing community protection of forests.

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Satellite, Sensor, and Remote Sensing Acronyms and Abbreviations

ALOS	Advanced Land Observing Satellite
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
FBD	Fine Beam Dual Polarization
FBS	Fine Beam Single Polarization
HH	Horizontal-Horizontal Backscatter
HV	Horizontal-Vertical Backscatter
EVI	Enhanced Vegetation Index
LiDAR	Light Detection and Ranging
MODIS	Moderate Resolution Imaging Spectroradiometer
PALSAR	Phased Array type L band Synthetic Aperture Radar
RADAR	Radio Detection and Ranging
SAR	Synthetic Aperture Radar
TRMM	Tropical Rainfall Measuring Mission Satellite

General Abbreviations and Acronyms

AGB	aboveground biomass
AIC	Akaike Information Criteria
ASF	Alaska Satellite Facility
BS	bare substrate
CPR	common property resources
DBH	tree diameter at breast height

DEM	digital elevation model
FRP	fire radiative power
GIS	geographic information systems
GLM	Generalized Linear Model
GLMM	Generalized Linear Mixed Model
ha	hectare
JAXA	Japanese Satellite Agency
kg	kilograms
km	kilometers
m	meters
Mg	megagrams
PES	payments for ecosystem services
PV	photosynthetic vegetation
NASA	National Aeronautics and Space Administration
REDD	reducing emissions from deforestation and forest degradation
SCPM	size-class proportion metric
SMA	spectral mixture analysis
UNEP	United Nations Environment Program
USGS	United States Geologic Survey

ACKNOWLEDGEMENTS

The student who walked into the PhD in 2009 is completely different from the student who walks out, and I would like to acknowledge all those who made this transformation possible. First, and foremost, I would like to thank Dr. Ruth DeFries, who walked me through everything, held my hand when I was in trouble, pushed me to expand my horizons, and never dismissed any of my ideas. She made me a better leader, manager, writer, figure-maker, and thinker.

Next, I would like to thank my advisors and committee members, who routinely listened to my plans, results and analyses, and gave me insights into the project that I might not have considered. In order of appearance, I would first like to thank Dr. K. Sivaramakrishnan, who introduced me to the ideas of environmental anthropology and history at Yale, and was always enthusiastic about the potential of this project. He clarified my ideas when I was confounded by results or analyses, and made me feel like I was doing something worthwhile. Next, I would like to thank Dr. Joshua Ginsberg, who kept me inspired about wildlife biology and conservation, and who gave me the critical advise of not missing the forest for the data, and to keep my head up. Working with him always made me feel that my work was meaningful. Although not on my committee, Dr. Maria Uriarte made me a scientist: she taught me the scientific method as I wrote my proposal, and taught me the tools to be a scientist in helping me understand statistics and R code, and looking at my results when I needed. Next, I would like to thank Dr. Y. V. Jhala, without him this thesis would not have been possible. He was enthusiastic about my project, and provided me with institutional support and connections necessary for this project. His notes and comments on my plans and results were critical feedback. He made me think beyond statistical analysis and into the biological meaning of my findings. Next, I would like to thank Mr. Qamar Qureshi, who was a critical partner in this project, in discussing critical shortages in my study, along with providing me with their potential solutions and directing me to previously unheard of sources. The thesis would definitely not have been possible without him. Next, I would like to thank Dr. Christopher Small, who not only taught me the tools of remote sensing, but also how to think in terms of what is actually quantifiable. He also always stopped by for a chat on Morningside Drive and made me feel like I was making progress. I would also like to thank Dr. Eleanor Sterling who taught me the importance of looking at other perspectives. In addition, Dr. Dustin Rubenstein and Dr. Shahid Naeem helped by walking me through proposals and looking at my results when needed.

This acknowledgement would not be complete without acknowledging the help and kindness of the Madhya Pradesh Forest Department, PCCF (MP), CF (Jabalpur-Central Circle), DFO (Seoni), DFO (Balaghat), Dr Shukla, and other staff at the department. They provided me with permits, data, accommodation, and insights. Particularly, CF (Central Circle) gave me suggestions that formed a major part of my thesis.

I would also like to thank the Department of Animal Husbandry for data on livestock abundances, Survey of India for toposheets, and Forest Research Institute for their archives. NSF Grant Number 1029219 supported this research. ALOS-PALSAR data was provided by NASA's Alaska Satellite Facility. This project was approved under IRB Protocol Number IRB-AAAI1677 and Animal Care Protocol ACAAAE070.

This thesis and my PhD would not have been possible without the institutional support of Columbia University in the City of New York and Wildlife Institute of India, Dehradun. At Columbia, Lourdes Gautier, Maria Estrada-Werst, Chiconia Anderson, Jetaime McFadden, and Amy Kohn. Instructors for the classes I assisted with also gave me experience and insights, particularly Dr. Jill Shapiro and Dr Matt Palmer. The Ruth DeFries lab gave me suggestions throughout my thesis, particularly Pinki Mondal, Krithi Karanth, Victor Guitierrez, Matt Fagan and Meha Jain. Pinki and Matt went out of their way in familiarizing me with new technologies, and without them, this PhD would have taken another year, and Krithi always kept me motivated. In India, Dipanjan Naha, Jennie Miller, Ujjwal Kumar, Neha Awasthi, Suniti Bhushan Datta helped me through this process. In the field, I would not have managed without Jennie Miller, Amrita Gangatirkar, Rishin Basu Roy, Anshuman Tiwari, Kaustubh Mulay, Banty Jain, M. Nafiz, Harish Uikey, Kuldip Tekam, Dharmendra Tekam, Arjun Srivathsa, Vishnupriya S., Yamuna and Gyaani Marabi. A special shout out to all those who did field work the same time as me and made me feel part of a field work community: Atreyee Majumder in Howrah, Jennie Miller in Kanha, Dipanjan Naha in the Sundarbans, Nandini Velho and Umesh Srinivasan in Eaglesnest; and to those who formed my respite during field work: Shivani Satija, Noor Jailkhani, Kadambari Mainkar, Nandini Nair. I would also like to acknowledge my New York support system: Chintu Masi and the Banerjees, Shefali Masi and Vikrant, Gauri Anand, Sambuddho Chakraborty, Apoorv Agarwal, Akanksha Khatri, Virat Markandeya, Joseph Cohen, Yi-Wen Lin, Amir Nadav, Priya Narayanan and Atreyee Majumder.

Also, I would not have reached this stage without all my previous experiences that taught me things: Sardar Patel Vidyalaya, Fergusson College, Jawaharlal Nehru University, Wildlife Trust of India, Yale School of Forestry and Environmental Studies, and internships at Greenpeace, Centre for Science and Environment, Wildlife Fund for Nature-India, and Nature Conservation Foundation. I would not have thought it but this thesis ended up using insights and knowledge from all these institutions.

And, of course, none of this would have even been remotely possible without the folks at 1055: Papa, mama, Seher, Anasuya, Pallavi, Sahib, Munni, Ogu, Renu, Sanchita, Aloka, Subhash Mondal, or Harry Potter.

DEDICATION

To the Kanha-Pench Landscape and the community of wildlife biologists, ecologists, anthropologists, political ecologists, managers and activists who work to make the conservation movement what it is.

CHAPTER 1

Background and Scope

1.1 Introduction

The impact of communities on the commons has been intensely debated since 1968 when Hardin argued that humans would necessarily degrade open-access resources without secure tenure (Hardin and Baden, 1977), and that private ownership or state management would support sustainable use (Agrawal, 2001). As this idea was translated to policy, and land with unclear tenure was transferred to private or state management, critique of Hardin's argument mounted (Ciriacy and Bishop, 1975, Runge, 1986, Ostrom and Nagendra, 2006). Critics argued that, in fact, lands with unclear tenure were managed by communities (Runge, 1986). These critics found that management by local communities often conserves resources (Feeny et al., 1990; Ostrom and Nagendra, 2006), which subsequently led to widespread adoption of practices that delegate resource management to local communities (Smith and Wishnie, 2000; Bowler et al., 2012). As early as 1998, governments in over 50 countries claimed to pursue initiatives that would decentralize resource management to local users (FAO, 1999; Brown, 2002).

Yet, as community resource management becomes more common (Feeny et al., 1990), and resources are transferred from state management to communities (Smith and Wishnie, 2000; Agrawal, 2001; Carlsson and Berkes, 2005), little is known about the effect that this transition has on the resource (UNEP, 2010; Bowler et al., 2012). There are several studies that show that decentralized community management correlates with more abundant resource (trees, species richness: Aggarwal et al., 2006; Mishra and Banerjee, 1997; Nagendra et al., 2008; Blomley et al., 2008; UNEP, 2010; fisheries and lobster: Acheson, 1975; Berkes, 1977; Schlager and

Ostrom, 1992; water: Wade, 1988), and many that show the opposite (Mishra et al., 2001; Johnson and Nelson, 2004; Siren, 2006). Therefore, there is little consensus on the effect of community management on the resource.

There are several reasons for this lack of consensus on the impact of community management on resource conservation. Most analyses of community management of natural resources have been based on case-studies rather than multi-site studies that explicitly identify factors associated with effective management at a given time (Agrawal, 2001; Agrawal and Chhatre, 2006). Very few studies attempt to identify causal impacts of community management by eliminating alternative explanations through hypothesis testing (Agrawal, 2001; UNEP, 2010), and even fewer attempt to study the impact of change in management on resources (UNEP, 2010). Therefore, few studies account for the original forest cover or baseline data when studying impact of community management, and many rely on memory and recall for this (UNEP, 2010; Bowler et al., 2012). Further, few studies account for other biophysical, socio-economic and institutional variables that may influence the effectiveness of management (Bowler, 2012). These are important to account for as forest type, elevation slope, climate, population change, and market access correlate with resource degradation (Agrawal and Chhatre, 2006; Nagendra, 2007; Ghate et al., 2009; Persha et al., 2011), and can confound studies testing the importance of other factors (Agrawal and Chhatre, 2006). Within studies that do exist, many rely on empirical designs that do not correct for selection effects and other sources of bias (UNEP, 2010) or where accounted for, the factor of interest may be correlated with some other variable, making it impossible to test the impact of the factor of interest (Agrawal, 2001).

Therefore, there is a need for studies with large sample sizes incorporating multiple causal factors that quantify changes in resource with changes in management, while controlling for baseline resource, technology, market access and strength of local institutions (Agrawal, 2001). A multi-site, multi-factor study will help identify biophysical, demographic, socio-economic and institutional pre-requisites that aid community management and that prevent resource degradation (Agrawal, 2001). In comparison with resources such as fisheries or ground water, forests may be a better resource to use as a response variable, as they are highly visible and more easily quantifiable.

1.2 Forest Degradation in Tropical Deciduous Forests

Quantifying forest degradation is complex as there are multiple debates around the definition of forest degradation itself (Sasaki and Putz, 2009; Turner et al., 2007; Olander 2008). Some define forest degradation as loss of biomass without change in area of forest cover (Olander, 2008), while others counter that the definition of forest itself should exclude plantations, and that forest degradation should include loss of ecosystem services, especially those essential for locally dependent people (Sasaki and Putz, 2009). Still other studies use variables such as soil nutrients (Seibert 1987), vegetation structure, and species diversity (Kumar & Shahabuddin 2005; Lefevre 2011, Nagendra 2012) to assess whether a forest has been altered so that it can no longer provide ecosystem-services or support livelihoods (Garcia 2008). Yet, some of these variables are poor indicators of the long-term impact on the forest. Forests that appear sustainable using these metrics may not be able to provide similar services in the future (Scheffer 2001; Heywood 2003) as the extent and intensity of use may already have altered the long-term trajectory of the forest and future forest composition may be very different from present forest composition.

Forest degradation is further complicated by the potentially long-term interactions of humans and their environment that may be responsible for the structure and community composition even in forests considered 'natural' (Heywood 2003). In such a scenario, it is difficult to establish baselines, rates of change, and assess when a forest may be considered 'degraded'. In this, use of data-driven analysis has the potential to understand long-term processes and human uses (Willis and Birks, 2006) in order to understand natural variations in disturbances (Lenoux et al., 2007; Warren et al., 2007), their underlying mechanistic processes (Cumming, 2007), and the resilience (Folke et al., 2004) of a given ecosystem.

Nevertheless, these changes impact ecosystem services such as hydrology, carbon storage and habitat for biodiversity (Fischer and Lindenmayer, 2007). Many current policies to promote ecosystem services and climate mitigation include incentives and payments to sustainable users of forests (Sasaki & Putz 2009; Hein 2012). Yet, it is difficult to assess whether a forest can continue to support livelihoods and provide ecosystem services in the future (Bawa & Seidler 1998; Garcia 2008; Schmidt 2011) and under what conditions of use it can do so (Ticktin 2004).

1.3 Remote Sensing as a tool for mapping forest degradation

Several strategies have been used to quantify forest components such as canopy, understory, biomass, structure and species composition as it is expected that changes in these components could serve as metrics for forest degradation. For instance, some researchers measure canopy opening and gaps and their changes over time as a measure of degradation (Asner et al., 2005; Matricardi et al., 2013). Others classify forests as degraded based on differences in heights of forest crown and other lower canopies (Falkowski, 2009; Kim, 2009; Margono, 2012; Martinuzzi, 2009). Yet other studies focus on measuring forest biomass (Englhart, 2011; Saatchi,

2009) because lower biomass constitutes degradation. Studies also classify forests as degraded based on changing forest composition. For instance, Asner and Vitousek (2007) mapped encroachment of invasive species because forests with invasive species may be considered degraded. In another example, Kim (2009) quantified average heights of forests with different species compositions, and classified forests as degraded based on forest composition. These techniques use a combination of optical sensors, RADAR, hyperspectral and LiDAR to ascertain and quantify degradation. However, since forest degradation varies with forest type, type of use and the type of changes that result from human use, it is important to understand which technique is most suitable for quantifying human-induced change in a particular study region.

Many of the successes in quantifying forest degradation are located in evergreen forests in the Amazon or South-East Asia (Asner et al., 2005; Englhart, 2011; Margono, 2012). There have been fewer attempts to quantify forest degradation in tropical deciduous forests. Human use in tropical deciduous forests cause changes in forests that are different from changes observed in other parts of the world (Olander, 2008). Deciduous forests form 17% of tropical forests (UNEP, 2000) and are ecologically different from rainforests (Sasaki and Putz, 2009). Structural differences include open canopy forests with low crown cover (UNEP, 2000) and high heterogeneity so that it is important for researchers to map variations in the existing forest before they can detect deviations from a relatively unused forest (Olander, 2008). These open canopy and dry forests are also more heavily used than rainforest because the former have higher human population densities and are thus highly threatened (Gaston et al., 1998; Miles et al., 2006). There is also evidence that these forests have been used for a longer time period that makes it difficult to establish baselines and ascertain what is ‘natural’, which complicates our interpretation of what constitutes a degraded forest as opposed to a relatively unused forest.

Therefore, there is a need to develop metrics for degradation in this understudied biome.

1.4 Promoters and Inhibitors of Forest Degradation

Understanding processes that lead to forest degradation can contribute information useful for efforts to reduce degradation. Forests can be altered by subsistence uses such as grazing, firewood removal, and small understory fires (Gaston et al., 1998; Olander, 2008) or large-scale market demand for timber, or global commodities such as oil palm or soy (Olander, 2008; Houghton, 2012). While clearing by subsistence farmers and land conversion for commodity production are drivers of deforestation (Lambin et al., 2003; Houghton, 2012), cattle-grazing, extraction of timber and fuelwood, and fire are practices that may be responsible for reduction in forest biomass (Asner et al., 2005; McApline et al., 2009, Houghton, 2012, Ahrends, 2010).

Simultaneously, several management practices serve to prevent deforestation and degradation. Several meta-analyses have found that parks, where local communities rarely manage resources, are effective at preventing deforestation and maintaining diversity (Bruner et al., 2001; DeFries et al., 2005; Naughton-Treves et al., 2005; Nagendra, 2008; Coetzee et al., 2014), although these may not be representative due to non-random park placement. Other studies find that effective community management may also conserve forests, although the impact of decentralization and local empowerment on conservation has also been questioned (Murphree, 2002; Landel-Mills and Serageldin, 1991; Henkel and Stirratt, 1996; World Bank, 1997; Guhan, 1998). Researchers suggest that where conservation does occur, it might be an unintentional by-product of community management rather than an intentional goal (Smith and Wishnie, 2000), and it is important to distinguish between the two as unintentional conservation may confound our understanding of factors that promote resource conservation.

As processes that promote and inhibit forest degradation exist simultaneously, and have different impacts at different scales, an effective conservation strategy requires that these processes be examined simultaneously.

1.5 Research Objectives

In this dissertation, I aim to gain a comprehensive understanding of forest degradation and governance and their impacts on the forest. This study is focused on a specific study region, where human activities that promote and inhibit forest degradation are examined simultaneously, and at various scales because processes may have different impacts at different scales.

I do this through a large-scale multi-site study with a large sample size, which enables the study to test several important questions in the landscape, with a larger aim of being useful to policy makers. This entails the use of field-based ecology, remote-sensing based landscape analysis, and interview-based political ecology applied at different scales in order to understand the ecological impacts, landscape processes, and human motivations and actions at appropriate scales. This dissertation reaches these goals by accomplishing the following objectives:

(1) Understanding the long-term impact of human use on forests, in addition to human impact on present forest attributes in order to understand forest degradation.

(2) Developing methods to quantify forest degradation at a landscape scale in order to understand drivers of forest degradation.

(3) Understanding the impact of decentralized forest governance on the resources they manage, and testing which variables are associated with positive change in resource.

1.6 Study System

It is particularly important to understand forest degradation and governance in tropical deciduous forests, which are studied less frequently than other forest types (Miles *et al*. 2006). Strong seasonality of these forests makes them ecologically very different from other tropical forests (Sasaki & Putz 2009). These forests are also highly threatened, as they are often located in highly populated areas (Miles et al. 2006). These forests are also difficult to study due to their natural heterogeneity and absence of forests that can serve as controls (with no historical human use). This is because the long history of human habitation and management in tropical deciduous forests suggests that long-term interactions of humans and their environment may be responsible for the structure and community composition even in forests considered 'natural' (Heywood 2003).

India is particularly well situated to be an appropriate study system, as its forest management has been well documented since the 1870s (detailed in Section 1.6.1). Further, since the 1990s, several regions have been implementing a Joint Management Scheme (explained in Section 1.6.2), wherein the management rights of plots of forest land is transferred to local communities (village forest management committees). Therefore, each village is a potential sample site with sufficient variation to enable a multi-site, multi-factor analysis of community-managed forests.

1.6.1 History of Forest Management In India

History of forest management in India prior to British colonialism is not very well documented, although scholars have used historical documents records and archaeology in an attempt to reconstruct it. One early work reports that forests in India were managed sustainably by local communities until disrupted by the scientific forestry of British colonialism (Gadgil and Guha, 1993). Other research claims that pre-colonial forest management was not this homogeneous, and differed between ruling dynasties and communities (Guha, 1999; Sivaramakrishnan, 1999; Rangarajan, 1996). Depending on the control extended by the ruler, management measures extended from outlawing timber-felling, to delegating management to local rulers (Guha, 1999; Skaria, 1998), to local management practices such as shifting cultivation (Prasad, 2003).

At the very least, historians have documented a shifting forest frontier, where conditions such as increased taxes would lead to reduction in land under agriculture and an increase in forest area while reduced taxes and weather patterns led to retreating forests (Rangarajan, 1996, Sivaramakrishnan, 1999; Skaria, 1998). Forests also did not have the same distribution as they do now, or even when the British colonized India (Guha, 1999). In addition to a shifting frontier, forests were maintained at the frontier of empires to make enemy attack more difficult (Parashar-Sen, 1998), and the present distribution of forests may reflect the old borders of empires (for instance, the Kanha-Pench corridor lies between the Mughal and Maratha empires in the 18th century). Forests were also planted by ruling agrarian empires (Parasher-Sen, 1998; Guha, 1999). However, the forest that regenerated was very different from the original forests and historians report that regenerating forests were a mass of bushes (Guha, 1999), had high understory and less tree growth (Prasad, 2003), or consisted of *Mimosa* and *Acacia* genera (Guha, 1999). Historians also report that these sorts of bushes and thorn forest had to be removed else they would remain in that state (Guha, 1999). This suggests that the forest formed due to human use was very different from the natural or original forest.

To briefly summarize the history of forest management in India, in ancient times, during the Mauryan empire (322-185 BCE), forests were maintained on the borders of empires, forest peoples were integrated in the armies of the Mauryan empire, and harvest of certain forest resources was restricted to the empire (fish, game, and elephants)(Trautman, 2012; Parasher-Sen, 1998). However, the impact of such restrictions on local populations is unclear (Parasher-Sen, 1998). The extent to which such policies were followed is also unclear as central control was not monolithic and was especially incomplete in forested areas (Parasher-Sen, 1998). At this time, forest management differentiated between ‘material forests’ that were a source of forest products and the superior ‘elephant forests’, considered superior because they housed economically and militarily importance elephants (Parasher-Sen, 1998). This suggests that even at this time, imperial agents were involved in managing forests. This management also yields an early example of wildlife management as the *Arthashastra* (a treatise on statecraft and economic policy of the time) recommends that the superintendent maintain a census of wild populations in ‘elephant forests’ and impose a death penalty for killing an elephant (Trautman, 1982).

During the medieval era, two ruling agrarian empires: the Mughal (1526-1857 C. E.) and the Maratha (1674-1818 C. E.); clashed with each other for territories, and maintained a forest belt between their territories. Records from this period have been used to demonstrate the expansion and contraction of forest frontiers as they relate with climate, taxation and government policy (Rangarajan, 1996). At this time, too, extraction of certain forest products was a royal prerogative. For instance, in some locations under the Mughal empire, locals could trap smaller animals like quail and hare but not larger game animals (Rangarajan, 2001, p17-18). Officials from the Maratha Empire have been reported planting teak and clearing ‘degraded’ forest (Guha, 1999). At these periods, there is little evidence that harvest of other forest resources by local people was curtailed.

Forest management under British colonial rule altered two things. First, they redirected the management of forests to maximize production of timber to supply market demand in Europe and lay the Indian railway system (Gadgil and Guha, 1993; Agrawal, 2005). This entailed introduction of scientific forestry (Agrawal, 2005), prevention of forest fires (Gadgil and Guha, 1993) and altering the forest composition of existing forests (Sivaramakrishnan, 1998). Second, they were interested in protecting forests and legislated a number of laws that limited the access of local people to the forest (REF). Significant legislations from this period include Forest Charter of 1855, where the first Inspector General of Forests was appointed, the Forest Department was organized and the trees of India were inventoried; the Indian Forest Act of 1865, amended in 1878 and 1927, which empowered the government to appropriate any land covered with trees, removed privileges and rights not explicitly granted by the state, and converted common property into state property (Gadgil and Guha, 1993). The Indian Forest Service was also instituted in 1864 under German forester Dr. Wilhelm Brandeis, and was made responsible for managing the forests (ifs.nic.in). In doing this, they were made sole purveyors of the forest as the foresters successfully argued that revenue officers would succumb to local pressure and convert land as a political solution to civil disputes and disturbances (Sundar, 2000, p29). This led to the formation of a category of villages called 'forest villages' that came under the management of the Forest Department rather than the civil government.

Upon gaining Independence in 1947, India's forest management continued to mirror the policies of its predecessor. It was only in 1972 that a new law, the Wildlife (Protection) Act, 1972 (WPA henceforth) was legislated, following drastic declines in wildlife populations that had occurred during British colonialism and the period following it. Population declines were attributed to hunting as most people could obtain a hunting license (Rangarajan, 2001). In 1913, lion populations had reduced to 13, and bounties claimed up to 50,000 wolf pelts a year (Rangarajan, 2001).

In forming a law for the protection of animals, the WPA was part of a larger global movement towards establishment of laws protecting species and establishing protected areas for their survival. The popularity of 'Silent Spring' had fuelled the environmental movement as one of the new social movements of the 1960s in the USA (Forsyth, 2003). Since most protesters were middle class Americans, this movement prioritized educated ideals such as Romantic natural beauty, and the preservation of biodiversity with an inherent right to exist which echoed earlier movements for preservation of natural sites in the West and in a few localities outside the west such as the Serengeti (Forsyth, 2003). Several transnational NGOs such as WWF and WCS were established in this period with a mandate to stem the biodiversity crises, although IUCN, an intergovernmental panel on biodiversity, was established earlier. These institutions aided the spread of the conservation agenda in the developing world and protected areas increased from 36 to 93 million square kilometers from 1971 to 1992 (Orlove and Brush, 1996).

In India, in addition to banning the hunting of wildlife, WPA was also used to establish wildlife sanctuaries, national parks, and tiger sanctuaries. Of these, national parks are set aside for complete protection where neither human activities, nor harm to wildlife is allowed, while wildlife sanctuaries were legislated to allow human activities as long as wildlife was protected. With decline in tiger populations, specific national parks were set aside as tiger reserves and these tiger reserves were focused on protecting the tiger. However, protection became stricter in 2002, when a Supreme Court ruling prevented human activities in wildlife sanctuaries as well (Robbins et al., 2009).

This sort of separation of nature from human activities was contested since the British first began restricting human activities in forests. Several historical studies report of intentional burning of forests, and covert use of forests by locals as resistance against such exclusion (Agrawal, 2005). Critics argue that separation of nature from human activities is essentially a western idea, and causes great injustices to inhabitants of the landscape.

This criticism was also part of a wider movement where researchers articulated the rights of indigenous communities and local people to natural resources and spaces (Peluso, 1992; Guha, 1997), and proposed that the fortress model of conservation had failed (Cronon, 1995, Brechnin et al., 2002; Sarkar and Montoya, 2011). They hypothesized that isolated islands of conservation would not succeed if surrounded by underdevelopment (Brechnin et al., 2002) as local people would aid poachers (Damodaran, 2007) and human-wildlife conflict would increase (Mishra, 1997; AFSG, 2007). The Brundtland report (1987) and the Convention on Biodiversity (1992) supported sustainable development, wherein environmental conservation, economic development and social equity would be simultaneously achieved (WCED, 1987; CBD, 1993), leading to an ecosystem approach to conservation, and the models of integrated conservation development projects (ICDP) (Albert, 1996), conservation-as-development (Naughton-Treves et al., 2005) and the Man and Biosphere Project (Price, 1990). Poverty alleviation was now an essential part of biodiversity conservation (Miller et al., 2011). To involve local communities, there was a greater emphasis on traditional environmental knowledge and community resource management (Berkes, 2004). It is in this context that Joint Forest Management (JFM) began in India (detailed in Section 1.6.2)

The imposition of 'western' conservation in the third world through historic colonialism and present-day advocacy of transnational environmental NGOs and aid agencies was considered problematic. Critics argue that the primacy given to wilderness preservation and biodiversity loss reflected the priorities of middle-class activists in the new social movements in the Global North rather than the global population they sought to represent (Forsyth, 2003).

In India, however, despite the legislation of WPA, a separation of nature from humans has not been achieved. Besides protected areas, there is another category of forests called 'reserve forests', which are multipurpose forests that are used for timber production by the Forest Department, for livelihood needs by local people (with rights varying by state), and by local wildlife. These forests could also be diverted for non-forest purposes, but this process was made more difficult with the Forest (Conversion) Act of 1980.

In addition to this, people originally living in the forests that had now been designated as wildlife sanctuaries, national parks and tiger reserves were still living there as very few people had been relocated from these forests. Since they lived in land that was technically a protected area, they did not have legal tenure, and lived at the privilege of the forest department (Kashwan, 2013). The movement for their claim on the forest became galvanized as a human-rights issue. Advocates claimed that narratives of environmental crises were used to deprive communities of their historic access to resources, impose unnecessary restrictions (Forsyth, 2003) and justify the use of military force to protect animals and trees against local inhabitants (Peluso, 1993).

By the new millennium, this movement had achieved sufficient momentum to lead to the legislation of the Forest (Dwellers) Rights Act, 2006 (henceforth FRA). This act seeks to redress historic injustices and inequities to people living in forests (Bose, 2013; Kashwan, 2013) by providing individual and community land rights to those already settled in these forest areas. This was justified using research on common property theory which found that local communities could create institutions to sustainably manage resources through 'moral economy'

(Ostrom, 1990). In the 1990s, studies in political ecology claimed that environmental conservation, social equity and redressal of historic injustices could be simultaneously achieved through decentralization and devolution of resource control to local communities (Section 1.1).

The FRA aims to provide two types of rights to forest dwellers. One is considered less problematic: individual land rights are given to families who have been cultivating land within the forest, and they now have tenure on their cultivated land. The other is more contentious: community rights grant the community living in the forest the right to manage the forest as they wish (Bose, 2013; Kashwan, 2013). This is contentious because Forest Department managers and conservation biologists argue that even if forest use was sustainable historically, population densities have increased since that time, as have market access, technology and aspirations. Therefore, presently, simultaneous use of forests by wildlife and people is untenable, particularly for tigers (and dholes) due to depletion of prey base by humans (Srivathsa et al., 2014). However, as of now, 400 villages in Maharashtra have been given community rights over forests, and 2000 villages in Odisha are expected to get community rights in the near future.

At around the same time as FRA, a new controversy surrounding the extinction of the tiger in a premier tiger reserve (tiger extinction in Sariska in 2005) redirected attention to tiger conservation. For this, a National Tiger Conservation Authority (NTCA) board was established under the WPA, to identify areas of significant wildlife importance. These critical wildlife habitats were well-funded and prioritized for relocation of people living in them. The NTCA has notified (term used by Indian government for designation) several new tiger reserves since its inception, and in doing so, has converted not only national parks and wildlife sanctuaries into tiger reserves, but also reserve forests that had hitherto allowed human activity (National Tiger

Conservation Authority, 2014). In many instances, people have to be relocated from forests under WPA, while simultaneously getting rights under FRA.

Therefore, there is a critical need to understand the impact of human use on management of forests in India as these landscapes continue to be used by tigers, wildlife, people and the state. To do this, we focus on forests under Joint Forest Management (JFM) in India (detailed in Section 1.6.2). These are multipurpose forests used by people, wildlife and the state, and are an example of an earlier example of decentralization to local communities. While FRA is still to be implemented in most states, examining JFM allows us to study the impact of community management on forest resources as it has been under implementation for ten to twenty years.

1.6.2 Joint Forest Management in India

Joint Forest Management (JFM) is a scheme for co-management of forests by the forest department and local communities. It was introduced through a national announcement and memorandums circulated to the states by the Ministry of Environment and Forests in 1990 (Sundar et al., 2000, p 4). This was given impetus by a new National Forest Policy Resolution in 1988, and a 1988 speech in the Lok Sabha (Indian Parliament) by the Minister for Environment and Forests that "used a new vocabulary" and emphasized the need for forest management to meet the basic needs of the people (Sundar et al., 2000, p 4). Within internal Forest Department documents and donor documents, the idea for JFM arose in East Midnapore district in West Bengal where local communities and the Forest Department worked together following conflict because villagers' needs were not met (Sundar et al., 2000, p 7). The deal negotiated between the local community and the Forest Department included that villagers could collect Non-Timber Forest Produce (NTFPs) and would receive twenty five percent of the sale value of Forest

Department-managed timber harvest. By 1988, over 500 committees had been formed, and over 70,000 hectares of forest were managed through Joint Forest Management (Sundar et al., 2000, p 8).

There were several rationales for the advent of JFM in India. Scholars suggest that the most important rationale for JFM was meeting the forest and livelihood needs of local people who had been excluded from their customary rights, and who expressed discontent with the favoring of commercial forestry. Alternative avenues for accessing wood products from farm forestry meant that forests were not as important in providing these resources. Other reasons were a realization of the limits of policing forest use and international pressure for environmental conservation and supporting local livelihoods (Sundar et al., 2000, p 13) as expressed in the Brundtland Report or Our Common Future (1988). Similar JFM movements were also initiated in other countries at the same time (Phiri, 2009).

1.6.3 Focal Region

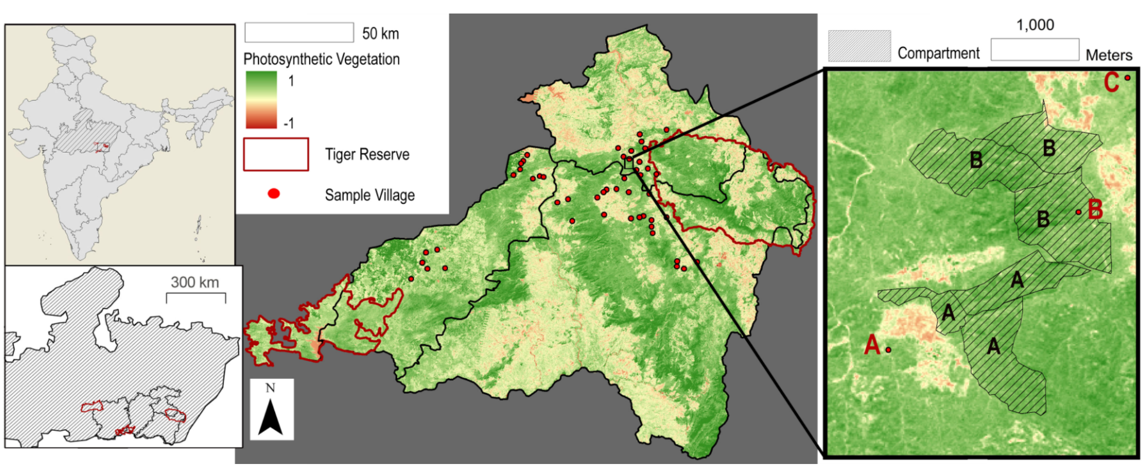

Figure 1: Study region. Letters in red indicate village, letters in black indicate forest managed by that village. Letters used to protect identity of village.

Within India, this dissertation's focal study region was located in dry tropical forests between Kanha and Pench Tiger reserves in Mandla, Balaghat and Seoni districts in Madhya Pradesh state in India and covered three forest divisions (East Mandla, South Seoni and North Balaghat: Figure 1; Table 1). The forests in the study region are typical of deciduous forests as they are highly seasonal, with leaf fall concentrated in the summer months. Fires generally occur during the dry season (Feb to May) and rainfall is concentrated in the monsoon months (mean annual rainfall is 1315 mm: India Water Portal, 2014). This site was chosen for its high forest cover (forest cover exceeded 30% in all 3 districts: Forest Survey of India, 2011), heterogeneous forest cover that included sal (*Shorea robusta*), teak (*Tectona grandis*) and miscellaneous forests as well as its importance for ecosystem services such as hydrology (part of the area is a watershed for River Narmada), and biodiversity (two protected areas with endangered species such as tiger *Panthera tigris* that use the unprotected forests as corridor between protected areas: Sharma et al., 2013). The region is of immediate concern as the Forest Department is in the process of designating these forests as a wildlife corridor area. Management of forest resources, therefore, becomes vital to wildlife persistence in the area.

1.6.4 Joint Forest Management in Madhya Pradesh

The Indian government has a quasi-federal structure and thus legislation and policies can differ widely between states. Joint Forest Management in Madhya Pradesh (MP) was a direct result of the central government's JFM policy in 1990 (Sundar, 2000, p69). In the very next year, the state passed its own order "Community participation in preventing illicit felling and rehabilitation of the forests" (Sundar, 2000, p69). This order was further revised in 1995 following World-Bank funding for JFM in MP and this was to be implemented in two phases (1995-2000, 2000-2005).

Three types of forest management committees were formed for different types of forests: Village Forest Committees (VFC) or *Gram Van Samitis* (GVS) where forest cover within 5 kilometers was poor, Forest Protection Committees (FPC) or *Van Suraksha Samiti* (VSS) for villagers near (<5 km) the forest, and Eco-Development Committees (EDC) in Tiger Reserve Buffer areas where human use was limited and payments included compensation for lost livelihood. People living within Tiger Reserve Core areas were to be relocated since this is an inviolate area for wildlife and habitat protection. It is important to note that all these forests are owned by the Forest Department, although Tiger Reserve forests are managed by the central government while reserve forests are managed by the state government.

When the order was first implemented in 1991, FPCs were to receive 20 per cent of net income from areas protected in return for protecting the forest. In 1995, this was modified and FPCs were now to receive free *nistaar* (nistaar is the customary right of people to harvest forest produce). Later still, FPCs were to receive nistaar, supplies from thinning, and 10 percent of final harvest from area protected (Sundar, 2000, p70).

Therefore, JFM in MP was top-down, influenced by an ICDP (World Bank) and aimed at conserving forests and preventing illegal use. It did not actually transfer management rights to local communities (although they are expected to make micro-plans for their forests), but was aimed at aiding the Forest Department in protection in return for some privileges. However, in implementing JFM, Madhya Pradesh was more generous that other states: it provided nistaar rights when other states were taking them away; it transferred even ‘good’ forests when most states only included 'degraded' forests; and the initiative came from the government and did not have to be demanded by the people as in other states (Sundar, 2000, p68-70).

1.6.5 JFM in the Kanha-Pench Landscape

A total of 1245 forest plots have been transferred from government management to local communities since 1996 in these three divisions in the Kanha-Pench landscape (East and West Mandla, North Balaghat and South Seoni divisions), with a bulk of the transfers and implementation occurring since 2001. Of these, 51 forests are now managed by Eco-Development Committees (EDC) in buffer zones of the protected areas, where there is much stronger external support to forest management through funding and technical support; 489 forests are managed by Village Forest Committees or *Gram Van Samitis* (GVS) which began with very degraded forests in 1996, and where the initiative has centered around community based afforestation; and the remaining 705 forests are managed by Forest Protection Committees or *Van Suraksha Samitis* (VSS). All three committees are elected bodies within the village, that are responsible for planning, hiring and managing the proceeds from Non-Timber Forest Products, planning future planting, and sharing the dividends from logging. This site further allows us to test whether economic benefits increase participation in resource management as only half the committees have received these shared profits to date.

1.6.6 People and forest use in Kanha-Pench Landscape

There has been little deforestation in the region since 2006 (Forest Survey of India, 2011) and people use forests differently depending on whether the forests are located in protected areas where use is minimal, or outside protected areas in reserve forests where forest use can account for up to 60% of income of local people (Saigal, 2010). Population density in the region also varies with distance from major towns and villages, and villages far from towns usually have lower populations, although average population density in all districts is >157 people per km^2 (Census of India, 2011). The districts contain rapidly growing populations, and development activities have led to increased literacy (Census of India, 2001; 2011). However, the populations are still predominantly rural. A majority of the population is not employed in an organized sector (Census of India, 2001), and these non-workers and marginal workers can be expected to depend on the natural forests in the area. All three districts are Schedule V districts, areas with special provisions for the protection of high tribal populations living here (lawmin.nic.in). On the surface, there appear to be some differences in the people and their economic activities in the three districts as Balaghat district has a highly developed mining sector and a forest insurgency issue, while Seoni has more irrigated agriculture. However, Table 1 suggests that the states are by in large quite similar.

Districts	Mandla	Balaghat	Seoni
Population Density in 2001	154	162	133
Population Density in 2011	182	184	157
% Literacy in 2001	60	69	66
% Literacy in 2011	68	78	73
% Rural Population	89.7	87.1	89.7
% Non-Workers	48	50	51
% Marginal Workers	16	17	16
% Forest Area	48.86	54.13	35.21

Table 1: Basic Information about Study Region
(Source: Census of India, 2001 and 2011; State of Forest Report, 2009)

The local people depend on forests for grazing, fuel wood and other subsistence needs (Saigal, 2008). People use forests seasonally, where they collect subsistence-use forest products throughout the year, and collection of non-timber forest produce (NTFP) for sale to markets is concentrated in the summer months. Important forest produce includes *Dendrocalamus strictus*, *Madhuca indica* and *Diospyros melanoxylon*, and use of fire augments the production of the latter two products. The main activities in the forest include cattle grazing, collecting firewood and other non-timber forest produce (NTFPs), and fire to augment production of NTFPs.

The forest department also uses the trees in reserve forests for timber. Extraction of timber by local people is outlawed, although they may collect a head-load of dry wood for subsistence. The legal way to procure timber is through a Forest Department auction, where contractors and local people can purchase timber that is selectively logged in these forests based on silvicultural plans laid out by the Forest Department in the management plan of the compartment.

There is evidence of people living in these forests since 323-185 BCE (Parasher-Sen, 1998). Some forest dwellers known as *Aranyacaras* at the time were documented as forest-dwellers (Parasher-Sen, 1998). These correspond to the Baiga people in the study region today. The activities of others, known as the *Atavikas* at the time, were integrated with larger historical processes (Parasher-Sen, 1998; Skaria, 1998; Guha, 1999; Rangarajan, 1996; Prasad, 2003), and historical studies have established the transformation of these forest tribes into agrarian landlords and viceversa (Guha, 1999; Rangarajan, 1996; Skaria, 1998). These correspond to the Gond people in the study region today. Further, forest communities are not historically known to be sedentary, and have been recorded as migrating to new areas (Guha, 1999; Sivaramakrishnan, 1999; Skaria, 1998; Sundar, 1997). Research in this locality further suggests that the Gonds were possibly sedentary cultivators, and marginalization from the 17th century led to their dependence on hunting, gathering and shifting cultivation (Prasad, 2003).

1.6.7 Limitations in answering question

Our choice of study area does pose certain limitations in addressing the question that is central to this thesis. Joint Forest Management in Madhya Pradesh was very top down and the state's explicit aim was to use JFM to help protect the forests (Sundar, 2000). In doing this, JFM in Madhya Pradesh does not create conditions where local communities could drive the Joint Forest Management, take initiative, or plan to work the forest in a manner that departed from its protection. For instance, in my study area, local communities were interested in planting *Eucalyptus* in their forests. This plan did not meet the approval of the local Forest Department because Eucalyptus has been documented to be harmful to the water table and other species. Therefore, such conflicts between the needs of the environment and livelihood needs (quick growing, harvestable species) were usually resolved in favor of the Forest Department. the potential of JFM was always limited in that the community did not have as much say in the management of the forest.

However, given the vast preponderance of similar schemes in the world, JFM in Madhya Pradesh is representative of decentralized resource management across the globe. International agencies such as World Bank have been promoting decentralized forest management, and decentralization has been top-down in most instances where it was implemented (World Bank, 2014). Therefore, while MP may not be ideal in terms of theoretical conditions, it is representative of ground realities.

1.7 Dissertation Structure

Forest degradation and governance appear to be key elements in coupled-human environment interactions, especially since protected areas are unlikely to increase and forests face the twin dilemmas of providing wildlife habitat for its intrinsic value and ecosystem services that include meeting human livelihood needs. However, our understanding of forest degradation (what it entails, how to measure it, what causes it) and effective forest governance (controlling for large number of variables, what factors improve forest quality) is limited. When they have been assessed, studies have largely focused on deforestation, and tropical deciduous forests are understudied, and few studies have examined landscape drivers in India (but see Velho et al., 2014). Governance studies are limited by sample size and use of baseline information. Overall, there is a lack of communication between different disciplines and the metrics they employ. This dissertation begins to fill that gap with a multi-factor, hypothesis-based multi-site study with a large sample size that combines analyses of ecological studies, satellite imagery, and political ecology to understand forest degradation and governance in Kanha-Pench landscape region in Central India.

The specific questions of this dissertation research are:

1. How does local forest use impact forest structure and regeneration? (Chapter 2)
2. How well can remote sensing quantify structural elements of the forest, and thus quantify forest degradation? What impacts forest degradation at the landscape-scale? (Chapter 3)
3. What institutional variables are associated with change in forest quality? (Chapter 4)

To answer the questions above, I first undertook an ecological study to understand the impact of local human use on forest structure and regeneration (Chapter 2). I then developed remote sensing methods that used optical and RADAR satellite imagery to quantify forest biomass, whose change was labeled as degradation (Chapter 3). I used these methods to understand factors associated with change in forest biomass at the landscape-scale. Finally, I used these to understand the impact of community participation and representation on change in forest degradation (Chapter 4).

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CHAPTER 2

Measuring sustainability of use and its drivers in dry tropical forests in Central India

Short title: Degradation in human-used forests in India

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SUMMARY

1. Understanding forest sustainability and its drivers is important to help formulate effective policies that promote future ability of forests to provide local livelihood needs, habitat, and ecosystem services. This is particularly important in dry tropical forests that are ecologically different from other forests and are heavily used by local, forest-dependent residents.

2. This study assesses sustainability in tropical deciduous forests of Central India by measuring abundance and size-class proportions for 16 forest species across 20 transects at different intensities of human use. We identify plant traits, biophysical site conditions and human uses associated with differences in species diversity, tree species composition, vegetation structure, biomass and size-class proportion to determine factors leading to lack of sustainability.

3. Higher frequency of use and population densities were associated with lower species richness, forest biomass and altered vegetation structure and forest composition. Size-class proportions were significantly different in forests used frequently by humans and cattle compared to less used forests for seven of 16 species. Predictors explaining differences in size-class proportions across forest species varied with size classes, where tree species resistant to fire and livestock populations were associated with higher proportions of higher size-class from saplings to small trees. Use for local construction was associated with lower proportion of higher size class from

small to medium-sized trees and use for local construction was also associated with reduced proportion of higher size class from medium-sized to large trees.

4. Synthesis and Applications: This study found that local use is associated with reduced species richness, biomass and altered vegetation structure and forest composition. Simultaneously, direct human use (e.g. use for local construction) and indirect impacts of human use (population densities, increased proportion of fire-resistant species) were associated with differences in size class proportions in heavily used forests. Results indicate that tree species that are currently important for local use and ecosystem services may be less available in the future. To promote sustainable forest use that supports livelihoods, managers should target specific drivers of change such as fire and livestock which may prevent species from reaching reproductive age.

KEYWORDS: fire, forest degradation, grazing, Kanha-Pench landscape, local construction, plant traits, size-class structure

1. INTRODUCTION

Many current policies to promote ecosystem services and climate mitigation include incentives and payments to sustainable users of forests (Sasaki & Putz 2009; Hein & van der Meer 2012). Yet, it is difficult to assess whether a forest can continue to support livelihoods and provide ecosystem services in the future (Bawa & Seidler 1998; Garcia-Fernandez *et al.* 2008; Schmidt *et al.* 2011) and under what conditions of use it can do so (Ticktin 2004).

At present, variables such as soil nutrients (Siebert 1987), vegetation structure, and species diversity (Kumar & Shahabuddin 2005; Lefevre *et al.* 2012, Nagendra 2012) are used to assess whether a forest has been altered so that it can no longer provide ecosystem-services or support livelihoods (Garcia-Fernandez *et al.* 2008). Yet, these variables may sometimes be poor indicators of the long-term impact on the forest. Forests that appear sustainable using these metrics may not be able to provide similar services in the future (Scheffer *et al.* 2001; Heywood & Iriondo 2003) as the extent and intensity of use may already have altered the long-term trajectory of the forest and future forest composition may be very different from present forest composition.

To understand whether the current rate of harvest is sustainable, some studies have used size distributions of harvested species to establish long-term impact on these species (Sullivan *et al.* 1995; Schmidt *et al.* 2011; Herrero-Jauregui *et al.* 2012; Venter & Witkowski 2013). For this, researchers use the size distribution of tree species to calculate a coefficient of skewness (Wright *et al*. 2003), which can predict direction of change for most species (Feeley *et al*. 2007). These methods may be modified to assess size-class survival of the species at different size classes.

It is particularly important to understand sustainability of forest use in tropical deciduous forests, which form 17% of currently standing tropical forests and are studied less frequently than other forest types (Miles *et al*. 2006). Strong seasonality of these forests makes them ecologically very different from other tropical forests (Sasaki & Putz 2009). These forests are also highly threatened, as they are often located in highly populated areas (Miles *et al*. 2006). These forests are also difficult to study due to their natural heterogeneity and absence of forests that can serve as controls (with no historical human use). This is because the long history of human habitation and management in tropical deciduous forests suggests that long-term interactions of humans and their environment may be responsible for the structure and community composition even in forests considered ‘natural’ (Heywood & Iriondo 2003).

This study assesses the sustainability of forest use in dry tropical forests in a study area in Central India by comparing sites with higher rates of use with a locally placed control with similar environmental conditions and species pool (Schmidt *et al.* 2011). The study evaluates the impact of forest use, and specifically addresses the following:

(i) whether current forest use has led to changes in vegetation structure, species diversity, vegetation biomass and forest composition.

(ii) whether current forest use is leading to long-term changes in forest composition.

(iii) which drivers, including site characteristics (extent and intensity of use, e.g. population densities, distance to market), types of human use (e.g. species part used, whether species is used consumptively, and whether species is used for subsistence or for commercial purposes), and plant trait (e.g. shade tolerance, fire resistance) are associated with changes in long-term forest composition.

This study assesses long-term impact on forest composition by examining species size-class proportions for 16 tree species. We conclude that human use is altering long term forest composition as population densities, plant traits and use-characteristics (such as plant part used, and purpose for which it is used) altered size-class proportions and reduced species richness at higher use sites. Such a study helps suggest interventions such as plantations and set-asides that will make current use sustainable and this approach can be extended to other forests to assess drivers of long-term change in forest composition in their contexts.

2. MATERIALS AND METHODS

2.1 Study Area and Sample Selection

The study region was located in dry tropical forests between Kanha and Pench Tiger reserves in Mandla, Balaghat and Seoni districts in India (~16,000 km^2: Fig. 1). The forests in the study region are typical of deciduous forests as they are highly seasonal, with leaf fall concentrated in the summer months. This study region was chosen for its high forest cover (forest cover exceeded 30% in all 3 districts: Forest Survey of India, 2011), heterogeneous forest cover that included sal (*Shorea robusta*), teak (*Tectona grandis*) and miscellaneous forests as well as its ecological importance. It is an important corridor for wildlife (Sharma *et al*. 2013) and serves as the headwaters for the River Narmada. Population densities are high (>157 people per km^2: Census of India 2011), and the main activities in the forest include cattle grazing, collecting fire-wood and other non-timber forest produce (NTFPs), and fires to augment production of NTFPs. Over 60% of the population in the region depends on selling forest products for their livelihood (Saigal 2008). The region is of immediate concern as the Forest Department is in the process of designating these forests as a wildlife corridor area. Management of forest resources, therefore, becomes vital to wildlife persistence in the area.

To explicitly test the impact of population densities, forest cover and distance to market on forest sustainability, we selected sample locations within the study region that represented this variation. To select representative villages, we conducted a cluster analysis using village-level livestock population (Department of Animal Husbandry 2012), human population, distance to market (Wildlife Institute of India 2011), extent of neighborhood forest (forest cover classified using Landsat imagery, see Appendix S1 in Supporting Information), and the distance between a village and its neighboring forest (see Appendix S2). Since the forests have been managed historically, we also included detailed history of management for each forest compartment or plot (which included details on logging and silvicultural management in the compartment: Madhya Pradesh Forest Department 2011). Based on compartment history, we only sampled plots that had no recorded history of logging and silviculture. This prevented us from introducing error in the study through sampling forests at different stages of management where one plot may have been logged recently while the other was not. Following cluster analysis, we randomly selected two villages from the each of the three largest clusters to represent the range of most common variation (see Appendix S2).

2.2 Quantifying Human Use and Identifying Treatments

In order to compare forest parameters between patches with higher rates of use and comparable localized controls in a heterogeneous forest, it is important to identify locations with different rates of use. It is particularly important to identify forest areas that are rarely used and can serve as localized controls. To quantify frequency of use, we collared one cow in each of the six villages using GPS trackers (manufactured by Holux, New Taipei City, Taiwan R.O.C.) as cattle in a village generally move as a group in the forest. We also requested local residents visiting the forest to carry GPS trackers with them daily. For each village, the family that was asked to carry the tracker was free to give the tracker to any family member visiting the forest that day. As a result, variation due to both gender and age were included in the tracker information and we expected that average use in a village would become representative of that village for the long time period over which movement was tracked. For both, forest activity was tracked for two seasons in 2012 (May-June: pre-monsoon and November-December: post-monsoon) as use was expected to vary with seasonal availability of resources. The trackers were meant to be carried everyday during the study period but some days were missed in the middle, either because no family member visited the forest or because there were errors in turning on the tracker (~ 20% days missing per tracker: see Appendix S3). The trackers recorded the GPS location every two minutes. We then used these GPS locations in a fixed kernel density estimator (Hawths Tools (Beyer 2004) in ArcGIS (9.3, Environmental Systems Research Institute, Redlands, California, USA) to calculate use percentages of forest pixels (30m x 30m) by cattle and humans for different seasons (Fig. 2, see Appendix S3). We assigned forest pixels outside 95% use interval a treatment value of 0 (Control), and those within 95% use interval for both cattle and humans for both seasons a treatment value of 2 (High). Remaining forest pixels were assigned an intermediate treatment value of 1 (Intermediate). Since adjacent villages may also use the same forest patches, we calculated a 2 kilometer buffer around each village (average distance travelled into forest by cattle and people: see Appendix S3). If a sample lay in an area that was used by more than village, it was automatically moved to treatment 2.

To understand the use of forest species by local residents, we surveyed two hundred and fifty residents in fifty villages in the landscape (five people per village). These villagers were members of forest protection committees (village-level institutions with 3-10 members, including both men and women, responsible for managing forests assigned to the village). Species recalled by the residents voluntarily when discussing the importance of the forest were recorded. Although most forest species have some use associated with them (Brandeis 2007), we considered recall as an indication that a species had a specific use or a use that was considered important by local residents. We also recorded the substitutability of each item with other forest products. For instance, species that were recalled and have few substitutes included bamboo (*Dendrocalamus sp*.) used for roof construction, *Madhuca indica* used for brewing alcohol, and teak (*Tectona grandis*) sold at high prices in markets. Other species such as *Cassia fistula* were recalled by a collective noun “Satkatha” which translates to mixed trees. These species are used for firewood or for poles for local construction, and other mixed trees can provide the same function (Table 3).

2.3 Field Surveys

Field surveys were conducted in forest patches with different treatment values (explained in Section 2.2) around the representative villages. For each village, we sought two replicates in each treatment, and plot locations were selected randomly using ArcGIS (Fig. 2). We used cardinal sampling design where we located 20m x 20m quadrats at 100-meter distance in four perpendicular directions from the center, and included one 20m x 20m quadrat at the center (see Appendix S4). To ensure that environmental variables were not responsible for differences in species growth, we measured soil compaction using an Soil Compaction Tester (agraTronix, Streetsboro, Ohio, USA), and soil pH and nutrient levels using a pH/soil analyzer analog (SA2000, Ben Meadows Company, Janesville, Wisconsin, USA) at two randomly selected points at each quadrat (See Appendix S4). We also measured canopy cover using a densiometer, and compiled information on temperature, precipitation, elevation and slope for each site (using TRMM, MODIS, and ASTER-DEM: see Appendix S4). For calculating population structure, we identified all floral species in four size classes: large trees (> 10 cm DBH), medium-sized trees (4-10 cm DBH), small trees (< 4 cm DBH and height > 2.1 meters), and saplings (height < 2.1 meters). Species were identified using a plant identification key (Brandeis 2007) and local residents with forest experience. Finally, we recorded species with visual signs of browsing in each sample (Seidl *et al.* 2011).

2.4 Analysis

2.4.1. Alterations in forest structure, species diversity, forest composition and vegetation biomass

We quantified abundance of individuals as saplings, small trees, medium-sized trees and large trees for each site. This provided us information on individual structural components of the forest. We used the Shannon-Weiner Diversity Index and the Simpson Index to represent species diversity at each site. To calculate vegetation biomass at a site, we used size-class abundances in allometric equations (Zianis 2008).

To detect whether differences in forest structure, species diversity, forest composition and vegetation biomass were significantly altered with human use, we compared these variables between plots at higher frequencies of use and their localized controls (Sites from villages from the same cluster were pooled for village-specific analysis, henceforth referred to as cluster). For this, we used one-tailed t-test to detect whether these variables were significantly lower at higher frequencies of use when compared with the control for each cluster. To detect differences in forest composition, we used ANOSIM (Vegan package in R: Oksanen *et al.* 2013) to determine if species composition was significantly different at higher frequencies of use when compared with their controls.

To test whether there were significant differences in forest structure, species diversity, and vegetation biomass with increasing frequencies of use, population densities (livestock and human) and distance to market, we used separate generalized linear mixed models (GLMM) for each dependent variable (forest structure, biomass, species diversity) where cluster was included as a random effect. The models included predictor variables for frequency of use, livestock density, human density, distance to market and extent of forest in a 1.5 km radius for 20 transects, and there was no co-linearity between predictors. We used least Akaike Information Criterion (AIC) score to decide between competing models (Burnham & Anderson 2003). Models were run in R software (version 3.0.1: R Core team 2014).

2.4.2. Assessing long-term forest composition

Understanding long-term changes in forest composition requires an understanding of the variable regeneration rates for the species in a forest, but the long-term sampling required for calculating species regeneration (Hall & Bawa 1993; Caswell 2001; Heywood & Iriondo 2003; Schmidt 2011) is not always possible (Feeley *et al*. 2007). Coefficient of skewness calculated from size distribution of trees (Wright *et al*. 2003) can predict direction of change for most species (Feeley *et al*. 2007) but gives an average value for the entire distribution of a species and masks the impact on individual size classes at which the drivers may operate. Our study modified this method by collecting species abundance at size class intervals (detailed in section 2.3; Herrero-Juaregui *et al*. 2012). We then calculated our metric, size-class proportion metric (henceforth referred to as SCPM) as the ratio of abundance of a species at a site in a higher size class to total abundance in both lower and higher size classes at that site separately for every species in each transect. We calculate SCPM as:

$C_{ijk} = F_{ij(k+1)}/(F_{ijk} + F_{ijk+1})$,where F_{ijk} is the Population of Species i at Site j at Class Size k (Fig. 3).

This variable, SCPM, quantifies the proportion of individuals in a species that are present in a higher size class, which represents the slope of the population distribution in the size-class intervals between lower size class and higher size class (Fig. 3). Proportion in higher size class varied from 0 (present in lower size class but absent in higher size class at a sample site) to a maximum value of one (present multiple times in higher size class but absent in lower size class). If the proportion in higher size class is significantly different at sites used at a higher frequency than the controls where environmental factors are constant, then we infer that human use is altering the proportion in higher size class. Over the long term, differences in SCPM would lead to differences in species composition in heavily used forests compared with the control.

This study minimizes the errors associated with static life table methods by using a localized control which reduces the impact of variations in size distributions due to past events such as logging, pathogen outbreaks, and droughts (Wright *et al*. 2003). It also does this by placing samples in forests without a history of logging and silviculture (detailed in Section 2.1). Further, some species are necessarily absent in certain size classes due to their natural growth form. For grasses such as bamboo (*Dendrocalamus sp*), we only recorded survival in the lower two size classes (height < 2.1 m; height> 2.1 m). Similarly, for species that do not reach large sizes (>10 cm DBH), survival for that size class was excluded from the analysis. Further, methods used to account for outliers produced due to low abundance of certain species at lower size classes, such as rarified sampling, were not possible due to small sample sizes. To control for this, we removed all those samples where total abundance (abundance in lower size class + abundance in higher size class) was less than one standard deviation below the mean abundance for that species in all transects.

A one-tailed t-test was used to test whether there was a significant increase in SCPM at higher frequencies of use compared with the localized control for each cluster. We did a separate analysis for each village cluster, where cluster identity controls for population densities, market access and forest type since these sources of variation can also impact the forest. We also constructed rank-abundance plots to illustrate change in rank of species at different size classes with higher frequencies of use.

2.4.3. Drivers that lead to changes in long-term forest composition

Factors associated with current differences in SCPMs can drive change in species composition over the long-term. To understand factors associated with differences in SCPM, we used generalized linear mixed models (GLMM) to test which site-specific conditions (standardized to the mean), species-specific plant traits and use characteristics were significant in explaining differences in SCPM for saplings to small trees (n=208), small trees to medium-sized trees (n=190), and medium-sized to large trees (n=96). The GLMMs were run separately for each size class, and each sample indicates the SCPM of one species at a site. We included plant traits known to influence size-class distribution (Wright *et al*. 2003) such as shade tolerance, wood density, resistance to fire and trampling, tolerance to planting density and growth form (Table 1). Shade tolerance has been identified as the most important plant trait in determining size-class distribution, and wood density is used as a proxy for physiological and morphological traits (Wright *et al*., 2003). Particularly, wood density represents the growth strategy of a species where species with lighter wood grow faster (Wright *et al*. 2003). We also selected characteristics of human use that are known to impact regeneration rates such as whether the species was considered important (species recalled), whether the species was browsed, which species part was used, whether use was consumptive, whether the species was used for subsistence or for the market, and the specific use of every species part (Table 3). Finally, we also included factors associated with the site that could impact regeneration due to human use (livestock and human population per forest area, distance to market and frequency of use) and site-specific characteristics (canopy cover, species diversity, elevation and slope). This analysis included species identity as a random effect. The global model for this analysis was:

Y (SCPM)=B0+B1*(site conditions) + B2* (species use)+ B3 *(plant traits) + (1|Species)

Because this global model used species traits, it could include individuals from species with lower frequencies. Therefore, the global model included 39 species. To account for collinearity, only predictors with correlations less than 0.3 were retained (See Appendix S5), and used to construct alternative models (See Appendix S7). We used least AIC score to select the best model for each analysis (Burnham & Anderson 2003). We cross-validated the results by conducting the same analysis using regression-tree (R package: randomForest: Liaw & Wiener 2002).

3 RESULTS:

3.1 Changes in species diversity, biomass, and vegetation structure

There was a significant reduction in species richness and change in diversity indices (e.g. Simpson Index), and vegetation structure (abundance of saplings, small trees, and medium-sized trees) at higher frequencies of use for each cluster (Fig. 4, see Appendix S6). Biomass also decreased at higher frequencies of use in all but one village cluster (DU). However, this effect of increased biomass in one village cluster was removed when large trees were removed from the analysis. Results from ANOSIM analysis show that forest composition was also significantly different from the control at higher frequencies of use in two out of three villages, with both villages showing a significant difference at sapling size-class (Table 2).

These differences may be attributed to site characteristics (Fig. 5): Biomass and vegetation structure (in the form of abundances of saplings, small trees, and medium-size trees) are negatively associated with population density per forest area; abundance of large trees shows no impact of use or site characteristics, but is positively associated with availability of forest; and species diversity increases with livestock population and frequency of use.

3.2 Changes in size-class proportion

SCPM was significantly different in frequently used forest when compared to the control (Treatment 1 and 2 together versus Treatment 0 or Treatment 2 versus Treatment 1 and 0) in seven of 16 species examined (Table 3). Of these, two of 10 species (*Cassia fistula* and *Lagerstroemia parviflora*) showed a significant decrease in SCPM from saplings to small trees, while two of 10 species (*Diospyros melanoxylon* and *Zizyphus xylopyrus*) showed an increased SCPM from saplings to small trees. Similarly, from small to medium-sized trees, two of 10 species (*Cormes macrophylla* and *Terminalia alata*) showed an increase in SCPM while one species (*Casearia graveolens*) showed reduced SCPM. There were no significant increases or decreases from medium-sized to large trees.

In addition to these, there were also significant increases or decreases in SCPMs at intermediate frequencies of use (Treatment 1) compared with other treatments (Treatment 0 and

2). From saplings to small trees, two of 10 species (D. *melanoxylon*, L. *parviflora*) were associated with significant increase in proportion of small trees at intermediate frequencies of use, while one species (T.*alata*; Table 3) was associated with a significant decrease. From small trees to saplings, four of 10 (C. *graveolens*, C. *macrophylla*, L. *parviflora*, T.*alata*) species showed an increase in proportion of higher size class at intermediate use frequency and one species (*Anogeissus latifolia*) showed a significant decrease in higher size class from medium-sized trees to large trees at intermediate use frequencies. The difference in relative abundance of these species at different size classes can be seen in Fig. 6.

3.3 Drivers of Difference

For differences in SCPM from saplings to small trees, increases in SCPM were associated with fire resistance, and use of fruit for non-food purposes, and decrease in SCPM was associated with livestock per forest area. From small to medium-sized trees, site conditions such as livestock density and species traits such as light dependence was associated with lower SCPM. Further, use of species as wood was associated with reduced SCPM while use of species for fuelwood was associated with increase in SCPM (Fig. 7). From medium-sized trees to large trees, higher SCPM was associated with higher population. Species that were tall but had a short trunk (and thus not ideal as wood), and that tolerated medium planting densities, were also associated with higher SCPM (Fig. 7). Analysis using regression tree (randomForest) for analyses from saplings to small trees, small trees to medium-sized trees, and medium-sized trees to large trees provided similar results as least AIC method (See Appendix S7).

Overall, increasing influence of human activities (where site conditions such as livestock and human populations are higher and distance to market is lower) are associated with lower

SCPMs from saplings to small trees, and small to medium-sized trees. This trend is reversed from medium-sized to large trees where frequency of use and human population are associated with higher SCPMs.

Plant traits appear to be important from saplings to small trees, where resistance to fire is the most important variable explaining differences. Some uses are consistently associated with reduced SCPMs such as use of wood for local construction, while non-consumptive use of species for fuel-wood, fruit (for non-food purposes such as sale, or local uses for poison) are associated with higher proportions of higher size class.

4. DISCUSSION:

4.1 Impact of human use on present and future forests

Human use is associated with reduced biomass and species richness and altered vegetation structure and forest composition of the forests in our study region. Further, over forty percent of the species studied (seven of 16 species) have significantly altered size-class proportions (similar to Esquivel *et al*. 2008). This suggests potential changes in long-term forest composition, which may reduce supply of many useful species in the future.

However, the present study is itself a conservative estimate of the long-term impact of human use on forest composition as SCPM in nearly sixty species was not examined due to low frequency of occurrence, because they were not present in sufficient sample plots, or because the species was absent in intermediate size classes (see Appendix S5). Although several of these species may naturally be rare in these forests, of those that are frequently present (Troup 1983), at least two forest species (*Bombax ceiba, Boswellia thuriferra*) were absent as small trees, suggesting that these may not be regenerating (although this could be a function of sampling effort).

4.2 Factors associated with changing forests and conservation implications

In forests that are managed by humans, only a few species are retained in each forest type (Crook & Clapp 1998), either because disturbances create conditions that cause increases in some species, or because forest users may actively manage forest to increase abundance of useful products by selectively removing other species (Crook & Clapp 1998). This study also suggests that human use is altering forest composition as direct use of some species that are used consumptively are associated with lower SCPM while those where specific parts are harvested are not. However, this study also showed evidence that the distribution of some species is influenced by disturbance as certain plant traits such as fire resistance were shown to influence SCPM. Increase in survival of species that are resistance to fire may be indirect impacts of disturbance such as burning forest understory to augment NTFP production.

Therefore, this study demonstrates that human use creates disturbances that may alter long-term forest composition as species that are resistant to human use (fire resistant or can withstand livestock trampling and grazing) may increase their proportion in the forest as overall species richness reduces. Over the long term, these other species may further reduce in frequency, become extinct locally and lead to shortages for local people. These changes could also to reduce species and ecosystem diversity (Crook & Clapp 1998). To counter this, management practices such as plantation of threatened species (Vantomme & Gazza 2010), such as is already present for *Dendrocalamus* sp. and *Phyllanthus emblica*, may promote persistence of species. Managers may also consider promotion of alternate construction materials.

The study also identifies specific factors associated with change, which suggest possible interventions that may prevent local extinctions or reduced abundance of some species. For instance, it identifies fire and cattle grazing as potentially major drivers of change in long-term forest composition (five of seven species had significantly different SCPM from saplings to small trees in frequently used forests, where variables associated with fire and cattle were the predictors of change). Cattle use and fire can damage saplings, alter rate of tree establishment and change the successional stage of the forest, and species with specific traits that may be able to defend themselves due to phenology, resistance and sapling defenses (Seidl *et al.* 2011) will grow at the expense of others. The fact that species composition is significantly different at sapling stage more often than it is at other stages (Table 2) further suggests that this size class is particularly vulnerable to intensity of human induced changes. Since cattle grazing and fire prevent affected species from reaching reproductive age, these species may be most vulnerable to local extinction. To counter this, managers may consider possible interventions such as fire prevention, set-asides from grazing (Jansen & Robertson 2001), quotas for grazing, and protection of threatened species at the sapling stage.

4.3. Significance of Study

The study highlights the importance of multispecies analysis as well as going beyond present-day impact on forests to examine long-term impact on forest composition. Most research on impact of harvest and forest use for sustainable forestry is restricted to a few species that are known for their commercial value (Schmidt *et al.* 2011). This study emphasizes the importance of extending analysis to other forest species, as their frequencies may be changing, thus altering long-term forest composition and the ability of forests to support local livelihoods as well as other ecosystem services. By using plant traits, this study is also able to demonstrate the importance of traits in community change (Amatangelo *et al.* 2014).

This study also has implications for a larger area, particularly dry tropical forests in Asia and Africa, which are a highly threatened ecosystem due to high population densities and continuous use, and the patterns and impacts of human use may differ widely in these forests in comparison with other types of forests. This study unearths some important processes that may lead to lack of sustainability in these forests, and highlights some impacts that may be measurable in other forests similar to the study area. For instance, fire and livestock may be a more important driver of degradation in these forests than human use for fuel-wood, construction and commerce, as these prevent species from acquiring reproductive age.

ACKNOWLEDGEMENTS

We are grateful to assistance and data from the Wildlife Institute of India, Madhya Pradesh Forest Department, PCCF (MP), CF (Jabalpur-Central Circle), DFO (Seoni), DFO (Balaghat) and Department of Animal Husbandry. NSF Grant Number 1029219 supported this research. This project was approved under IRB Protocol Number IRB-AAAI1677 and Animal Care Protocol AC-AAAE0703. We also thank Maria Uriarte, Shahid Naeem and the DeFries Lab for comments and to Kuldip Tekam, Dharmendra Tekam, Yamuna and Gyaani Marabi on site.

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Tables

Table 1: Variables used as predictors in generalized linear models to predict size class proportion metric (SCPM). .

SPECIES TRAITS (Brandeis 2007; Troup 1983)	SITE CHARACTERISTICS (field surveys)	USE CHARACTERISTICS (field surveys, interviews, Brandeis 2007)
Shade tolerance (Light demanding, light demanding but some shade tolerated, requires shade when young, shadebearer) Growth Form (Tall tree with a crooked trunk, tall tree with a short trunk, tall tree with a straight trunk, moderate sized tree with a crooked trunk, moderate sized tree with a straight trunk, small tree, shrub, other) Resistance to fire (No, Somewhat, Yes, Yes when the plant is older) Resistance to trampling/cattle (None, Not at high intensity, Yes) Resistance to planting density (Species is thrusting, species grows better with weeding, species grows better with weeding overhead) Wood density	Frequency of Use Livestock per Forest Area Population per Forest Area Distance to Market Canopy Cover Elevation, slope Species Diversity	Species Browsed Species Recalled Species Part Used (Bole, Branch and Leaves, Bark, Sap, Fruit, Flower) Species Use (Food, Market, Fodder, Fuelwood, Construction, Implements, Other)

Table 2: Differences in species composition with frequency of use at each village. Values indicate p-values for anosim test (vegan package in R). Figures in bold indicate significant differences in species composition at higher frequency of use for each village.

Village	Population	Livestock	Distance to Market	Species Richness	Simpson Index	Large Trees (p-value)	Medium-sized Trees (p-value)	Small Trees (p-value)	Saplings (p-value)	All (p-value)
DH	926.5	509.5	9.5	17.5± 9.85	7.38± 3.58	1	0.44	0.16	0.37	0.31
DU	579	703.5	31	21 ± 3.54	9.14± 0.80	0.30	**0.04**	0.10	**0.09**	0.10
HA	831	480.5	14.5	21.66± 4.92	10.09± 2.18	**0.05**	0.44	0.42	**0.03**	**0.06**

Table 3: Differences in proportion of higher size class in 16 species examined. Columns 3-5 indicate differences in mean and significance of differences (p-values) between first and second groups using one-tailed t-test (Sample size, n=20). Column 6 lists the percentage of residents who voluntarily recalled the species when asked about the use of the forest. Columns 7-8 list resistance to fire and cattle in the form of grazing and trampling and % of species browsed. Columns 9-11 list use of species.

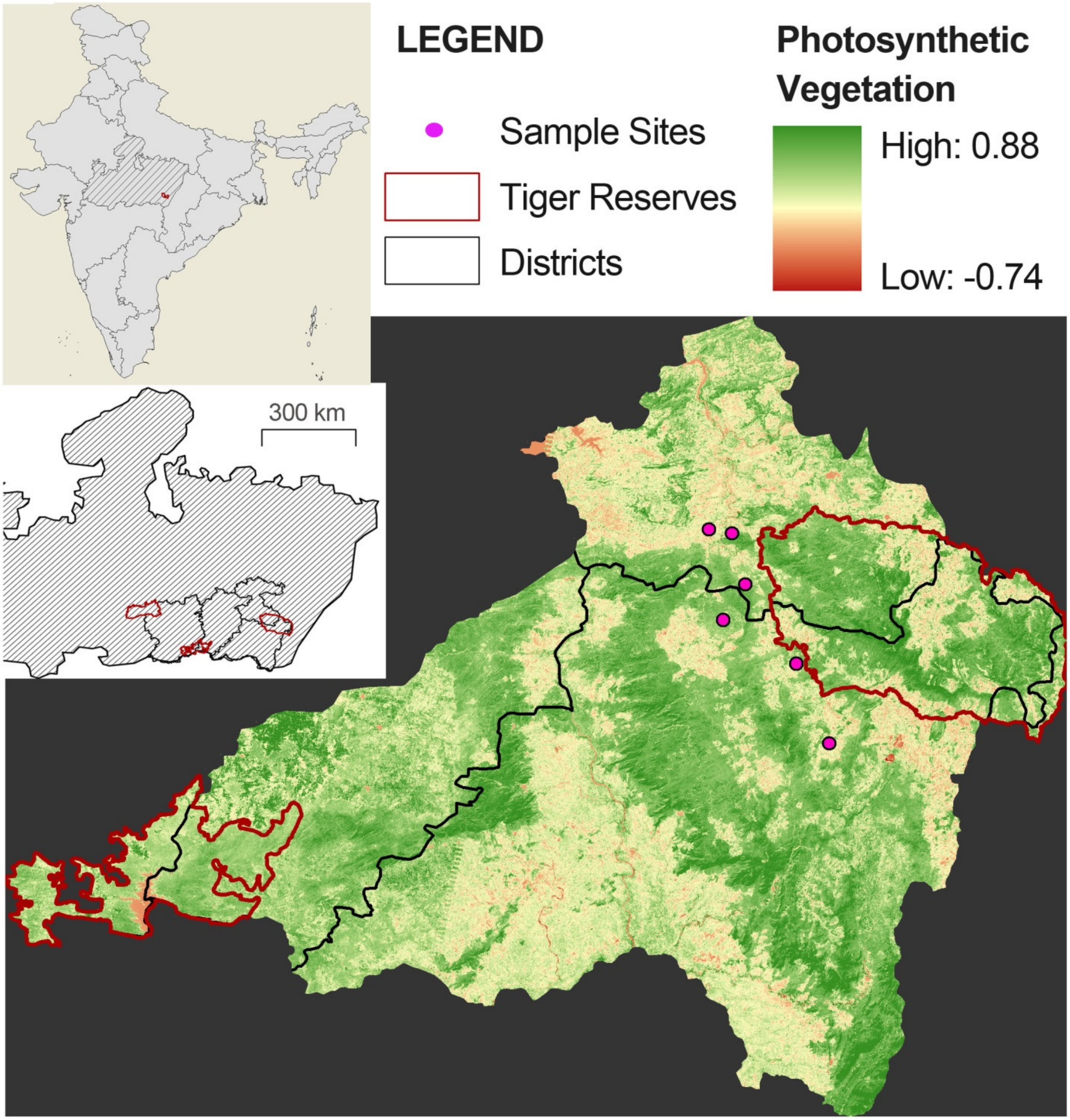
1	2	3			4			5			6	7	8	9	10	11
Species	Village	Saplings to Small Trees			Small Trees to Medium-Sized Trees			Medium Sized Trees to Large Trees								
		Control vs Use	High Use vs Others	Int. Use vs Others	Control vs Use	High Use vs Others	Int. Use vs Others	Control vs Use	High Use vs Others	Int. Use vs Others	Recalled	Trampling Resistant	Fire Resistant	Use: fruit and flower	Use: leaf and wood	Use: bark and sap
Anogeissus latifolia	DH			0.22 (0.19)			0.17 (0.10)					Yes	Yes	None	Leaf: tanning Wood: charcoal, agricultural implements	None
	DU	0.032 (0.39)	-0.07 (0.41)	-0.08 (0.25)	-0.05 (0.18)		0.06 (0.15)	0.005 (0.47)		**-0.09 (0.09)**						
	HA															
Bridela retusa	DH															
	DU							-0.25 (0.25)		0.25 (0.25)						
	HA															
Buchanania latifolia	DH			0.16 (0.29)							2.15	Yes	Not Known	Fruit: eaten , trade	Leaf: plates	Bark: tanning
	DU	-0.24 (0.14)	-0.33 (0.25)	-0.08 (0.34)	-0.09 (0.11)	-0.08 (0.28)	0.011 (0.46)								Wood: light construction	Sap: pellucid gum
	HA															
Casearia graveolens	DH			-0.03 (0.35)			0 (all 0)					Not Known	Not Known	Fruit: poison	Leaf: browse	
	DU	0.044 (0.32)	0.008 (0.46)	-0.04 (0.23)	-0.01 (0.48)	**0.45 (0.018)**	**0.46 (0.014)**	0 (all 0)		0 (all 0)		37.5				
	HA		0.14 (0.25)	0.14 (0.25)		0 (all 0)	0 (all 0)									
Cassia fistula	DH											Yes	Not Known	Fruit: purgative,	Leaf: cattle fodder (in	Bark: tanning

														medicine	UP)	, dying
	DU	**-0.15 (0.01)**	-0.17 (0.14)	-0.01 (0.45)		-0.08 (0.40)	0.08 (0.40)								Wood: agricultural implements	Sap: gum
	HA															
Cormes macrophylla	DH												Not Known			
	DU				**-0.62 (0.09)**		**0.62 (0.09)**									
	HA															
Diospyros melanoxylon	DH		**0.19 (0.05)**	0.21 (0.10)							6.45	Yes	Not Known	Fruit: eaten	Leaf: commerce	None
	DU	-0.006 (0.45)	-0.10 (0.27)	**-0.07(0.08)**	-0.05 (0.18)	-0.13 (0.25)	-0.05 (0.18)					16.67		Flower: None		
	HA															
Euononymus hamiltonii	DH			**0.22 (0.05)**								Not Known	Not Known			
	DU															
	HA															
Garuga pinnata	DH											Not Known	Yes	Fruit: eaten, pickled	Leaf: fodder Wood: fuel, indoor work	Bark: tanning Sap: used
	DU				-0.19 (0.18)		0.06 (0.39)	-0.04 (0.33)		0.08 (0.27)						
	HA								-0.01 (0.48)	0.01 (0.48)						
Lagerstroemia parviflora	DH		0.19 (0.16)	**0.39 (0.03)**			0.06 (0.36)				<1	Yes	Yes	None	Leaf: tanning Wood: agricultural implements, construction	Bark: tanning Sap: sweet gum eaten
	DU	-0.04 (0.29)	-0.05 (0.39)	0.003 (0.48)	-0.11 (0.20)		**0.21 (0.06)**	-0.04 (0.19)		0.05 (0.21)						
	HA		**-0.47 (0.06)**	-0.34 (0.13)												
Miliusa tomentosa	DH											Not Known	Not Known		Leaf: cattle fodder Wood: sheds, lopping	
	DU											22.2				
	HA		0.20 (0.01)	0.20 (0.01)												
	DU							0.08 (0.43)				50 (n<5)		Flower: alcohol, trade	Wood: protected (even though	Sap: gum

	HA														good for railway sleeper)	
Schleichera trijuga	DH											Yes	Not Known	<u>Fruit:</u> oil (South India) <u>Flower</u>: None	<u>Leaf</u>: lac, cattle-fodder (UP) <u>Wood</u>: crushers, ploughs, etc. (hard wood)	None
	DU															
	HA					-0.17 (0.30)										
Terminalia alata	DH			-0.04 (0.34)			0.012 (0.40)			0 (all 0)	<1	Not at high intensity	Some what	None	<u>Leaf:</u> silkworm, lac pollarded <u>Wood:</u> fuelwood (excellent), potash, heavy construction	<u>Bark:</u> tanning , chewed with betel leaf
	DU	0.05 (0.26)	-0.05 (0.10)	**-0.09 (0.03)**	**-0.31 (0.06)**	-0.11 (0.22)	**0.26 (0.03)**	0.008 (0.48)	0.07 (0.26)	0.05 (0.40)		53.13				
	HA					0.45 (0.13)			-0.15 (0.31)							
Terminalia chebula	DH										3.23	Not Known	Yes	<u>Fruit:</u> commerce , tanning, dying, medicine <u>Flower</u>: None	<u>Leaf:</u> galls-ink, dye <u>Wood:</u> furniture, agricultural implements, house building	<u>Bark</u>: tanning and dying
	DU						0.25 (0.25)									
	HA															
Ziziphus xylopyrus	DH			0.12 (0.30)			0.02 (0.46)					No	Yes	<u>Fruit</u>: dye for trade <u>Flower</u>: None	<u>Leaf:</u> fodder <u>Wood:</u> torches, cart-building	<u>Bark:</u> tanning <u>Sap:</u> None
	DU	0.25 (0.13)	**0.39 (0.001)**	0.11 (0.26)	-0.18 (0.21)		0.18 (0.21)									
	HA															

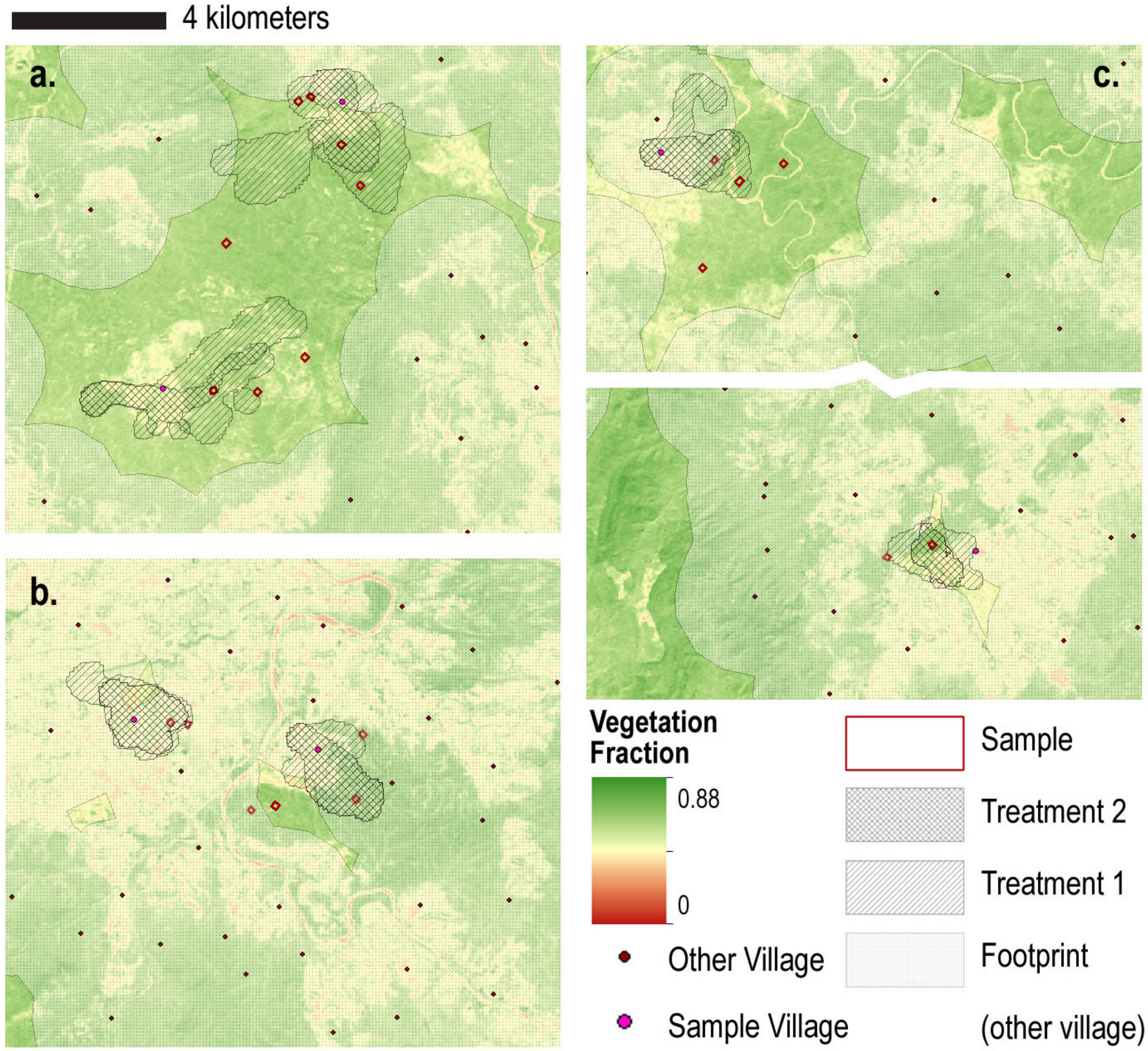
Figures:

Figure 1:



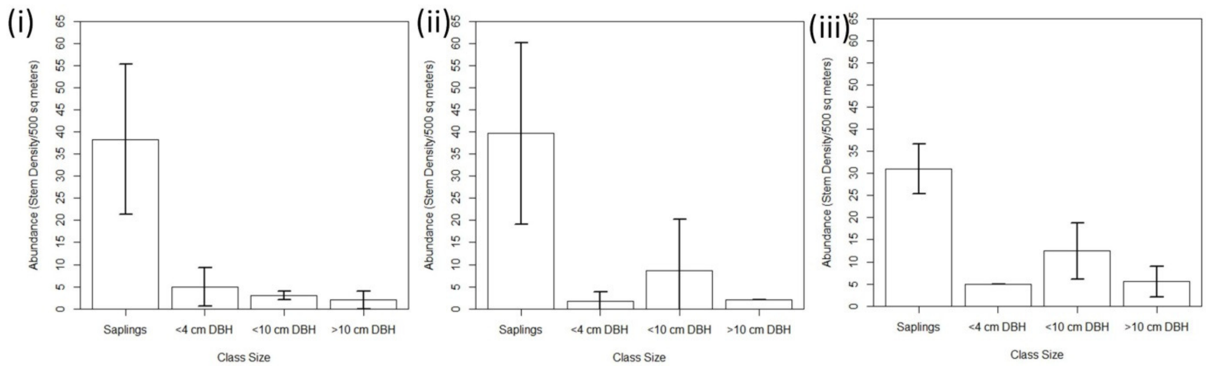
Study Area: Kanha-Pench Landscape in Central India. PV Fraction calculated from Landsat, Dec 2009.

Figure 2:



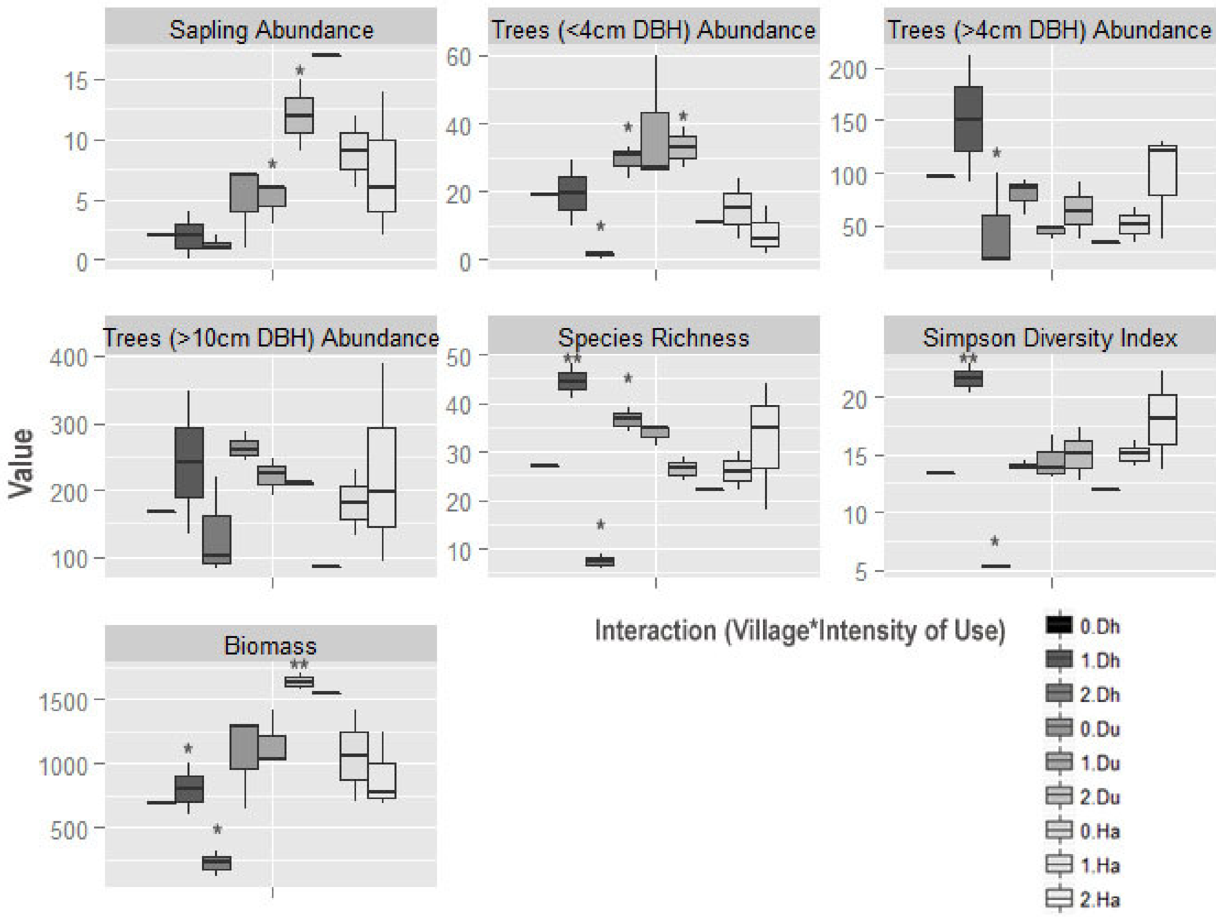
Distribution of treatments in sample plots in three clusters in six representative villages.

Figure 3:



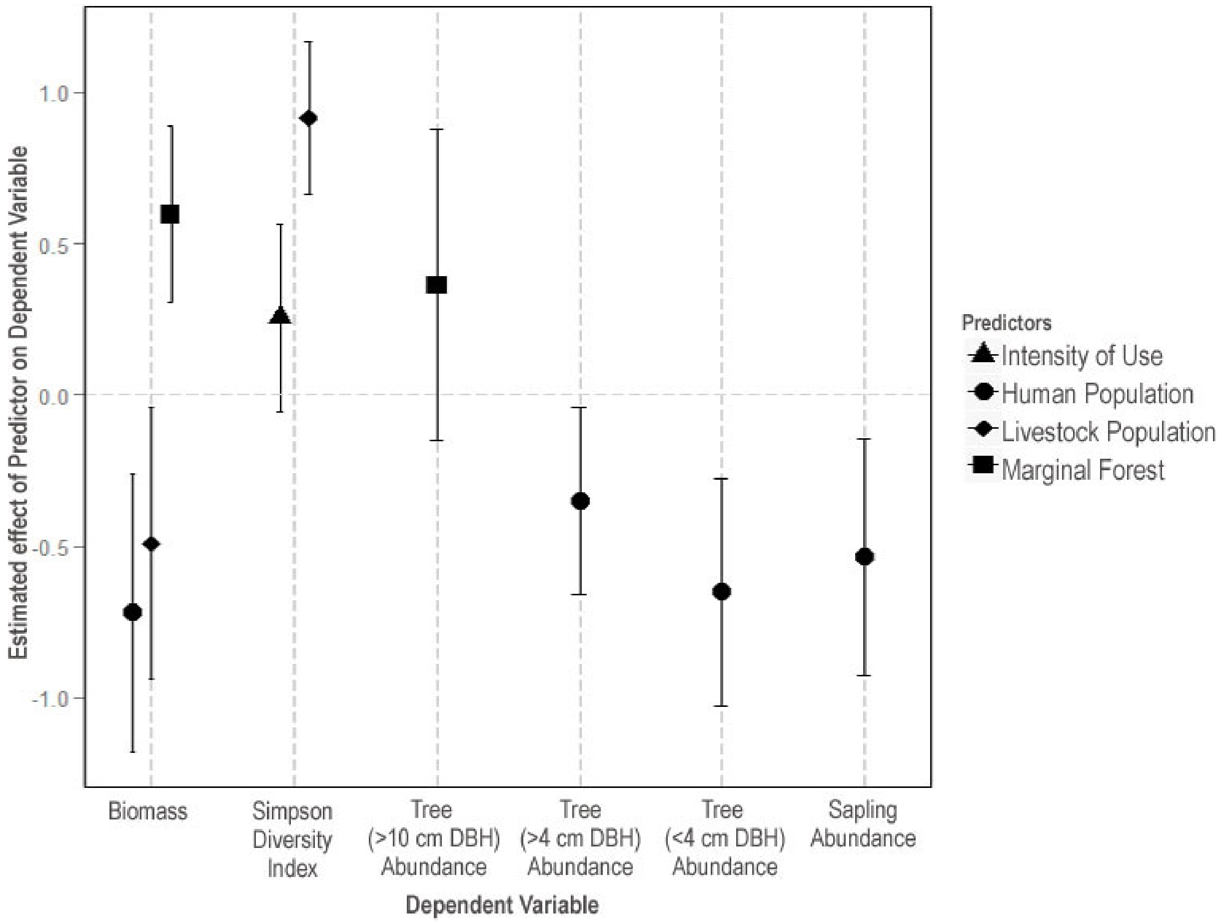
Schematic for understanding size class proportion metric (SCPM) in species *Terminalia alata*. Figures show size-class distribution in (i) control, (ii) intermediate-use frequency, and (iii) high frequency of use. Removal of individuals at small tree size class alters the size distribution and the survival probability from small trees to medium-sized trees.

Figure 4:



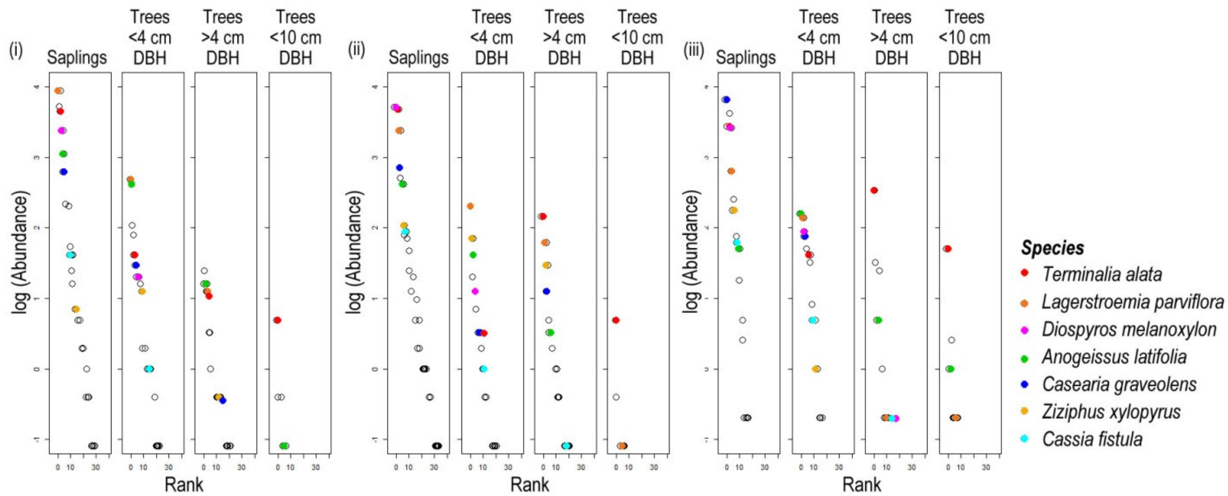
Differences in forest attributes (species diversity, biomass, vegetation structure) with frequency of use at each village. Significance of p-values for one-tailed t-test are indicated as * (p<0.05), ** (p<0.01)

Figure 5:



Estimated effect of population densities, frequency of use, distance to market and area of forest in the vicinity on species diversity, biomass and vegetation structure. Only significant predictors from linear mixed effects model displayed. Values indicated -coefficients and their 95% confidence intervals.

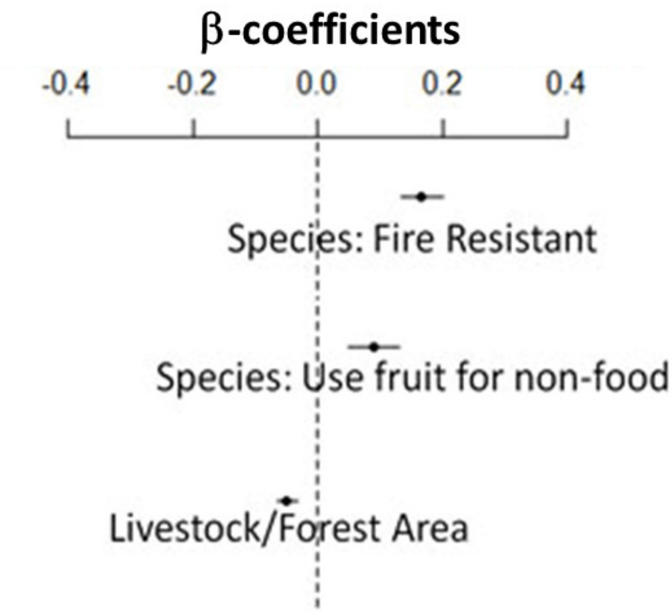
Figure 6:



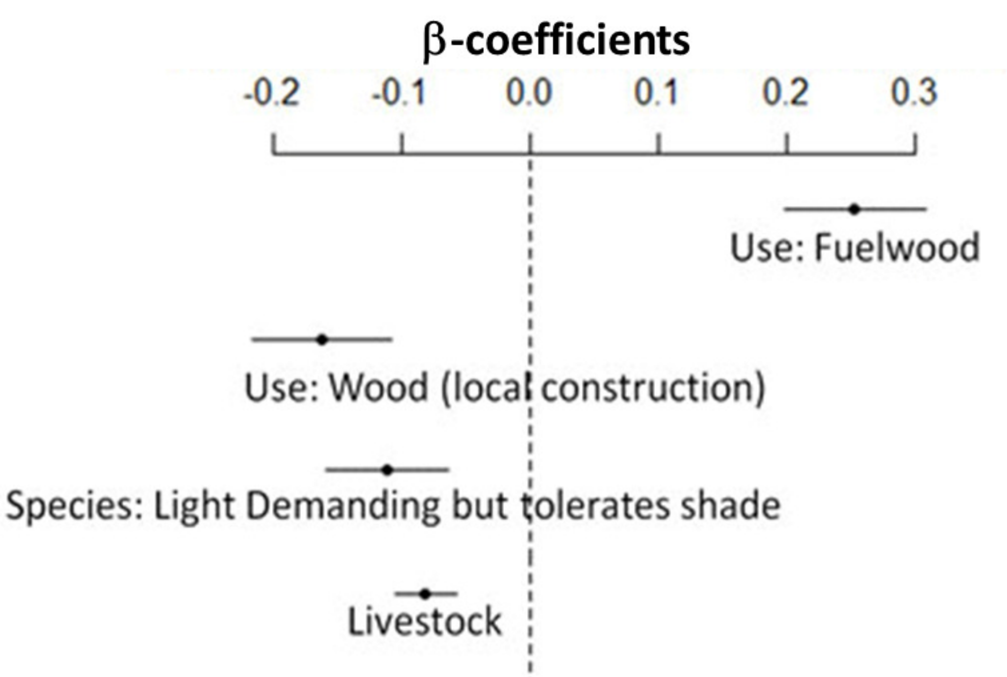
Rank-order plots show changing dominance of species at different size classes in (i) control forests, (ii) forests used at an intermediate frequency, and (iii) forests used at a high frequency. For instance, *Diospyros melanoxylon* has a higher rank at intermediate use frequency for saplings when compared with control forests. Further, the species is present as trees > 4 cm DBH in highly used forests while it is not present in this size class at lower frequencies of use.

Figure 7:

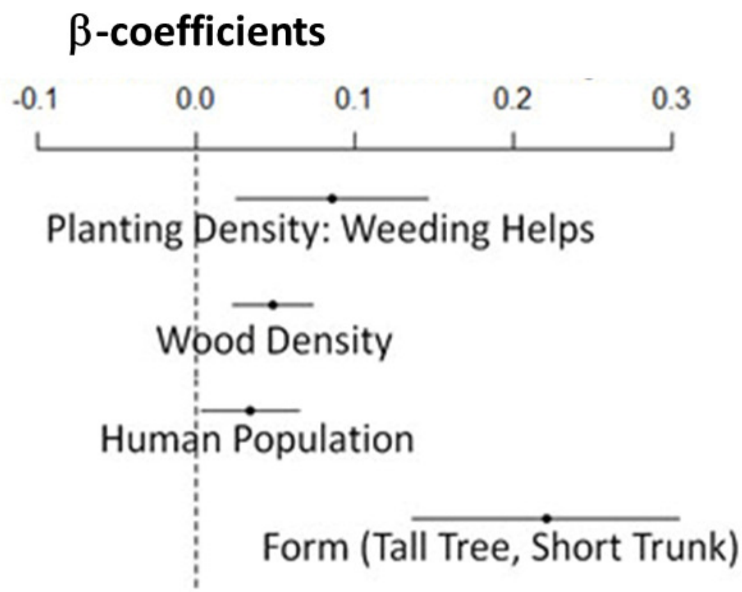
(i)


β-coefficients
-0.4
-0.2
0.0
0.2
0.4
Species: Fire Resistant
Species: Use fruit for non-food
Livestock/Forest Area

(ii)


β-coefficients
-0.2
-0.1
0.0
0.1
0.2
0.3
Use: Fuelwood
Use: Wood (local construction)
Species: Light Demanding but tolerates shade
Livestock

iii)



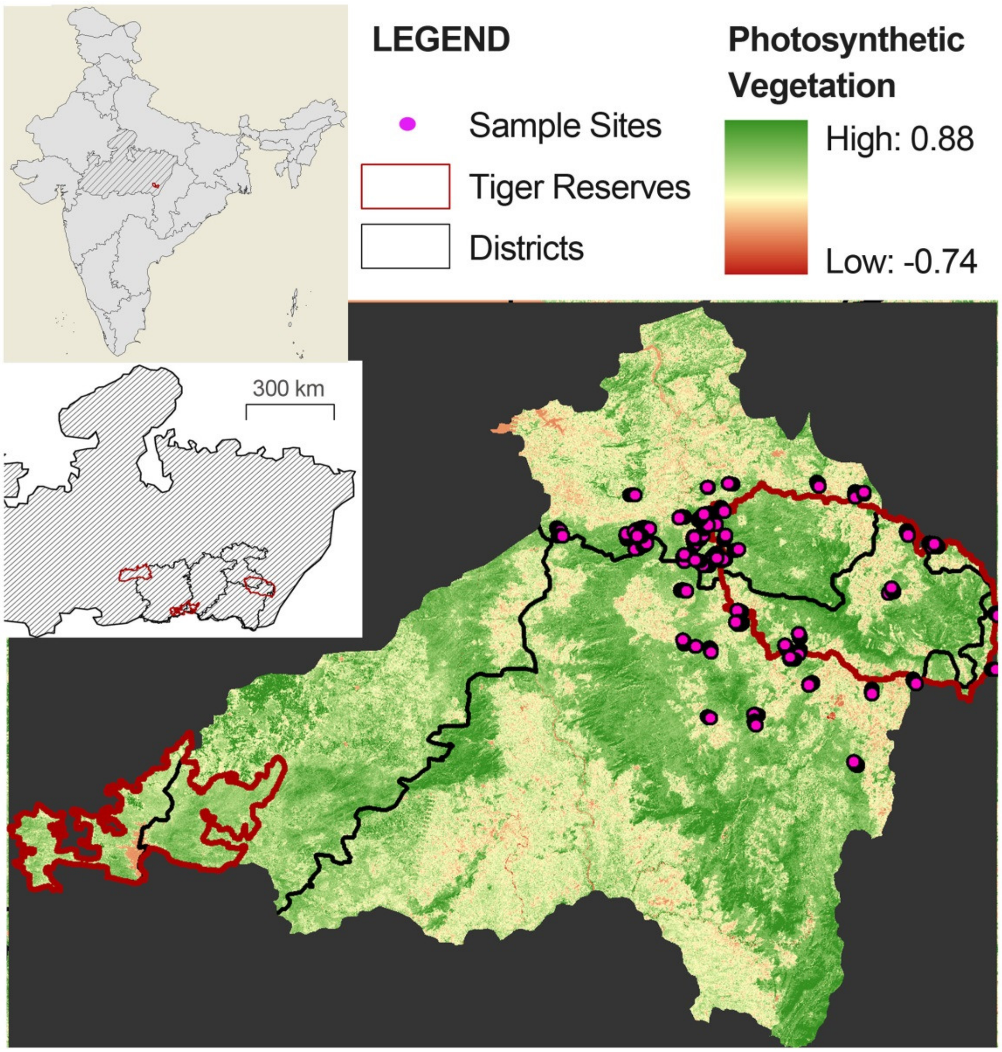
Coefficients of significant predictors of SCPM in general linear models for (i) saplings to small trees, (ii) small to medium-sized trees, and (iii) medium-sized to large trees.

SUPPORTING INFORMATION

S1. QUANTIFYING FOREST COVER IN STUDY REGION

We used Landsat imagery (Path: 143, Row: 045, acquired on Dec 07, 2009; Path 143, Row: 044, acquired on Dec 7, 2009, and Path: 144, Row: 045, acquired on Jan 31, 2010) from winter 2010 to classify forest cover in the study region. We used iMAD to radiometrically normalize these images (Canty & Neilson 2008), and classified forest and non-forest using supervised classification. Training data was based on seventy-six 1-km long transects conducted in the area in 2009-2010, where land cover (forest, non-forest) and forest type was recorded every 100 meters. Accuracy of classification based on a validation dataset randomly selected from training data was 93.02%. Following this, we used ArcGIS 9.3 to quantify available forest cover in 2-km buffers around each village using ArcGIS 9.3.

Figure S1:



Study area and sampling to quantify forest cover.

S2. SAMPLING STRATEGY

To select representative villages for sampling, data on 1125 villages in the study region were compiled from various sources: village-level livestock population (Department of Animal Husbandry 2012), human population, distance to market (Wildlife Institute of India 2011), distance between village and forest, available forest area (explained in S1), forest type and its historical legacy of management (Madhya Pradesh Forest Department 2011). For historical legacy of management, we obtained detailed compartment history of each forest compartment from the Divisional Forest Offices, and classified forest compartments based on management plan followed and the year of implementation in the management cycle. For distance between village and forest, we did not use metric units but based distance on the number of villages between forest and village. A village surrounded by forests on all sides was given a value of 0, and a village where half its perimeter was forest was given a value of 1. For villages that were not themselves adjacent to forests, a village that had only one village between it and the forest was given a value of 2, and those with more than one village between it and the forest were given a value of 3. Distance to market was obtained from existing census (Wildlife Institute of India 2011), and this distance was based on distance to market by road.

Cluster analysis (using Ward's method) was used to cluster villages according to similarity. Six villages were randomly selected from three of the largest clusters (two villages from each cluster).

Table S2: Details on Villages Selected, based on data collected by Wildlife Institute of India (Total Population, Nearest Town, Distance to Town) and Department of Animal Husbandry (Cattle and Buffalo populations).

Village#	Total Population	Cattle +Buffalo	Nearest Town	Dist. To Town (km)
Village1-Dh	1007	500	BAMHNI	7
Village6-S	846	519	BAMHNI	12
Village5-M	881	373	BAIHAR	15
Village3-H	781	588	BAIHAR	14
Village2-Du	403	737	BAMHNI	21
Village4-K	755	670	BAIHAR	41

S3. QUANTIFYING FOREST USE

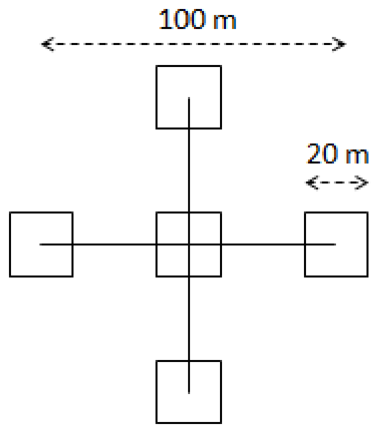
In all villages and both seasons, cattle were not recorded moving further than 2.5 kilometers from their starting point in the village. In the three villages where the cattle went to the forest in the summer, the forest area covered was either larger than it was in the post-monsoon season, or they used a different section of the forest. Local residents also visited a smaller area of the forest in the post-monsoon season than they did in the summer, when they were recorded to go up to 4 kilometers from their village to obtain commercial products.

Table S3: Total forest area available for each treatment in each village

Village	Total Forest Area (km^2)	Forest Treatment 2 (km^2)	Forest Treatment 1 (km^2)	Forest Treatment 0 (km^2)	Proportion of Forest in Treatment 2	Proportion of Forest in Treatment 1	Proportion of Forest in Treatment 0
Vill 1-Dh	1.75	1.16	0.59	0	0.66	0.34	0
Vill 6-S	4.534	1.49	0.15	2.89	0.33	0.03	0.64
Vill 5-M	2.4	0.44	0.38	1.59	0.18	0.16	0.66
Vill 3-H	4.42	0.92	1.24	2.26	0.21	0.28	0.51
Vill 2-Du	7.94	1.75	2.55	3.64	0.22	0.32	0.46
Vill 4-K	8.41	1.25	2.43	4.73	0.15	0.29	0.56

S4. FIELD SAMPLING DESIGN AND RESULTS

Figure S4: Field sampling design



We measured soil compaction (using agraTronix soil compaction meter: agraTronix, Streetsboro, Ohio, USA), pH and nutrients (using pH/soil analyzer analog: SA2000, Ben Meadows Company, Janesville, Wisconsin, USA) at 10 locations in each plot (two randomly selected points in each quadrat where other field measurements such as canopy cover and understory were also taken).

During measurements, grass and debris were removed from sampling location. For measuring soil compaction, soil compaction meter was held perpendicular to the ground and pressed with full force for reading. For soil and pH, a 15 cm hole was dug, and water was poured into the hole and mixed. Analog was placed in hole to measure pH and wiped before measuring soil.

Temperature data was obtained from MODIS 11A1 (reverb.echo.nasa.gov), and precipitation data was obtained from TRMM 3B43 (trmm.gsfc.nasa.gov) for the year 2012, and average values for the year were calculated. We obtained 30-meter resolution digital elevation model from ASTER (reverb.echo.nasa.gov) and used it to calculate slope. Average temperature, precipitation, elevation and slope for each of our sample plots was extracted and analyzed using ANOVA.

Analysis of Variance (ANOVA) tests revealed that there were no significant differences in pH, soil compaction, soil nutrients, temperature and precipitation across treatments for any site (Table S4).

Table S4: p-values for significance of difference in soil compaction, pH and nutrients based on village identity, frequency of use and interaction of village and frequency of use. Only soil compaction is significantly different across villages but not across treatments, and does not differ across treatments for a given village.

	Village (p-value)	Frequency of Use (p-value)	Village x Frequency of Use (p-value)
Soil Compaction	0.03*	0.87	0.55
pH	0.74	0.63	0.83
Nutrients	0.35	0.67	0.94
Fire	Modis did not record fire in any sample.		
Temperature	7.17e-09	0.1887	0.3192
Precipitation	No difference across regions.		
Elevation	6.9e-06***	0.3438	0.4547
Slope	0,4334	0.5940	0.7185

S5. GENERAL FIELD RESULTS

Eighty-four total species (including trees, shrubs, climbers and grasses) were recorded in the study region in which 105 species have been recorded previously (Madhya Pradesh Forest Department, 2011). Since species had to be present in at last four plots in each village for analysis, only 16 species could be analyzed. These represent ~19% of total species, which is similar to the proportion of species used in other studies (Feeley *et al*. 2007).

S6: Results for differences in forest components (species diversity, biomass, vegetation structure)

Table S6

Differences in forest attributes (species diversity, biomass, vegetation structure) with frequency of use at each village. Significance of p-values for one-tailed t-test are indicated as * (p<0.05), ** (p<0.01)

Forest Attribute	Village	Control vs. All Use	Others vs. High Use	Intermediate Use vs. Others
Species Richness	DH		**11(0.05)**	**-15.75(0.009)**
	DU	**4.26(0.034)**	5.3(0.15)	0(0.5)
	HA		-2.66(0.29)	0.25(0.47)
Species Diversity (Shannon-Weiner Diversity Index)	DH		1036.36(0.10)	-1187.62(0.19)
	DU	**352.76(0.05)**	128.069(0.30)	250.30(0.13)
	HA		-677.74(0.19)	232.75(0.34)
Species Diversity (Simpson Index)	DH		**4.82(0.04)**	**-6.2(0.003)**
	DU	-0.34(0.29)	-0.13(0.45)	-0.24(0.34)
	HA		-2.33(0.11)	1.06(0.34)
Biomass	DH		**545.38(0.01)**	**-468.18(0.09)**
	DU	-269.58(0.18)	**-519.82(0.004)**	146.27(0.26)
	HA		324.84(0.18)	1.70(0.49)
Abundance (Large Trees)	DH		0.66(0.31)	-0.5(0.42)
	DU	-2.8(0.18)	-7(0.11)	2.8(0.15)
	HA		4.33(0.20)	0.75(0.43)
Abundance (Medium-sized Trees)	DH		**18(0.03)**	-13.75(0.17)
	DU	-6.46(0.19)	0.5(0.47)	-6.86(0.30)
	HA		5.66(0.22)	-6.25(0.30)
Abundance (Small Trees)	DH		**87.6(0.07)**	-93(0.17)
	DU	**28.26(0.04)**	-2(0.47)	**29.86(0.02)**
	HA		-51.33(0.10)	30(0.19)
Abundance (Saplings)	DH		82(0.18)	-98(0.25)
	DU	**47.86(0.02)**	**33(0.02)**	21.46(0.19)
	HA		-77.33(0.24)	10(0.45)

S7. Random Forest Results and AIC Values

S7.1 Saplings to Small Trees

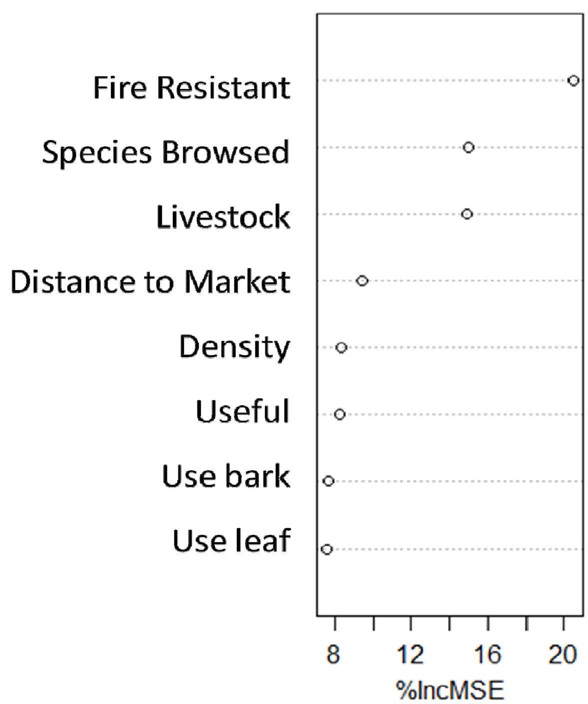
Table S7.1.1. Selection of best model using AIC

SNo	Model	AIC
1	Fire Resistant + Livestock+ Species recalled as useful (% of population)+Intensity+(1|Species)	13.19
2	Fire Resistant + Livestock+ Market for leaf +Intensity+(1|Species)	10.11
3	Fire Resistant + Livestock+ Use leaf+Intensity+(1|Species)	12.79
4	Fire Resistant + Livestock+ Use fruit for non-food +Intensity+(1|Species)	8.57
5	Species browsed + Livestock+ Species recalled as useful (% of population)+Intensity+(1|Species)	19.93
6	Planting Density + Livestock+ Species recalled as useful (% of population)+Intensity+(1|Species)	20.27
7	Light Dependence + Livestock+ Species recalled as useful (% of population)+Intensity+(1|Species)	33.22
8	Trampling Resistant + Livestock+ Species recalled as useful (% of population)+Intensity+(1|Species)	20.78
9	Use sap + Livestock+ Species recalled as useful (% of population)+Intensity+(1|Species)	20.79
10	Use bark + Livestock+ Species recalled as useful (% of population)+Intensity+(1|Species)	16.26
11	Fire Resistant + Livestock per forest area+ Species recalled as useful (% of population) +(1|Species)	7.75
12	Fire Resistant + Population per forest area+ Species recalled as useful (% of population) +(1|Species)	11.16
13	Fire Resistant + Canopy Cover+ Species recalled as useful (% of population)+Intensity+(1|Species)	22.86

14	Fire Resistant + Simpson Diversity Index+ Species recalled as useful (% of population)+Intensity+(1lSpecies)	13.39
15	Fire Resistant + Human population+ Species recalled as useful (% of population)+Intensity+(1lSpecies)	21.48
16	Fire Resistant + Distance to town+ Species recalled as useful (% of population) +(1lSpecies)	11.90
17	**Fire Resistant + Livestock per forest area+ Use fruit for non-food +(1lSpecies)**	**2.12**

Fig S7.1.2: Variable Importance Plot for RandomForest Results for saplings to small trees.

Percentage variation explained: 10.7%



Although there are some differences in variables for GLM and randomForest, the most important variables (Fire Resistance, Livestock Density) are the same.

S7.2 Small to Medium-sized Trees

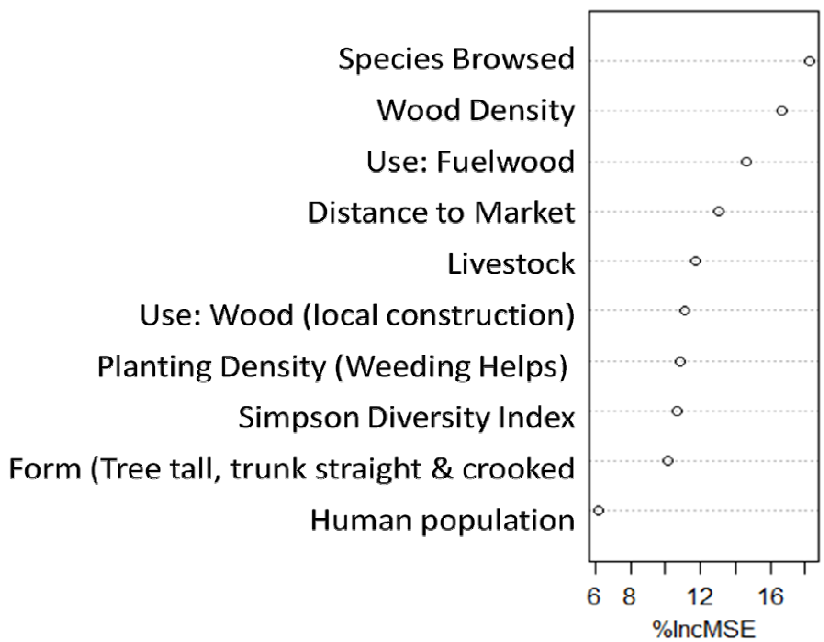
Table S7.2.1 Selection of best model using AIC

SNo	Model	AIC
1	Simpson Diversity Index +Use as fuelwood +Livestock per forest area +Use as wood for local construction +Growth Form+(1|Species)	92.35
2	Simpson Diversity Index +Use as fuelwood +Population per forest area +Use as wood for local construction +Growth Form+(1|Species)	88.83
3	Simpson Diversity Index +Use as fuelwood +Intensity of Use +Use as wood for local construction +Growth Form+(1|Species)	89.09
4	Use as fuelwood +Livestock +Use as wood for local construction +Growth Form+(1|Species)	80.02
5	Use as fuelwood +Human population +Use as wood for local construction +Growth Form+(1|Species)	89.12
6	Use as fuelwood +Distance to Market +Use as wood for local construction +Growth Form+(1|Species)	81.30
7	Simpson Diversity Index +Species browsed +Livestock per forest area +Use as wood for local construction +Growth Form+(1|Species)	95.92
8	Simpson Diversity Index +Species recalled as useful +Livestock per forest area +Use as wood for local construction +Growth Form+(1|Species)	94.03
9	Simpson Diversity Index +Trampling Resistant Species +Livestock per forest area +Use as wood for local construction +Growth Form+(1|Species)	93.25
10	Simpson Diversity Index +Fire Resistant Species +Livestock per forest area +Use as wood for local construction +Growth Form+(1|Species)	93.57
11	Simpson Diversity Index +Use of fruit as food +Livestock per forest area +Use as wood for local construction +Growth	86.616

	Form+(1|Species)	
12	Simpson Diversity Index +Use as fuelwood +Livestock per forest area +Use as wood for furniture+Growth Form+(1|Species)	96.20
13	Simpson Diversity Index +Use as fuelwood +Livestock per forest area +Use leaf +Growth Form+(1|Species)	93.82
14	Simpson Diversity Index +Use as fuelwood +Livestock per forest area +Use as wood for local construction + Light Dependant Species+(1|Species)	86.96
15	Simpson Diversity Index +Use as fuelwood +Livestock per forest area +Use as wood for local construction + Market for Product+(1|Species)	85.59
16	Simpson Diversity Index +Livestock per forest area +Use as wood for local construction +Use for commercial purpose+(1|Species)	86.55
17	Simpson Diversity Index +Livestock per forest area +Use as wood for local construction +Wood density+(1|Species)	90.37
18	Simpson Diversity Index +Use as fuelwood +Livestock per forest area +Use as wood for local construction + Use bark+(1|Species)	90.72
19	Simpson Diversity Index +Use as fuelwood +Livestock per forest area +Use as wood for local construction + Use sap+(1|Species)	89.79
20	Use as fuelwood +Livestock +Use as wood for local construction + Growth Form+(1|Species)	80.03
21	Use as fuelwood +Human Population +Use as wood for local construction + Growth Form+(1|Species)	89.12
22	Use as fuelwood +Distance to market +Use as wood for local construction + Growth Form+(1|Species)	81.30
23	**Use as fuelwood +Livestock +Use as wood for local construction + Light Dependant Species+(1|Species)**	**72.86**

24	Use as fuelwood +Livestock +Use as wood for local construction + Market for leaf+(1lSpecies)	72.94
25	Use of fruit as food+Livestock +Use as wood for local construction + Light Dependant Species+(1lSpecies)	74.83
26	Use as fuelwood +Livestock +Use as wood for local construction + Light Dependant Species +Planting Density+(1lSpecies)	77.90
27	Use as fuelwood +Livestock +Use as wood for local construction + Light Dependant Species +Wood Density+(1lSpecies)	77.81

Fig S7.2.2: Variable Importance Plot for RandomForest Results. Variation explained: 33.72%



S7.3 Medium-sized Trees to Large Trees

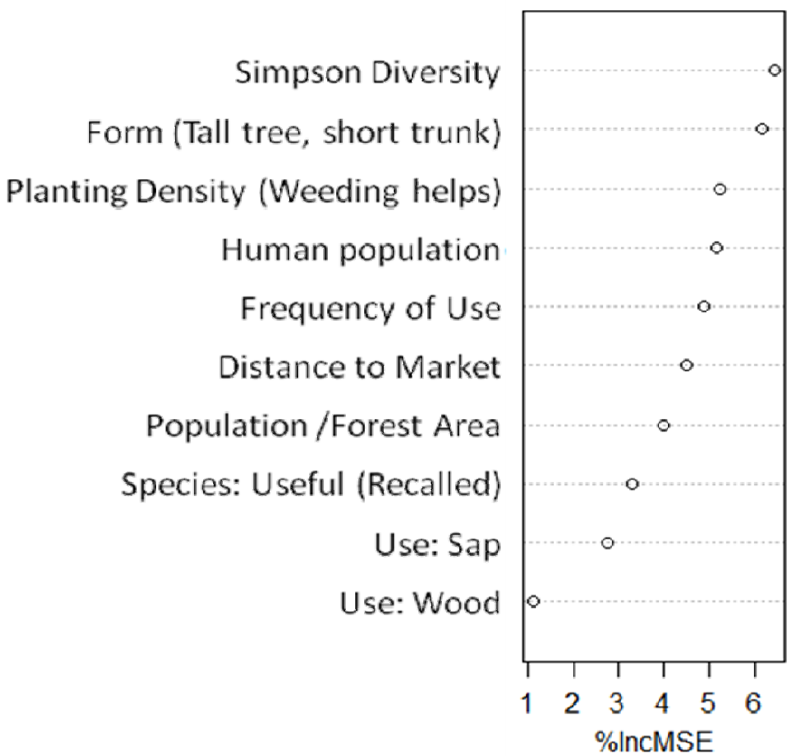
Table S7.3.1 Selection of best model using AIC

SNo	Model	AIC
1	Wood density + Frequency of Use + Simpson Diversity Index +	25.047

	Growth Form + Planting Density	
2	Wood density +Distance to Market + Growth Form + Planting Density	22.88
3	Wood density + Frequency of Use + Canopy Cover + Growth Form + Planting Density	27.37
4	Wood density + Frequency of Use + Human population + Growth Form + Planting Density	24.599
5	Wood density + Population per Forest Area + Growth Form + Planting Density	20.31
6	Wood density +Human population + Growth Form + Planting Density	20.26
7	Wood density + Frequency of Use + Simpson Diversity Index + Light Dependence + Planting Density	33.91
8	Wood density + Frequency of Use + Simpson Diversity Index + Fire Resistance	30.40
9	Wood density + Frequency of Use + Simpson Diversity Index + Use Fruit as Food + Planting Density	30.73
10	Wood density + Frequency of Use + Simpson Diversity Index + Use for Market + Planting Density	31.26
11	Wood density + Frequency of Use + Simpson Diversity Index + Use leaf + Planting Density	27.89
12	Wood density + Frequency of Use + Simpson Diversity Index + Use fruit + Planting Density	30.80
13	Wood density + Frequency of Use + Simpson Diversity Index + Growth Form + Use wood for furniture	25.40
14	Wood density + Frequency of Use + Simpson Diversity Index + Growth Form + Use wood for local construction	25.74
15	Wood density +Human population + Growth Form + Use wood for local construction	22.59
16	Wood density +Human population + Growth Form + Use wood	21.61

	for furniture	
17	Wood density +Human population + Use Fruit as Food + Planting Density	27.38
18	Wood density +Human population + Use leaf + Planting Density	25.98
19	Wood density +Human population + Use fruit + Planting Density	28.27
20	Wood density +Frequency of Use + Growth Form + Planting Density	20.98

Fig S7.3.2: Variable Importance Plot for RandomForest Results.



Although some factors are different, the important factors are largely the same across generalized linear model and randomforest: Growth Form (tall tree, short trunk, planting density (species where weeding helps), Human population and frequency of use.

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CHAPTER 3

Comparing the ability of ALOS-PALSAR, Landsat and MODIS-based EVI in quantifying and identifying drivers of degradation in tropical deciduous forests of Central India

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ABSTRACT

Human use of biomass in tropical deciduous forests is high, with potential impacts on ecosystem services such as watershed protection, wildlife habitat and provision of forest products for local needs. This study assessed the comparative ability of Landsat, MODIS, and ALOS-PALSAR data to accurately quantify forest biomass in tropical deciduous forests in Central India based on field measurements. We then used generalized linear mixed models to identify landscape-level factors associated with changes in biomass from 2007 to 2010. The study finds that HV Backscatter from ALOS-PALSAR Fine Beam Dual (FBD) polarization data has the highest ability to accurately predict biomass, the ability of Landsat is ~ 10% less, and MODIS based EVI has low ability to predict biomass. Loss of biomass was positively associated with human population density (which in turn is associated with increased fuelwood collection and livestock grazing), and fire after controlling for biophysical factors and harvesting that reduces biomass. Distance to town was also positively associated with reduced forest biomass, counter-intuitively suggesting that biomass loss increases in forests further from towns. Fire (~25%) and harvest (~14%) together contributed ~39% to biomass loss while pressures associated with population density contributed ~26%. The methodology for monitoring forest degradation and identifying risk factors in tropical deciduous forests, which are an understudied forest type, can be

generalized for other tropical deciduous forests.

KEYWORDS: ALOS-PALSAR; biomass; change detection; Kanha-Pench landscape; Landsat; MODIS; forest degradation

HIGHLIGHTS:

- Predicted aboveground forest biomass using RADAR, MODIS, and Landsat.
- We used resulting algorithms to map changes in forest biomass from 2007 to 2010.
- Identified factors associated with changing forest biomass.
- Predictive ability for forest biomass was highest using ALOS-PALSAR FBD.
- Biomass loss positively associated with population, fire and distance to towns.

1. INTRODUCTION:

Human use of forests has led to changes in forest canopy, understory, biomass, structure and species composition. Such human-induced changes in the forest can constitute degradation, although there are multiple debates around the definition of forest degradation (Sasaki and Putz, 2009; Turner et al., 2007; Olander et al., 2008). While some define forest degradation as loss of biomass without change in area of forest cover (Olander et al., 2008), others counter that the definition of forest itself should exclude plantations, and that forest degradation should include loss of ecosystem services, especially those essential for locally dependent people (Sasaki and Putz, 2009). Nevertheless, these changes impact ecosystem services such as hydrology and habitat for biodiversity (Fischer and Lindenmayer, 2007). Therefore, several researchers have attempted to quantify these forest components in order to accurately quantify change in these components as metrics for forest degradation.

For instance, some researchers measure canopy opening and gaps and their changes over time as a measure of degradation (Asner et al., 2005; Matricardi et al., 2013). Others use a combination of optical imagery and LiDAR to classify forests as degraded based on differences in heights of forest crown and other lower canopies (Falkowski et al., 2009; Kim et al., 2009; Margono et al., 2012; Martinuzzi et al, 2009). For this, LiDAR is especially useful as active sensors measure vegetation height accurately. Yet other studies focus on measuring forest biomass using RADAR and optical sensors (Englhart et al., 2011; Saatchi et al., 2011), where RADAR is useful as substrates absorb energy from the active RADAR sensors in proportion to their mass (Bergen et al., 2009), and lower biomass constitutes degradation. Studies also classify forests as degraded based on changing forest composition. For instance, Asner and Vitousek (2005) used hyperspectral data to map encroachment of invasive species (forests with invasive species may be considered degraded). In another example, Kim et al. (2009) used LiDAR to quantify average heights of forests with different species compositions, and classified forests as degraded based on forest composition. These techniques use a combination of optical sensors, RADAR, hyperspectral and LiDAR to ascertain and quantify degradation. However, since forest degradation varies with forest type, type of use and the type of changes that result from human use, it is important to understand which technique is most suitable for quantifying human-induced change in a particular study region. This would further provide information on spatial distribution of forest change, an aspect that has the highest uncertainty in REDD+ (Mitchard et al., 2013a).

Human use in tropical deciduous forests cause changes in forests that are different from changes observed in other parts of the world (Olander et al., 2008). Deciduous forests form 17% of tropical forests (UNEP, 2000) and are ecologically different from rainforests (Sasaki and Putz, 2009). Structural differences include open canopy forests with low crown cover (UNEP, 2000) and high heterogeneity so that it is important for researchers to map variations in the existing forest before they can detect deviations from a relatively und forest (Olander et al., 2008). These open canopy and dry forests are also more heavily used than rainforests because the former have higher human population densities and are thus highly threatened (Gaston et al., 1998; Miles et al., 2006).

Forests can be altered by subsistence uses such as grazing, firewood removal, and small understory fires (Gaston et al., 1998; Olander et al., 2008) or large-scale market demand for timber, or global commodities such as oil palm or soy (Olander et al., 2008; Houghton, 2012). Depending on the human uses associated with a forest as well as the type of forest, remote sensing potentially captures changes induced in forests due to such processes through accurate measurement of biomass and its change through time, particularly as many of these changes involve loss of forest biomass.

Understanding processes that lead to alteration in these forests can contribute information useful for efforts to reduce degradation. While clearing by subsistence farmers and land conversion for commodity production are drivers of deforestation (Lambin et al., 2003; Houghton, 2012), cattle-grazing, extraction of timber and fuelwood, and fire are practices that may be responsible for reduction in forest biomass (Asner et al., 2005; McAlpine et al., 2009, Houghton, 2012, Ahrends et al., 2010). However, studies understanding drivers of degradation are largely located in evergreen forests in the Amazon and South East Asia, and it is important to extend such studies to other forest types (such as Ahrends et al., 2010). This is particularly important in India, where forest conversion is largely outlawed, and forests are tightly managed and controlled. Therefore, mapping deforestation underestimates human impact on these forests.

Further, there are few landscape-scale studies that attempt to understand drivers of forest change in India (exceptions such as Velho et al., 2014 examine drivers of deforestation).

This study addresses two questions. First, we assess remote sensing techniques that are most suitable for monitoring biomass changes in tropical deciduous forests in Central India where pressures for subsistence and local livelihoods are high compared with humid forests. Of the multiple sensors available, there was no coverage of LiDAR or hyperspectral imagery in the study area. This limitation is representative of many areas globally as high costs and security concerns preclude the availability of LiDAR and high resolution hyper-spectral data. This limited coverage prevents retrospective analyses at large scales. Global coverage of ALOS-PALSAR has made RADAR accessible globally, and the launch of new satellites (Japanese Satellite Agency JAXA, 2014) suggests that RADAR coverage may become more generally available. Besides these, Landsat and MODIS are already publicly available, and while Landsat is used more frequently for quantifying forest change and is available for a longer period of time and at a higher resolution, MODIS imagery lends itself more easily for global and continuous monitoring protocols. Therefore, this study uses sensors available in the study region (Landsat, MODIS and ALOS-PALSAR) for testing the ability to accurately predict forest biomass. Secondly, we use the remotely-sensed results from 2007 to 2010 to assess factors associated with change in biomass in the landscape.

2. MATERIALS AND METHODS

2.1 Study Area

The study is located in the forests between and surrounding two national parks, Kanha and Pench Tiger Reserves in Mandla, Balaghat and Seoni districts and covers three forest divisions (East

Mandla, South Seoni and North Balaghat: Figure 1). This site was chosen for its heterogeneous forest cover that includes sal (*Shorea robusta*), teak (*Tectona grandis*) and miscellaneous forests as well as its importance for ecosystem services such as hydrology (part of the area is a watershed for River Narmada), and biodiversity (two protected areas with endangered species such as tiger *Panthera tigris* that use the unprotected forests as corridor between protected areas: Sharma et al., 2013). As deciduous forests, these forests are also highly seasonal, with leaf fall concentrated in the summer months. Fires generally occur during the dry season (February to May) and rainfall is concentrated in the monsoon months (mean annual rainfall is 1315 mm: India Water Portal, 2014). There has been little deforestation in the region since 2006 (Forest Survey of India, 2011) and people use forests differently depending on whether the forests are located in protected areas where use is minimal, or outside protected areas (reserve forests) where forest use can account for up to 60% of income of local people (Saigal, 2010). Population density in the region also varies with distance from major towns and villages, and villages far from towns usually have lower populations, although average population density in all districts is >157 people per km^2 (Census of India 2011). This variation in forest type and frequency of human use makes the study region ideal for assessing the ability of remote sensing indices to quantify changes in the forest due to human use.

The local people depend on forests for grazing, fuel wood and other subsistence needs (Saigal, 2010). People use forests seasonally, where they collect subsistence-use forest products throughout the year, and collect produce for sale to markets in the summer months. Important forest produce includes *Dendrocalamus strictus* or bamboo, *Madhuca indica* whose flower is used for brewing alcohol and *Diospyros melanoxylon* whose leaves are sold, and use of fire augments the production of the latter two products. Locally situated studies find that increasing forest use is associated with lower biomass (Agarwala et al, Submitted), thus accurate quantification of biomass using existing satellite sensors is important for monitoring forest degradation and progress of efforts to reduce it.

2.2 Quantifying forest biomass

2.2.1. Satellite Data

Landsat: We downloaded Landsat imagery for our study region (path 143, row 45 and path 144, row 45 on Dec 12, 2009, path 143, row 44 for Jan 31, 2010). These were radiometrically calibrated (Canty and Nielson, 2007), and all 6 Landsat Bands were unmixed using global spectral end-members generated by Small (2004). These endmembers were used to calculate spectral mixture fractions: % bare substrate (BS), % photosynthetic vegetation (PV), and % dark materials for each pixel. We used spectral mixture analysis as it provides sub-pixel information on a continuous scale. Instead of classifying each pixel as forest or non-forest, spectral mixture fractions provide percentage composition of a pixel (Smith et al., 1990; Adams et al., 1995; Asner et al., 2005). Since loss of biomass is more fine-scale than deforestation, we expected that spectral mixture analysis may be able to quantify the difference more accurately than other techniques.

MODIS: We downloaded MOD13Q1 EVI band for December 3, 2009, a date that was closest to the date of the Landsat imagery. We used MODIS Reprojection Tool (www.lpdaac.usgs.gov) to reproject and resample the imagery to 30 meter pixel size to make it comparable to the Landsat data. Although MODIS has coarser resolution (250m) than Landsat (30m), its temporal coverage and the technological ease of use suggest that MODIS might be more useful for continuous monitoring, which is important for developing operational monitoring protocols.

ALOS-PALSAR: We used L-band ALOS PALSAR images from NASA's Alaska Satellite Facility (NASA Distributed Active Archive Center DAAC), which were available from 2007 to 2010 (July and August 2007 and 2010). This sensor provides two types of imagery for the study region in each year: fine beam dual (FBD) polarization data (Level 1.1) that is collected in July-August and fine beam single (FBS) polarization (Level 1.5) data available in winter (January-February). Of the two, FBD imagery includes phase information (Santoro et al., 2009) which provides information on polarization of RADAR waves by the earth materials that reflect RADAR and is not available in other sensors (Bergen et al., 2009; Mulder et al., 2011). Information on polarization may be helpful because it captures the dielectric direction of earth materials (for instance data on polarization may assist us in identifying a canopy layer as the water molecules in the leaves of a canopy layer may be aligned in one direction: Bergen et al., 2009; Jin, 2010). Since FBS is available more often than FBD, we used both FBS imagery (2010) and FBD imagery (2010) to assess whether both sensors were as useful in quantifying forest biomass, and whether one was better able to quantify forest biomass. ASF Mapready version 3.0.6 (Alaska Satellite Facility, Fairbanks) was used to geo-code, resample, and terrain-correct the downloaded images using 30-meter ASTER DEM (echo.nasa.gov). We converted the imagery to γ_0 ('gamma-nought', normalized backscatter coefficient scaled to a log based dB [decibel] scale), which provided us with imagery in HH (Horizontal-Horizontal) and HV (Horizontal-Vertical) polarizations for FBD imagery and only HH polarization for FBS imagery. Although the imagery can be normalized to a pixel-size of 6.5 meters, we used 30-m ASTER DEM for terrain-correction, which led ASF MapReady to alter the resolution of the final imagery (HH-backscatter and HV-backscatter) to a pixel-size of 49.5 meters.

In addition, we downloaded ASTER-based 30-m digital elevation maps (DEM) from echo.nasa.gov, and used this to estimate elevation, slope, and hill-shade, which was used to supplement information provided by Landsat, MODIS and PALSAR.

2.2.2 Field Data

We collected data along 44 randomly located 1-km long transects from January to March, 2010, where we took samples every 100 meters, leading to a total of 484 samples. In each sample, we measured tree abundance, understory cover, canopy cover, and size-class distribution in 20 m^2 quadrats at the center of each sampling point. We measured abundance of large trees (>10 cm DBH) and medium-sized trees (<10 cm DBH, > 1.7 m height). We also measured understory biomass at two randomly located 1-meter quadrats at each sampling point. We used size-class abundances in allometric equations to estimate aboveground biomass at each sample (Zianis, 2008; Supporting information, S1).

2.2.3 Analysis

We calculated mean and standard deviation of PV Fraction, BS fraction, HH back-scatter, HV back-scatter and EVI within a 30-m radius circle around each sample point. Sample locations were stratified through field surveys according to biomass (as recommended in Olander et al., 2008). Due to high variation of biomass within the 1-km long radius, we selected those points where three consecutive points fell within a similar forest type (standard deviation below 0.5). This reduced the number of samples from 484 to 261. To reduce the impact of over-sampling at certain class intervals of biomass (there were fewer samples at very low and very high biomass levels), we did a stratified sample selection of 100 samples for calibration and 75 samples for validation. Equal numbers of samples were randomly selected from low ($value_{min}$ to $value_{min}$+(1/3) $value_{range}$), medium ($value_{min}$+(1/3) $value_{range}$ to $value_{min}$+(2/3)$value_{range}$) and high ($value_{min}$+(2/3)$value_{range}$ to $value_{max}$) biomass values.

The aim of the analysis was to predict field-measured forest biomass using relationships derived between satellite indices and field measurements (Table 1). We used generalized linear models (GLM) for this analysis where the response variable was field-measured biomass and predictors were satellite-based indices (Supporting information, S2). To separately understand the ability of different satellite sensors in predicting biomass, we used the sensors separately: only Landsat-based PV Fractions and BS Fractions; only EVI values derived from MODIS; only HV and HH back-scatter values derived from ALOS-PALSAR FBD imagery; and only HH back-scatter values derived from ALOS-PALSAR FBS imagery. Least Akaike Information Criteria (AIC) score was used to determine the best model (Burnham and Anderson, 2002). We tested both linear and exponential relationships due to their precedence in existing studies (exponential relationship between aboveground biomass and RADAR: Englhart et al., 2011; Mitchard et al., 2013b; linear relationship between aboveground biomass and RADAR: Saatchi et al., 2011). Although theory suggests that such relationships are sigmoidal (Woodhouse et al., 2012), the biomass in our study region was low and we did not extend analysis beyond the saturation limit. To understand whether predictive ability is higher when sensors are used in combination, we combined the satellite-based indices from multiple sensors using principle component analysis as the information provided by the sensors were highly correlated. We then used the principle components to construct models (no collinear predictors in a model) to predict biomass and used AIC to select the best model (Supporting information, S2).

Our measure for accuracy was predictive ability (the R^2 value) of satellite-based metrics in predicting field-measured variables. We report the R^2 value between predicted and observed values for the calibration as well as a separate sample of validation data. For validation, we used the coefficients obtained from the best models in our analysis (Supporting information, S2) to predict biomass in the study region and compare field-measured variables with their predicted values for the validation dataset. Finally, to create maps of forest biomass, we used the coefficients obtained from our best models to map biomass for 2010 and 2007 using Landsat, MODIS and PALSAR, and subtracted the biomass images for 2007 from the 2010 biomass image to obtain change from 2007 to 2010.

2.3 Factors associated with Degradation

2.3.1. Data

To identify factors associated with differences in forest biomass from 2007 to 2010, our models included biophysical, spatial, and demographic variables from the landscape. We collected information on the following biophysical variables (sources in Table 2): temperature, precipitation, fire, elevation and slope. We calculated mean temperature, precipitation and fire radiative power (FRP) for each pixel, total numbers of years that a pixel was burnt, and number of years prior to 2010 that the pixel was last burnt (see Table 2 for data sources). We resampled precipitation, temperature and fire data to 30-meter resolution to make them comparable with ASTER-DEM. Besides biophysical variables, we collected data on forest edge and distance to roads and major towns (Table 2). Our metric for edge was the shortest distance to a non-forest for that pixel using a Landsat-based forest/non-forest classification (Agarwala et al., Submitted). Forest use can also be influenced by the availability of forest in the general vicinity as use of one forest patch may be influenced by the presence and abundance of other forests. We therefore calculated mean forest cover within a 1.5 kilometer radius from a 30-m forest pixel (based on average forest use distance from a village, Agarwala et al., Submitted). For estimating distance to road, we obtained a shapefile of major highways in the region from open-street map data (http://download.geofabrik.de/asia.html) and calculated distance to highways for each forest pixel. We used estimates of distance to nearest town by road for each village from a dataset (Wildlife Institute of India, 2011) which lists distance to nearest town by road for all villages, to determine proximity to markets and major economic centers. This is a 2001census-based dataset where village level data is attached to a shapefile of village locations. Due to potential importance of demographics in explaining differences in biomass change through the years, we needed high resolution data on demographics for human and livestock populations. For human populations, we used village-level total population from the same 2001 census-based dataset (Wildlife Institute of India, 2011). For livestock populations, we used village-level cattle and buffalo populations from the 2005 India Livestock Census (Department of Animal Husbandry, 2011), and estimated livestock abundance in each village as the sum of cattle and buffalo populations. Although we could also use populations of smaller ruminants such as goats, these were very infrequently present or present at very low densities, and were therefore excluded. For each village, we also calculated proportion of literate population as ratio of literate population to total population. We then used bilinear sampling to interpolate population abundances of livestock and people and proportion of literate population for each 30-meter pixel, and used these data layers in our analysis.

Finally, due to active management of forests outside protected areas, it was important to account for management activities in these forests in order to accurately interpret changes in biomass. We collected compartment management histories, where a compartment is a well-defined forest management unit ranging in size from 0.1 to 5.3 km^2 (mean 2.3 ±1.06 km^2) with its own management plan (Madhya Pradesh Forest Department, 2011). These compartment histories list the dates that payments were distributed for harvest of forests, which can serve as proxies for dates the forest was harvested. The number of harvests between 2007 and 2010 was also used as a predictor. Since there were some imbalances in this data (in some forest ranges, all the compartments had been harvested, while none had been harvested in other regions), we selected 8 ranges in East Mandla (Bamhni, Bichhiya, Jagmandal) and South Seoni Forest Divisions (Amagarh, Ari, Barghat, Keolari, Ugli), as these divisions had both villages with and without payments (In total, for 105 villages examined, payments were received in 102 compartments and not received in 78 compartments).

2.3.2. Analysis

To calculate change in biomass from 2007 to 2010 where biomass is estimated using PALSAR-based HV back-scatter, we downloaded PALSAR images for July and August, 2007 in addition to the images we had for 2010. We prepared the imagery and estimated biomass for 2007 using techniques as described for 2010 (Section 2.2.3). For the final map of change from 2007 to 2010, we subtracted the 2007 biomass image from the 2010 biomass image.

We used a generalized linear mixed model (GLMM) to test whether human and cattle populations, fire, distance to towns and roads, and literacy rates were significant in predicting changes in biomass estimated using HV backscatter at pixel-resolution (biophysical variables and number of payments were included in these models as controls). In these models, we did not include predictor variables that had a correlation coefficient higher than 0.4 in order for the individual predictors to be independent (Supporting materials, S3). To avoid spatial autocorrelation, we randomly selected fifty thousand pixels from our landscape for the analysis. We used least AIC scores to select the best model (Burnham and Anderson, 2002). R (3.0.3) software was used for all analysis (R Core Team, 2014).

3. RESULTS

3.1 Ability to accurately predict biomass using Landsat, MODIS and ALOS-PALSAR (FBS and FBD data)

For PALSAR backscatter and EVI, best models for biomass included only one predictor (Supporting information, S2), and fitted relationships were of the form (Figure 2) similar to Englhart et al., 2011; Mitchard et al., 2013b which found an exponential relationship between above ground biomass and RADAR backscatter. Although other studies have found a linear relationship between aboveground biomass and RADAR back-scatter (Saatchi et al., 2011), the only other study in open canopy deciduous forests (in Miombo woodlands in Mozambique) also showed an exponential relationship (Mitchard et al., 2013b):

$x = a + b*\log_{10} (B)$

Which was rearranged to:

B=10^(x -a/b)

Where B= field measured aboveground biomass, and x = either γ^0_{HV} or EVI for the sample.

For Landsat-based spectral mixtures, best models for biomass included more than one predictor (Table 1), and fitted relationships were of the form (Figure 2d):

B=10^(a +b*PV+c*BS)

Where B= field measured aboveground biomass, PV=Photosynthetic Vegetation Fraction, BS=

Bare Substrate Fraction.

Predictors for Landsat-based analyses included BS Fraction (Supporting information, S2) which could be important in providing supplementary information to the model as it constitutes the proportion of bare substrate and non-photosynthetic vegetation exposed in a pixel (Adams et al., 1995; Small, 2004). However, to enable comparison with EVI and HV models, Figure 2c also shows the relationship when only PV-fraction was used since EVI and PV fraction are highly correlated (Small and Milesi, 2013).

Predictive ability of biomass using FBD-based HV backscatter was similar to previous studies (R^2=0.53: Englhart et al., 2011; R^2=0.60-0.64: Mitchard et al., 2013b). Predictive ability using only Landsat-based spectral mixtures was ~10% lower than that using HV backscatter, while predictive ability using EVI was very low (Table 1).

3.2. Factors associated with change in biomass

Results suggested that several factors are associated with changes in forest biomass (Table 3, Figure 3 and 4, Supporting information, S4): number of payments (which indicates number of harvests), population density, distance to town, and mean fire radiative power (FRP) from 2007 to 2010, in a final model that controlled for slope and temperature. As expected, number of payments for harvest (~14%), population density (~26%) and fires (~25%) are associated with decrease in forest biomass as forests with greater number of harvests in the time period studied, more frequent and intense fires and greater population density would show reduced biomass. However, counter-intuitively, distance to town (~22%) was also associated with decrease in forest biomass.

Distance to town is negatively correlated with elevation (supporting information, S3), and could suggest alternative explanations for greater loss of biomass in forests that are far from town: Forests with lower elevation may have greater forest loss because they are more easily accessible. However, models with distance to town instead of elevation had the lowest AIC scores which suggests that distance to town is a more accurate predictor than. Another explanation suggests that management activities and harvests could have been biased towards forests distant from towns (as there tends to be higher forest cover there). However, distance to town was a significant factor associated with biomass loss even after controlling for management activities (harvests). Further, although human population density (which is correlated with livestock density) maybe associated with increased biomass loss due to higher pressure on forests through local removal of forest biomass for fuel-wood and other subsistence uses, people and livestock usually travel ~2-4 kilometers into the forest for local use (Agarwala et al., Submitted). Therefore, some other mechanism may be operational for biomass loss beyond these distances. Possible alternatives include under-representation of fire in this study (Section 4.2) or undocumented removal of biomass. Other studies have also found patterns where subsistence use is closer to habitation, and undocumented extraction for markets are at greater distances from habitation (Ahrends et al., 2010) or where fires occur at greater distances from habitation (Uriarte et al., 2012).

4. DISCUSSION

4.1 Predictive ability

Predictive abilities for models that estimated biomass were comparable to similar analyses where a continuous variable was quantified using remote sensing (R^2=0.53: Englhart, 2011; R^2=0.60-0.64: Mitchard et al., 2013b). The remaining unexplained variation in the analyses could be due to natural variation within a sample and heterogeneity of forest at the sub-pixel level (Jiang et al., 2006).

The properties of sensors can explain the differences in predictive ability of analyses that used ALOS-PALSAR, Landsat and MODIS. As an active sensor, ALOS-PALSAR can quantify the quantity of a given substrate more accurately as vegetation absorbs synthetic energy sent by the satellite in proportion to its biomass (Bergen et al., 2009). Secondly, the wavelength of RADAR is comparable to the average distance between branches (Bergen et al., 2009). This suggests that RADAR will scatter off branches but penetrate canopy leaves (Bergen et al., 2009). As a result, scattering off layers of branches may be able to provide us information on canopy structure. Thirdly, orientation of a substrate can also be captured by RADAR sensors due to dielectric properties of a substrate (Bergen et al., 2009), and higher ability of HV-backscatter compared with HH-backscatter may reflect this. It is possible that the orientation of water molecules in canopy leaves helps RADAR capture canopy layers with certain orientations (Bergen et al., 2009). In combination, such properties probably contribute to higher predictive ability for biomass when using ALOS-PALSAR. Other studies also suggest that RADAR is typically the best remote sensing tool for mapping forests and their change (Woodhouse et al., 2012)

In contrast, Landsat-based spectral mixture analysis is only able to record reflection of light at different optical wavelengths from the surface of the canopy or soil. This necessarily misses sub-canopy reflection and absorption at multiple layers. Therefore, it lends itself to quantifying forest elements visible from above the canopy such as canopy cover, whereas the wavelength of RADAR allows it to penetrate canopy better (Bergen et al., 2009). Therefore, Landsat-based spectral mixture analysis is not able to quantify forest biomass as accurately as

PALSAR-based HV backscatter. However, use of bare substrate (BS) fraction improved the ability of Landsat in measuring biomass. Because BS fraction measures the proportion of reflection from bare soil and senescent vegetation in a pixel, this index is able to account for canopy opening that allows light to penetrate the canopy, which may indirectly account for forest biomass as it quantifies the proportion of forest in the pixel where biomass is low enough for reflection from the bare substrate.

The poor results of MODIS-based EVI measures may be due to the resolution of MODIS pixels, which at 250 meters is an order or magnitude lower than Landsat or PALSAR. Therefore, this sensor probably misses changes at the scale at which changes in forest biomass occurs, and it may be difficult for this sensor to monitor such changes in this forest type.

Overall, this suggests that given current data sources, FBD-based HV backscatter may be the most accurate method to map changes forest biomass in tropical deciduous forests in India. Although MODIS is easier to operationalize at a large scale, it does not provide necessary accuracies in determining vegetation biomass, while use of Landsat-based spectral mixture indices provides higher accuracies and its data is more accessible than RADAR at present. However, the potential of using RADAR increases as FBD imagery may become more easily available with the data available from newly launched satellites (Japanese Satellite Agency JAXA, 2014).

4.2. Factors driving changes in biomass

This study underscored the importance of fire in altering forest biomass in tropical deciduous forests. Several studies have already identified the importance of fire in altering forests (Houghton, 2012). Fire has been identified as the primary method for land conversion

(Houghton, 2012, Uriarte et al., 2012), and its increasing frequency has been noted (Uriarte et al., 2012). Locally situated field studies have found that fires could potentially change forest composition through an increase in fire-resistant saplings (Agarwala et al., Submitted), which suggests that fires may be associated with long-term decrease in forest biomass as the forest that replaces the original forest has a higher proportion of fire-resistant species that may have lower biomass. Further studies examining the impacts of fire on forests are particularly important in India, where the country invests many resources in fire management.

This study also demonstrated that local management activities can significantly impact changes in forests, as 14% of biomass loss from 2007 to 2010 could be attributed to Forest Department harvests, although these may regrow and increase biomass over longer time scales. In landscape-level studies, it is possible to omit such management-related factors as these are more difficult to obtain at a useful resolution. However, the absence of such data could lead to misinterpretation of the results and trends in the landscape.

Results suggest that local use may be associated with loss of forest biomass and degradation in this study region as higher population density was significantly associated with biomass loss. Thus, results corroborate other studies in tropical areas that suggest that local pressure pressures may also significantly reduce forest biomass in addition to commercial demand for forest products (Asner et al., 2005; McAlpine et al., 2009, Houghton, 2012, Ahrends et al., 2010). In addition, the fact that forests distant from towns showed greater biomass loss, despite controlling for biophysical variables and management-cycle led harvests, is counter-intuitive. While different from studies assessing factors associated with deforestation (Young et al., 1994), this pattern is similar to factors associated with fire (Uriarte et al., 2012) and with undocumented timber extraction (Ahrends et al., 2010). This suggests that potential explanations for this pattern could be due to under-representation of smaller fires in the medium-resolution 250-meter MODIS fire product or undocumented forest use.

4.3. Management Implications

These results suggest that managers need to focus their attention on fires and pressures from local populations as these factors may drive loss of forest biomass. The local authorities already invest significant resources in fire-fighting and fire-management, and in managing local use of forests (Agarwala et al., Submitted), and this has led to significant achievements. However, management authorities may need to focus their efforts on vulnerable forests at risk for biomass loss. In this region, forests at a distance from towns are usually larger, have higher biodiversity and biomass, and contain more forest products that are considered essential by local people such as bamboo *Dendrocalamus strictus* (Agarwala et al., Submitted). Therefore, the loss of such forests is potentially more damaging than forests that are closer to towns, and management authorities should focus on preventing biomass loss in such vulnerable forests.

Continuous monitoring of forest degradation would be an important tool in identifying and tracking risks to forests and delineating vulnerable forests at the regional central India scale.. Local management authorities have already developed remote sensing capabilities and protocols to continuously monitor fire, and should extend their capabilities to include forest degradation. The use of PALSAR data would enable them to track changes in forest biomass more accurately than other sensors, and local governments and agencies may obtain easier access to this data as it becomes more readily available with the launch of new satellites.

5. CONCLUSION

This study quantified forest biomass with acceptable accuracy in tropical deciduous forests in Central India. ALOS-PALSAR (FBD) -based HV scatter was best able to quantify forest biomass, followed by Landsat-based spectral fractions, whose predictive ability was ~10% lower and still acceptable. However, MODIS-based EVI had low accuracy and may not be able to quantify changes in forest biomass. These results suggest that ALOS-PALSAR may be the most appropriate sensor for quantifying change in forest components in the study region. In the absence of such data, Landsat can provide useful results with publicly-available data.

This study also identified factors associated with loss in forest biomass and found that fires, population densities and distance to town were positively associated with loss in forest biomass. This result underscores that local pressures, and not only market demand, may drive change in forests. The study also identified that forests that are located away from towns are vulnerable to forest degradation. Managers should develop remote sensing capabilities, including use of ALOS-PALSAR, to continuously monitor changes in forest biomass and identify vulnerable forests. Managers should also focus on vulnerable forests that are located away from towns as these are repositories of biodiversity and contain essential products to meet local needs. The results focus on a particular study region, but the methods and conclusions are more broadly applicable to dry tropical forests throughout the world.

Acknowledgements:

We are grateful to assistance and data from the Wildlife Institute of India (WII), Madhya Pradesh Forest Department, PCCF (MP), CF (Jabalpur-Central Circle), DFO (Seoni), DFO (Balaghat) and Department of Animal Husbandry. NSF Grant Number 1029219 supported this research. Alaska Satellite Facility (NASA Distributed Active Archive Center DAAC) provided RADAR imagery. We also thank Christopher Small, Pinki Mondal, Swati Saini, Arjun Shrivathsa, Vishnupriya S., Harish Uikey, Kuldip Tekam, Yamuna and Gyaani Marabi.

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TABLES WITH CAPTIONS

Table 1: Predictive ability (R^2) for aboveground biomass using PALSAR, Landsat and MODIS (Model selection and final models in supplementary information, S2). Calibration (n=100), Validation (n=75).

Sensor	log(Biomass)	
	Calibration	Validation
FBD	0.58	0.67
FBS	0.15	0.28
Landsat	0.45	0.58
MODIS	0.25	0.42

Table 2: Predictor Variables Used in Landscape Analysis

Level	Predictors	Data Source	Metric
Biophysical Variables	Temperature	MODIS 11A1 (reverb.echo.nasa.gov)	Mean (Nov-Jan: 2007-2010-11) Mean (May-Oct: 2007-2010)
	Precipitation	TRMM 3B43 (trmm.gsfc.nasa.gov)	Mean (Jan-June: 2007-2010) Mean (July-Dec: 2007-2010)
	Elevation	ASTER-DEM (reverb.echo.nasa.gov)	
	Slope	ASTER-DEM (reverb.echo.nasa.gov)	
	Fire Radiative Power (FRP)	MODIS 14A1 (reverb.echo.nasa.gov)	Years since last fire Number of fires from 2007-2010

	(2007 to 2010)		Mean FRP (Jan-June:2007-2010)
Landscape Variables	Forest cover Edge Forest Distance to Road Distance by Road to Market	Landsat Imagery (glovis.usgs.gov) Landsat Imagery (glovis.usgs.gov) http://download.geofabrik.de /asia.html (Wildlife Institute of India, 2011)	Average forest cover (within a 1.5 km radius) Average distance to non-forest from a forest pixel (1.5 km radius) Distance to road calculated using GIS Distance by road to nearest town reported for each village, and interpolated to pixel resolution.
Demographic Variables	Human Population Density Livestock Population Density Proportion of literate population	(Wildlife Institute of India, 2011) Department of Animal Husbandry, 2011 (Wildlife Institute of India, 2011)	Human populations reported for each village. Interpolated to pixel resolution. Livestock populations reported for each village. Interpolated to pixel resolution. Literate population reported for each village. Proportion of literate population calculated for each village and interpolated to pixel resolution.

Management Variables	Payments for harvests	Madhya Pradesh Forest Department, 2011	Number of years that a forest compartment was harvested between 2007 and 2010.

Table 3: β-coefficients for factors significant in predicting biomass change (estimated using HV-backscatter) from 2007 to 2010.

Predictor	**Biomass change (2010-2007) (biomass estimation based on PALSAR-based HV)**
Number of Payments for harvest	-27.45
Distance to Town	-42.05
FRP	-47.57
Total Population	-49.74
Slope	1.04
Temperature	-22.92

FIGURES

Figure 1: Study area located in forest divisions in Mandla, Seoni and Balaghat Districts, Madhya Pradesh, India. Photosynthetic Vegetation fraction is a Landsat-based spectral mixture index and scaled from -1 to 1.

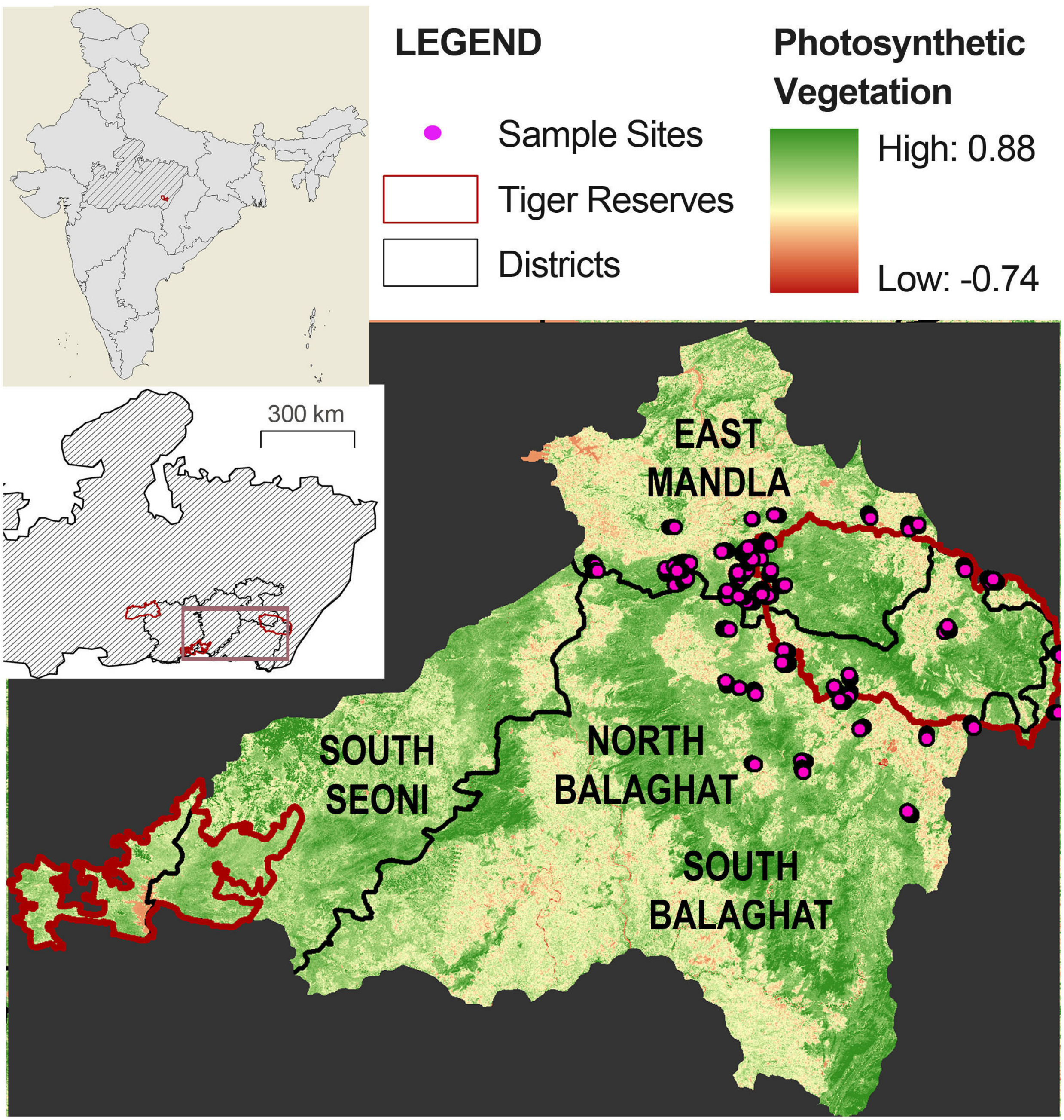


Figure 2: Predictive ability (R^2) of aboveground biomass using (a) PALSAR-based HV back-scatter, (b) MODIS-based EVI, (c) Landsat-based PV-Fraction, and (d) Landsat-based spectral mixture indices (using equation Biomass=10^ (2.6837+17.0284*PV-5.9721*BS)).

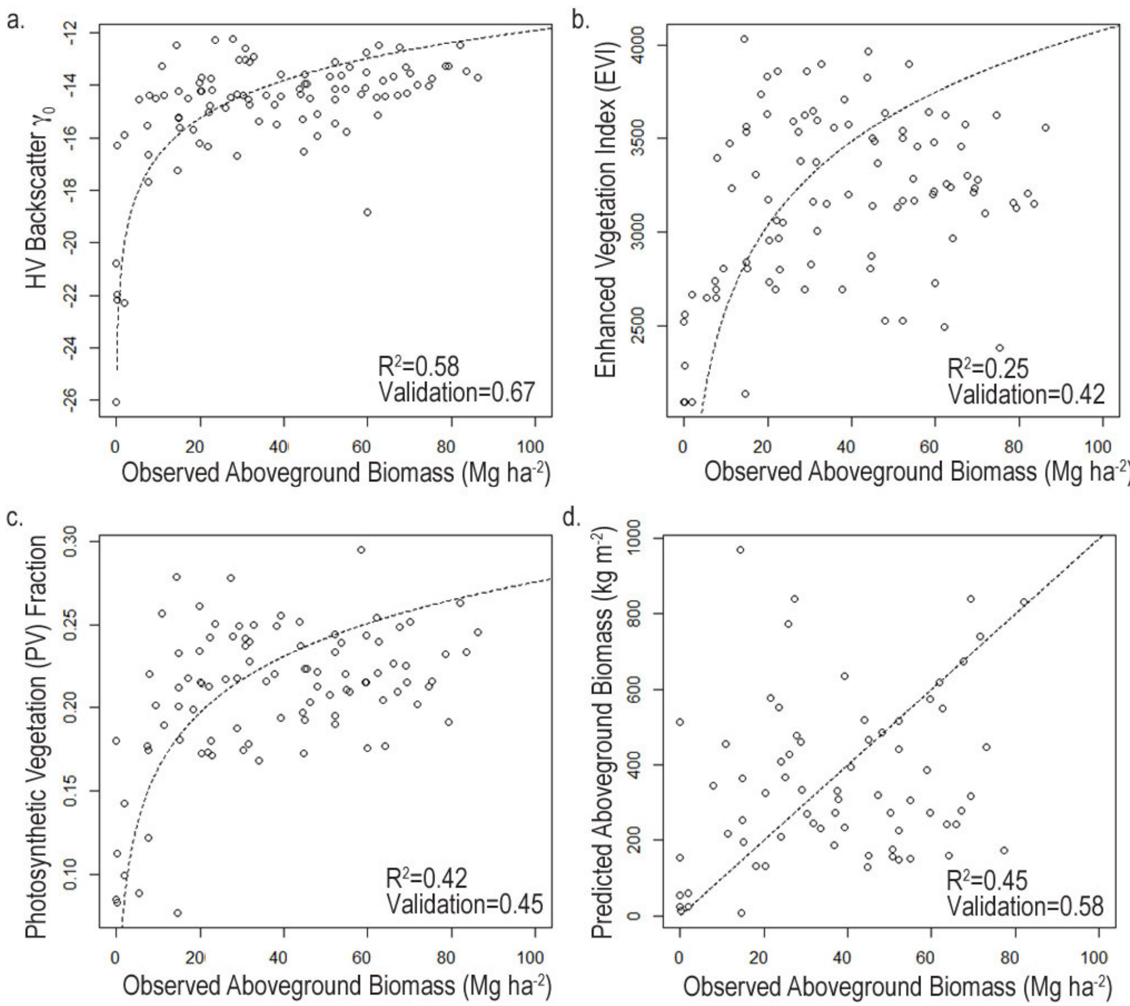


Figure 3a: Map of predicted aboveground biomass using (a) ALOS-PALSAR and (b) Landsat for 2010

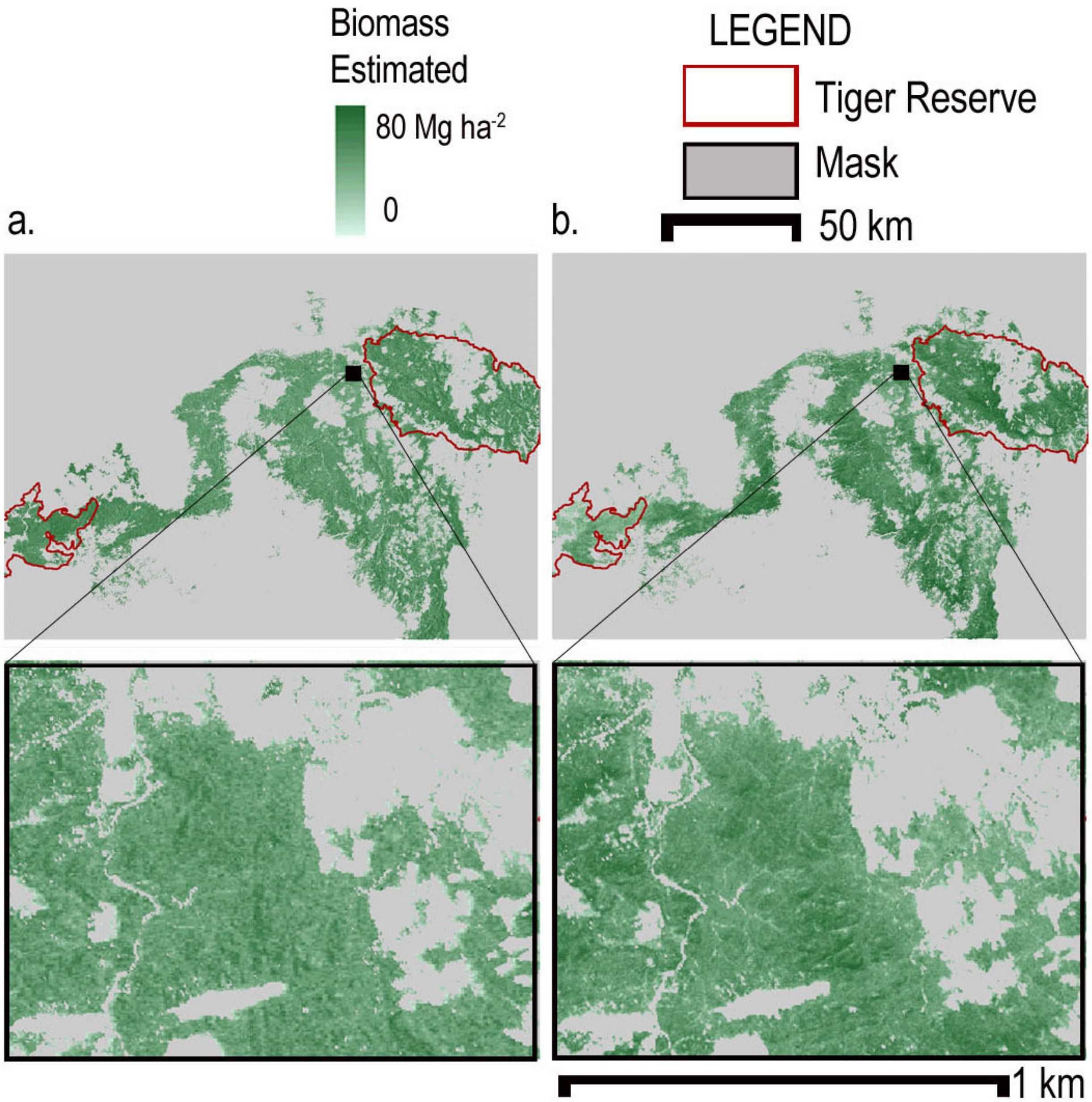


Figure 3b: Change in aboveground biomass (estimated using PALSAR-based HV back-scatter: 2010-2007)

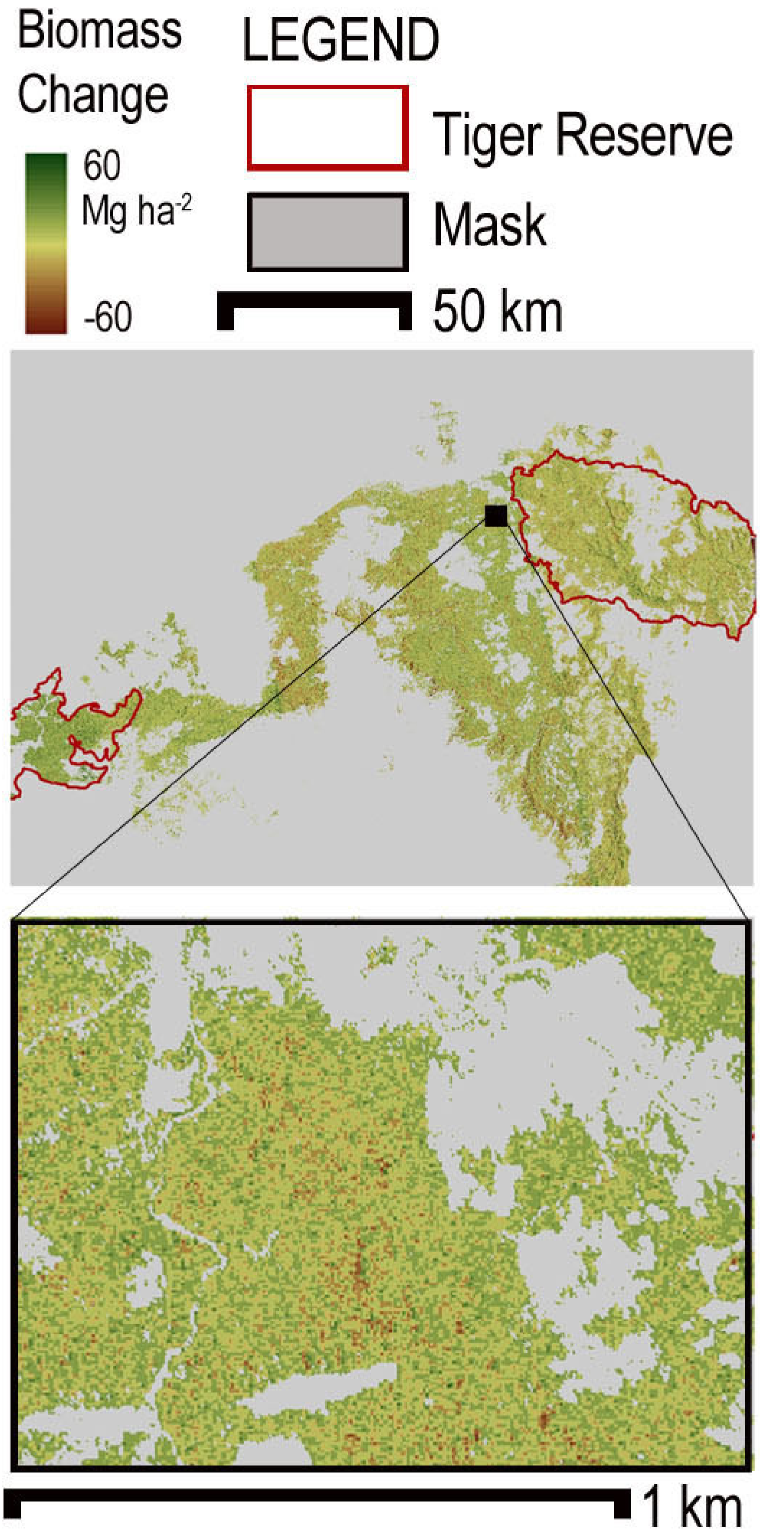
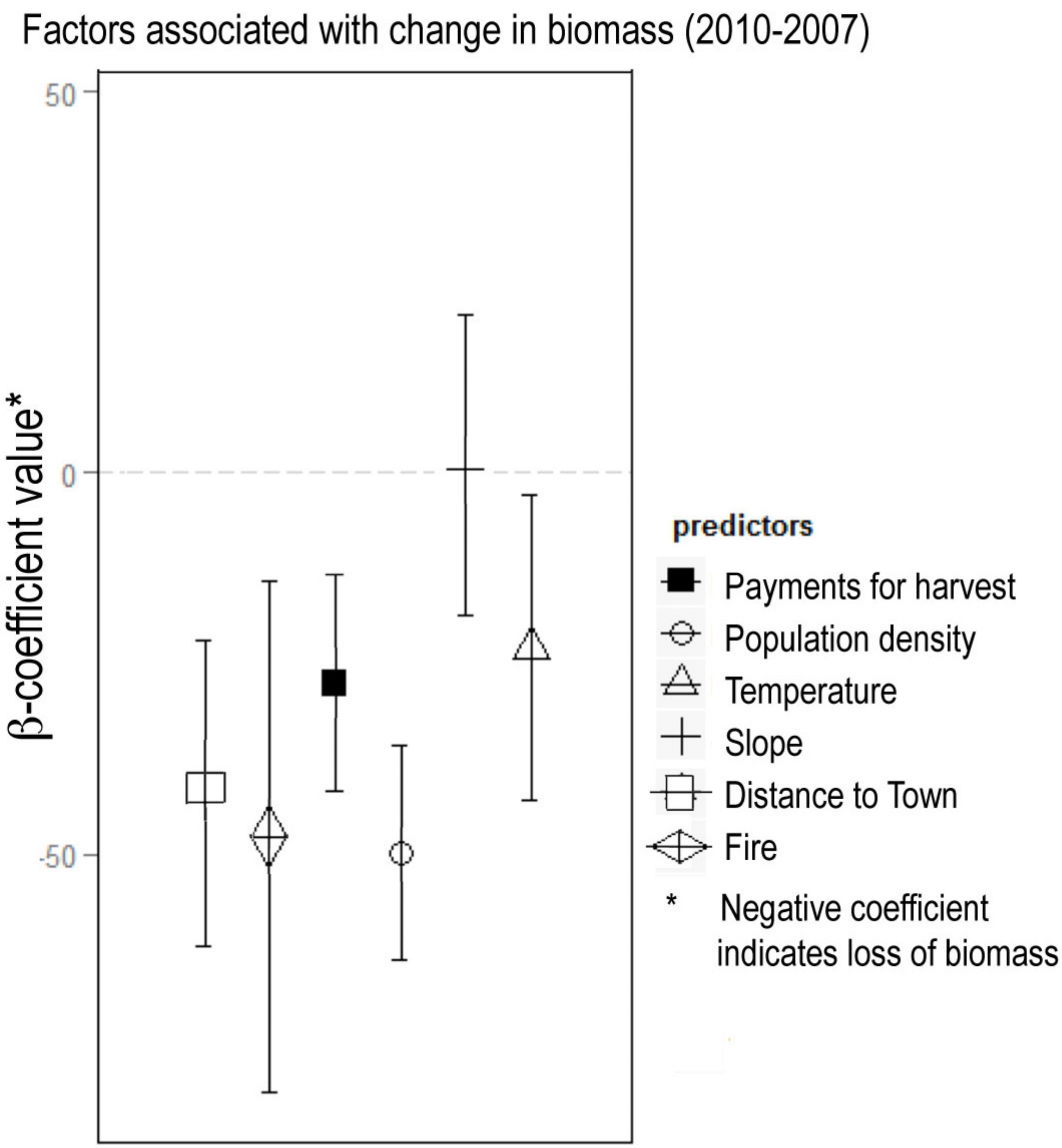


Figure 4: Predictors for change in aboveground biomass (2010-2007)



Supplementary Materials

MATERIALS AND METHODS

1. Calculating biomass

We calculated aboveground biomass in a sample plot using this equation:

Aboveground biomass in 20 x 20 m sample plot= Aboveground tree biomass in 20 x 20 m plot

(Sum of biomass of all trees in sample plot)

+ 400*(Average understory biomass in 1 x 1 m quadrat)

We used the following equation to convert DBH measurements into tree biomass based on the global model developed in Zianis, 2008:

Aboveground biomass of tree= $0.1424*(DBH)^{2.3679}$

For the understory, we measured understory biomass in two 1 x 1 meter quadrats in each sample plot. For average understory biomass in a plot, we averaged the values for each sample plot.

RESULTS

2. Final models for predictive ability

For FBD: $Log(Biomass+1)=12.6288+0.48032*\gamma^0_{HV}$

For FBS: $Log(Biomass+1)=7.67359+0.34103*\gamma^0_{HH}$

For Landsat spectral fractions: Log(Biomass+1)=2.6837+17.0284*PV-5.9721*BS

For EVI: Log(Biomass+1)=0.6143793+0.0015436*EVI

Table S1: Model Selection for Landsat, PALSAR-based FBD, PALSAR-based FBS, MODIS-based EVI, and combination of Landsat and FBD.

Sensor	SNo	Model	AIC

Landsat			
	SNo	Model	AIC
	1	log(Biomass+1)~PV + PV (St. Dev.)	292.095
	2	log(Biomass+1)~Bare + PV (St. Dev.)	317.0235
	3	**log(Biomass+1)~PV + Bare**	**289.347**
	4	log(Biomass+1)~PV	291.5978
	5	log(Biomass+1)~Bare	316.848
	6	log(Biomass+1)~PV (St. Dev.)	292.178
	7	log(Biomass+1)~log(PV)	292.67
PALSAR-based FBD			
	SNo	Model	AIC
	1	log(Biomass+1)~HV+HV(St. Dev.)	261
	2	log(Biomass+1)~HH+HV(St. Dev.)	276
	3	log(Biomass+1)~HH	274
	4	**log(Biomass+1)~HV**	**259**
	5	log(Biomass+1)~HV (St. Dev.)	338
	6	log(Biomass+1)~HH (St. Dev.)	333
	7	log(Biomass+1)~log(HV)	267
PALSAR-based FBS			
	SNo	Model	AIC
	1	log(Biomass+1)~HH + HH (St. Dev.)	330.99
	2	**log(Biomass+1)~HH**	**328.99**
	3	log(Biomass+1)~HH (St. Dev.)	342.86

	SNo	Model	AIC	
	4	log(Biomass+1)~log(HH)	330.48	
MODIS-based EVI				
	SNo	Model	AIC	
	1	log(Biomass+1)~EVI + EVI (St. Dev.)	317.99	
	2	**log(Biomass+1)~EVI**	**316.86**	
	3	log(Biomass+1)~EVI (St. Dev.)	343.57	
	4	log(Biomass+1)~log(EVI)	318.12	
Combination of FBD and Landsat using PCA: Step-wise deletion of variables based on least important variables (ascertained using R package: randomForest: Liaw & Wiener 2002). Adjusted R^2 and predictive ability obtained from randomForest bootstrapping.				
	SNo	Model	Adj R^2	Predictive Ability (Validation)
	1	Pca1 +pca2 +pca3 +pca4 +pca5 +pca6 +pca7 +pca8 +pca9 +pca10+pca11	0.1644	1.27%
	2	Pca1 +pca2 +pca3 +pca4 +pca5 +pca6 +pca7 +pca9 +pca10 +pca11	0.1709	4.95%
	3	Pca1 +pca2 +pca3 +pca4 +pca5 +pca6 +pca7 +pca9 +pca11	0.1703	7.3%
	4	Pca1 +pca2 +pca3 +pca5 +pca6 +pca7 +pca9 +pca11	0.1728	6.45%
	5	Pca1 +pca2 +pca3 +pca5 +pca6 +pca9 +pca11	0.1837	8.22%
	6	Pca1 +pca2 +pca3 +pca5 +pca6 +pca11	0.1896	7.13%

	7	Pca1 +pca2 +pca3 +pca5 +pca6	0.1986	9.54%
	8	Pca1 +pca2 +pca3 +pca6	0.2087	12.47%

Table S2: Correlation matrix of predictors for Landscape Analysis

	Dist to Roads	Fire	Pop Density	Livestock	Elevation	Temperature	Precipitation	Dist to Town	Slope	Proportion literate	Forest Cover	Edge	Years to Fire
Fire Radiative Power (2007-2010)	0.19												
Human population density	0.12	0.06											
Livestock density	0.11	0.08	**0.48**										
Elevation	-0.18	0.05	-0.08	0.32									
Temperature	-0.13	-0.08	0.08	0.03	0.19								
Precipitation	-0.28	-0.02	0.07	-0.11	**-0.48**	0.02							
Distance to town	0.33	0.05	-0.28	-0.04	**-0.41**	-0.04	0.17						
Slope	-0.01	-0.05	-0.12	-0.02	0.003	0.06	0.01	0.16					
Proportion literate	**0.45**	0.09	0.21	0.12	-0.35	-0.18	0.24	0.38	-0.05				
Forest Cover	**0.51**	0.19	-0.03	-0.04	-0.27	**-0.56**	0.12	0.21	-0.09	0.31			
Edge	**0.43**	0.31	-0.12	0.01	0.11	-0.43	-0.15	0.14	0.29	-0.03	0.52		
Years to Fire	0.14	0.39	0.08		0.03	-0.05		0.02	-0.06	0.02	0.14		
Number of payments	**0.56**	-0.05	-0.11	0.26	-0.31	-0.14	0.16	0.37	-0.02	**0.40**	**0.49**	0.24	0.04

Table S3: Selecting best models using AIC method (Burnham and Anderson, 2002)

SNo	Model	AIC (predicting change in biomass from 2007 to 2010 using HV)
1	Number of payments + Elevation + Population Density + Slope + Temperature + Mean Fire Radiative Power	22440
2	**Number of payments + Distance to Town + Population Density + Slope + Temperature + Mean Fire Radiative Power**	**22415**
3	Number of payments + Proportion Literate + Population Density + Slope + Temperature + Mean Fire Radiative Power	22428
4	Elevation + Distance to Roads+Population Density + Slope + Temperature	22457
5	% Literacy + Distance to Roads+Population Density + Slope + Temperature	22457
6	Forest Cover + Elevation + Population Density + Slope + Temperature + Mean Fire Radiative Power	22405
7	Total cash+ Elevation + Population Density + Slope + Temperature + Mean Fire Radiative Power	22430
8	Forest Cover + Elevation + Population Density + Slope + Mean Fire Radiative Power	22442
9	Forest Cover + Distance to Town + Population Density + Slope + Mean Fire Radiative Power	22418
10	Elevation + Population Density + Slope + Temperature + Mean Fire Radiative Power	22461
11	Distance to Town + Population Density + Slope + Temperature + Mean Fire Radiative Power	22435
12	Number of payments + Population Density + Slope + Temperature+ Mean Fire Radiative Power	22436
13	Number of payments + Distance to Town + Slope + Temperature + Mean Fire Radiative Power	22467
14	Number of payments + Distance to Town + Population Density + Temperature + Mean Fire Radiative Power	22419
15	Number of payments + Distance to Town + Population Density + Slope + Temperature +	22428
16	Number of payments + Distance to Town + Population Density + Slope + Mean Fire Radiative Power	22424

Order of importance of variables is (in decreasing rank): Population density, Distance to Town, Number of payments for harvest, Fire Radiative Power, Temperature, Slope.

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CHAPTER 4

The Impact of Institutions on Community-Managed Forests of Central India

Abstract

Many resources such as water and forests are managed cooperatively, yet there is little consensus on the effect of community management on these resources. This study examines the roles of institutions, including economic payment, community representation and local participation in preventing degradation of community-managed forests. We used remote sensing to examine change in canopy cover in 96 forest compartments in reserve forests managed by 50 villages in Central India, half of which had received economic payments for forest conservation. We quantified institutional variables by interviewing representatives of forest management committees in these villages, and used generalized linear models to assess factors associated with changes in canopy cover. We find that economic payments are associated with an increase in awareness and participation in forest governance but are not significantly associated with differences in actions taken against illegal users. We also find that action taken to exclude outsiders is associated with positive change in canopy cover. Positive change is also associated with committees that do not hold meetings, which in turn is associated with higher incumbency for Chairpersons. Positive change in canopy cover in these villages is presumably because individuals accrete institutional capital and become better at excluding illegal users from depleting the resource. Results suggest that economic payments are not sufficient motivation to take action against outsiders, and that incentives and mechanisms are needed to enable villagers to exclude outsiders from degrading forest resources.

KEYWORDS: Common property resources, elite capture, forest governance, Kanha-Pench Landscape, remote sensing

1. INTRODUCTION

Hardin's argument that humans would necessarily degrade open-access resources without secure tenure (Hardin and Baden, 1977) led to transfer of land with unclear tenure to private or state management. This idea was refuted by studies on the commons which found that management by local communities often conserves resources (Feeny et al., 1990; Ostrom and Nagendra, 2006), which subsequently led to widespread adoption of practices that delegate resource management to local communities (Smith and Wishnie, 2000; Bowler et al., 2012). Yet, as resource is transferred from state to communities, little is known about the effect of this transition on the resource (UNEP, 2010; Bowler et al., 2012). Although there is some evidence of higher forest cover and quality with community forest management, few studies account for the original forest cover or baseline data (Bowler et al., 2012) or other biophysical, socio-economic and institutional variables that may influence the effectiveness of management (Bowler, 2012). These are important to account for as forest type, climate, population change, and market access correlate with resource degradation (Agrawal and Chhatre, 2006; Nagendra, 2007; Persha et al., 2011), and can confound studies testing the importance of other factors (Agrawal and Chhatre, 2006). Further, remote sensing has the potential to evaluate long-term impact on forests. To date, few studies have used remote sensing techniques to examine the impact of community management on long-term trajectory of forests (Bowler, 2012). Success of projects has often been measured with respect to uptake of community management rather than the resulting outcomes (Bowler, 2012). In addition, the role of institutions, such as economic incentives, participation and community representation, have not generally been assessed based on empirical measures of resource condition (Agrawal, 2001, CIFOR, 2011). Assessing the effectiveness of community management schemes with empirical data in particular settings, specifically studies with large sample sizes (Agrawal, 2001), can inform the development of this approach, particularly as funding for such schemes increases (Bowler, 2012).

The establishment of the Joint Forest Management (JFM) initiative in Madhya Pradesh provides a unique opportunity to conduct such a study. Forests in India were reportedly managed sustainably by local communities until disrupted by the scientific forestry of British colonialism (Gadgil and Guha, 1993). Other research claims that pre-colonial forest management was not this homogeneous, and differed between ruling dynasties and communities (Guha, 1999; Sivaramakrishnan, 1999; Rangarajan, 1996). Depending on the control extended by the ruler, management measures extended from outlawing timber-felling, to delegating management to local rulers (Guha, 1999; Skaria, 1998), to local management practices such as shifting cultivation (Prasad, 2003). To redress injustice and inequity to forest dwellers whose land was transferred to the state under colonialism, the Indian state began decentralizing forest management in the 1990s. In this scheme, every village elects a forest protection committee which is then responsible for managing the forest assigned to it.

The study area selected (forests located in Mandla, Balaghat and Seoni districts in Madhya Pradesh: details in methods) is ideal for examining this question for several reasons. First, the area affords a large potential sample size as forests were transferred to over one thousand forest protection committees. Further, the forests were transferred over a period for which satellite imagery is available. This allows the study to quantify the change in canopy cover for forests assigned to every committee. Third, the study region lies between two Tiger Reserves.

Therefore, the degree of central management and control in these committees varies as the Forest Department is more involved in setting committee agendas close to the reserves. Hence, there is sufficient variation in the study region to account for influencing factors and test specific hypotheses related with institutions.

Community based conservation programs have introduced economic incentives and direct payments for ecosystem services to motivate local communities to use resources sustainably, but these have had mixed results (Spiteri and Nepal, 2006; Cranford and Mourato, 2011). This study tests the role of direct payments in engendering local participation through a natural experiment where only half the forest protection committees have received payments (details in methods).

The literature on community representativeness, homogeneity and participation is also ambiguous as some studies find that user-groups that are small, or well represented in a smaller decision making body are associated with improved resource management (Smith and Wishnie, 2000; CIFOR, 2011), but there is less information on actual impact on resources. Most criticisms of these programs are centered on non-representative governance in the form of elite capture of resources (Barbier, 2012). As participation in resource management is limited by the value local communities place on conservation, and their awareness and consent to community based conservation (Spiteri and Nepal, 2006; CIFOR, 2011), this study further tests the impact of local participation, community homogeneity and representation on change in forest canopy, while controlling for variables such as value for environment, awareness of payment linked forest conservation scheme and consent to its rules. We aim to understand the impacts of (a) economic payments, (b) participation and (c) community representativeness on changes in forest canopy in the time period in which forests were transferred to local communities.

2. METHODS

2.1 Study Region

The study is located in the forests between Kanha and Pench Tiger Reserves and includes three forest divisions (East Mandla, North Balaghat and South Seoni) in three districts (Mandla, Balaghat and Seoni) in Madhya Pradesh (Figure 1). This region has high forest cover (30%) relative to ~24% for India as a whole (State of Forest Report, 2009). The local population is mostly rural and not employed in an organized sector (Census of India, 2001 and 2011) and they are dependent on the natural forests in the area for non-timber forest products, fuelwood, and other livelihood needs. There are 1125 villages in the study region, and in some localities, forest products contribute up to 70% of house hold income (Saigal, 2008).

Community forest management was first introduced in the area in 1996, under a scheme known as the Gram Van Samiti (GVS), where compartments that the Forest Department classified as degraded forests were transferred to local communities. Since then, starting in 2002, other forest compartments have been transferred to local communities under a scheme known as the Van Suraksha Samiti (VSS). The committees elected to implement this scheme, together known as Joint Forest Management (JFM) committees, are ideally composed of 10 to 12 members, and include an elected chairperson and a deputy chairperson. Elections for these posts occur every 5 years, at which time the village also selects other members of the forest protection committee. In selecting a committee, village members usually select a few members from each hamlet within a village.

The committee then works with the local forest department to devise plans for managing the forest. Ideally, meetings are held monthly, where committees discuss proposals to submit to the Forest Department, discuss remuneration issues, or the Forest Department uses these meetings to impart environmental awareness. The funds for committee-funded activities are disbursed into a joint account operated by the local Forest Guard and the Elected Chairperson of the committee, and committee members then discuss proposals for spending the money. Funds are only spent on community goods: usually ponds, water catchments, roads or a local building, and some committees use these funds to hire temporary fire watchers. The committee meetings are also ideally the venue for hiring people for committee-funded work.

At the time of the study, only half the committees had received economic payments for protecting the forest, and this was dependent on whether the forest compartment assigned to the committee had reached the end of a ten-year coup cycle after 2005. The remaining committees were yet to receive payments in 2010 and awareness of payment scheme varied in these committees (Section 4.1). This created a random distribution of committees that received payments since coup cycles are staggered across the landscape.

2.2 Sampling

Because nearly every forest compartment has been transferred to a village committee in the landscape, we did not have any localized controls where forests had not been transferred (except protected areas which may be located far away). Therefore, we compared change in forest canopy between compartments and used 2002 to 2010 as our study period because forest compartments were transferred starting from 2002 (see section 2.3 for description of forest canopy data). To understand the impact of institutional variables, we quantified institutional parameters (Table 1) in fifty randomly-selected villages in the landscape. To select villages that represented the range of biophysical, demographic and socio-economic variables, we used cluster analysis to cluster all 1125 villages by biophysical (temperature, precipitation: details below), landscape (distance to nearest town by road, distance between village and forest: details below), and demographic (human and livestock population: details below) variables. We then randomly selected 10 villages in each cluster of identical villages, leading to a total of 50 villages in 5 clusters.

We then interviewed five members of forest protection committees in each of these fifty villages. In requesting interviews, we attempted to speak with the elected chairperson, people in minor hamlets and at least one female member. We conducted structured and informal interviews and spoke to informants separately about the history and functioning of JFM in their village.

2.3 Data

2.3.1 Change in Canopy Cover

We calculated photosynthetic vegetation (PV) fraction using Landsat imagery for January 2002 and January 2010 with a mixture modeling approach (Agarwala, in prep). We also collected data on location, extent and other details about forest compartments (Madhya Pradesh Forest Department, 2011), where a compartment is a well-defined forest unit ranging in size from 0.1 to 5.3 km^2 (mean 2.3 ±1.06 km^2) with its own management plan (Madhya Pradesh Forest Department, 2011). The number of compartments transferred to a village could range from 1 to 5, although most villages received at least one compartment. All non-forest areas were masked out based on supervised forest classification using ground truthing (Agarwala, in prep), and we calculated average PV Fraction for all compartments. PV fraction represents canopy at an accuracy of 68% (Agarwala, in prep). We then calculated canopy change by subtracting PV Fraction in 2002 from PV Fraction in 2010. Therefore, negative values indicate that canopy in

2010 was lower than the canopy in 2002, while positive values indicate that canopy is higher than it was in 2002.

2.3.2 Biophysical, landscape variables and demographic variables:

We collected information on biophysical variables (temperature, precipitation, fire radiative power (FRP), elevation and slope: Table 1), as differences in forest canopy could be a result of variation in these variables. Since the study period was between 2002 and 2010, we calculated mean temperature, precipitation, and FRP from 2002 and 2010, number of years between 2002 to 2010 that MODIS detected fire, and number of years prior to 2010 that the most recent fire was detected by MODIS for each pixel. We then used bilinear resampling to assign values from coarser resolution precipitation (originally 1 km resolution), temperature and fire (originally 250 meter resolution) datasets to finer resolution pixels that fall within the coarser resolution grid to make them comparable with 30-meter resolution Landsat and ASTER-DEM. As the study examined change in canopy cover at the compartment-level, we calculated mean and standard deviation of these parameters for every compartment.

Besides biophysical variables, differences in forest canopy through time could also be influenced by forest edge, available forest area, and distance to roads and major towns for a forest compartment (detailed metrics in Table 1). Metrics for edge and available forest area used a Landsat-based supervised forest classification (Agarwala, in prep), distance to roads used open-street map data (OpenStreetMap, 2013), and distance to town used a census-based dataset (Wildlife Institute of India, 2011). For edge, we calculated average distance to non-forest in a forest compartment. To measure available of forest, we calculated mean forest cover within a 1.5 kilometer radius from a 30-m forest pixel (based on average forest use distance from a village, Agarwala et al., in prep), and then estimated its average value for each forest compartment. We also calculated area of compartment. For estimating distance to road, we calculated distance to highways for each forest pixel, and averaged distance to road for each compartment. We used estimates of distance to nearest town by road for each village from a census-based dataset (Wildlife Institute of India, 2011), which lists distance to nearest town by road for all villages, to determine proximity to markets and major economic centers. This may be a more accurate measure of distance as it reliably estimates the amount of time it may take to reach town from a given village.

To account for demographics (Agrawal and Chhatre, 2006; Nagendra, 2007), we collected information on population and livestock density. For human populations, we used village-level total population from the 2001 census-based dataset (Wildlife Institute of India, 2011; village level census for 2011 was not yet available). For livestock populations, we used village-level cattle and buffalo populations from the 2005 India Livestock Census (Department of Animal Husbandry, 2011), and estimated livestock abundance in each village as the sum of cattle and buffalo populations. Although we could also use populations of smaller ruminants such as goats, these were very infrequently present or present at very low densities, and were therefore excluded.

2.3.3 Socio-economic variables

To represent the socio-economic constitution of each village, we used the 2001 census-based dataset (Wildlife Institute of India, 2011) to calculate a number of village-level parameters (detailed metrics in Table 1). We calculated proportion of non-formal employment in each village, as these people may be more dependent on forests to supplement their income (importance of dependence is explained in Gibson et al., 2005). For this, we used the census category "Non-Working" which captures those without formal employment, which might be a good measure of population dependent on seasonal or informal employment. We calculated both proportion of non-formal employment and total population in non-formal employment as some villages may have the same number of people employed in the non-formal sector, yet their proportions may vary as total village population increases. We also calculated proportion of literate population. Finally, we calculated % Scheduled Tribes (ST), % Scheduled Caste (SC) and % Other from the census as caste and tribe significantly impact access, income-generation (Borooah, 2005), participation in forest governance (Chhetri et al., 2013), and form the basis of social heterogeneity (Pandit and Bevilacqua, 2011)

2.3.4 Committee Constitution

To account for the constitution of the forest protection committee, we calculated average number of years that each respondent had been a member of the committee, their average age, their average education level, and proportion of women on the committee. We quantified incumbency by asking respondents whether they had also represented their village in the previous committee. We also calculated the proportion of committee members that had not been selected by the village, but placed on the committee by other powerful agents.

2.3.5 Measuring Forest Value for Users

We used two questions to quantify value of forests and environment to local people (Spiteri and Nepal, 2006; CIFOR, 2011): the first asked informants about their expectations and hopes for the future. If the informant voluntarily included concern for forests and environment in speaking about the future, we coded the response as 1. For a village committee, we averaged response values for all 5 respondents. The second question asked informants what they considered when asked about the use of the forest. Their responses were noted and could be categorized into three categories: Forests are important for the environment, forests are useful for services such as forest produce and income, and forests are useless. We used proportion of respondents that gave each response in a committee as predictors.

2.3.6 Measuring Awareness and Consent

Because participation and ultimately, impact on forests, are contingent on awareness of the Joint Forest Management (JFM) scheme, we also quantified awareness of this scheme and its mechanisms, as well as thoughts on the rules of the scheme. We used several questions for this: we asked respondents what they understood about the Joint Forest Management Scheme and their answers were coded to quantify their extent of knowledge. A separate question asked respondents if they knew the location of the forest assigned to them.

We also asked respondents about their rights on the forest. Some people were very specific and discussed their rights in detail. Others either claimed they had no rights at all, or every right possible, or that they had the right to purchase wood from the forest department auction. We quantified the proportion of people in each committee that provided each of these responses. We also asked respondents whether people of their village and other villages had the right to use this forest and quantified proportion of people in each committee that said that people from their village had every right to use the forest, and people from other villages had every right to use the forest.

2.3.7 Measuring Participation

Finally, we asked several questions to quantify actual participation in forest protection committee activities. One set of questions asked whether the respondents had contested the election for Chairperson of the Forest Protection Committee in the last election, and whether they intended to contest in the next elections. We used their answers to quantify the proportion of people who had stood for elections, and the proportion that intended to stand next time. Their reasons for not standing were also noted. The next set of questions asked who looks after the forest, and we obtained only four answers: either everyone looks after the forest, or no one looks after the forest, or the government appointed watchman looks after the forest, or that temporary fire watchers hired by the committee look after the forest. To categorize a village, we used the majority answer. We also asked how often a meeting takes place, and obtained a range of answers that could be categorized into 4 categories: never, once a month, every few months, or at least once a year. To categorize a village, the majority answer was used. We also asked who called the meeting and what was discussed at these meetings. Most meetings were called either by the Forest Guard or the Committee Chairperson. Therefore, we only quantified exceptions to these answers (proportion of respondents that said no one called the meeting, or that some other person called the meeting). We also coded answers based on what was discussed at committee meetings into 4 categories: meeting had no discussions, the Forest Department told the committee about the importance of environment and forests at the meeting, members and Forest Department representatives discussed work-related issues such as payments, appointments, and other business matters at the meeting, or they used meetings to discuss possibilities for future projects and wrote proposals for work they should do in the future. Most of these answers did not vary across villages. The exceptions were that no discussion took place, or that they met to discuss proposals, and we quantified the proportion of these answers in a village. Finally, we asked respondents what they did when someone from another village used the forest assigned to them, and could categorize answers into four classes: either they stopped outsiders and sometimes took them to the Beat Office and fined them, or they explained to outsiders that they could not use this forest, or they did nothing, or they claimed that no action was possible. We quantified the proportion of each of these answers and noted their reasons for not stopping outsiders.

2.3.8 Other External Factors

We also noted any other issues that would be brought up in the interviews, and could code the presence of certain external factors in a village. For instance, we coded outside traders as 1 in villages where respondents spoke voluntarily (without prompting) about outside traders in timber. We also coded as present those villages where they had received economic payments and the year they received economic payments.

2.4 Data Analysis

To analyze the data, we tested impact of economic payments on participation, and impact of participation and representation on changes in canopy cover. We could not test impact of economic payments on change in canopy cover, as economic payments necessarily follow harvests.

2.4.1. Role of economic payments on participation

We tested whether receiving economic payments are associated with increased awareness, participation and action taken to exclude outsiders from using forest resources in a community's designated forest, as villages that have not yet received payments expect to do so in the future. We used t-tests to determine whether there were significant differences in answers between individuals in villages that had received economic payments and those in villages that had not. We tested this on individual responses for interview questions listed in Table 1, Section 4-7, and used proportional t-tests for categorical variables and students' t-test for continuous variables. Where differences were significant, we also conducted a generalized linear model (GLM) that tested whether differences were associated with age, gender, education or number of years on the committee (Burnham and Anderson, 2002).

2.4.2. Impact of institutional variables on changes in forest canopy

We tested impact of institutional variables on change in canopy cover (2010-2002), while controlling for confounding factors. For testing the impact of participation and representation, we used all the variables listed in Table 1 as predictors (all continuous variables standardized to the mean), and noted those variables that had correlations exceeding 0.4 (Supporting information, S1). Twenty-five variables were eliminated for collinearity, leaving us with eighteen variables. We then used generalized linear model (GLM) and least Akaike Information Criterion (AIC) score to determine the best model from a series of comparative models (none of which had two predictors whose correlation exceeded 0.4) (Burnham and Anderson, 2002). We also used results from the generalized linear model (GLM) to test whether there was spatial autocorrelation in the results (S2). To control for this, we constructed a distance matrix between centroids of the compartments using R package spdep and included it in the generalized linear models.

3. RESULTS

3.1. Role of receiving economic payments on participation

Overall knowledge of JFM (Figure 2, t-test, p-value<0.001) and understanding of the scheme for economic payments (Figure 2, t-test, p-value<0.001) was significantly higher in committees that had received economic payments. However, these committees were no better informed on the location and boundaries of the forest for which they were responsible (Figure 2, t-test, p-value=0.33). This suggests that while awareness of the scheme had increased, it is possible that this awareness did not include sufficient detail for people to perform their duties effectively. People in villages that had received economic payments were more aware that funding for their committee was generated from the forests assigned to and protected by them (Figure 3, proportional t-test, p-value<0.001), but there was still a lack of clarity. Equal proportions of committee members in both types of villages had no information about the source of these funds (Figure 3, proportional t-test, p-value=0.14).

The number of years served on the committee (Figure 4, t-test, p-value<0.0001) and incumbency (Figure 4, t-test, p-value=0.005) were significantly higher in committees that had received economic payments. Committee members may have recognized some benefit of participating in this scheme as we can expect people to be reluctant to spend time on a committee that they consider a waste of time.

Yet, there are fewer differences in actual participation and action taken on the ground. There was no overall increase in meeting frequency in committees that had received economic payments (t-test, p-value=0.55). These meetings were usually called by the Chairperson of the committee and the local Forest Department, and there were no significant difference in the frequency of meetings called by anyone other than the forest department (proportional t-test, p-value=0.99). While most committees discussed work and received information on the importance of environment and forests, there was no significant difference in discussion of proposals (proportional t-test, p-value=0.66), or in how to spend the money (proportional t-test, p-value=0.51) between the villages that had and had not received economic payments.

There were also no differences in action taken when outsiders used the forest assigned to a committee. People were equally likely to report that they stopped outsiders (t-test, p-value= 0.35), explained to outsiders that they could not use this forest (t-test, p-value=0.67) and that they took no action (t-test, p-value=0.79) (S3). There were also no differences in the proportion of people who claimed that no action was possible or necessary (t-test, p-value=0.79). This is despite the fact that a significantly higher proportion of people in villages that were yet to receive economic payments thought that people from other villages could unconditionally use their forest (proportion t-test, p-value=0.02). People had many reasons for not stopping outsiders: people reported that people come secretly at night when it was not possible to see them (40%, n=45), that people come anyway and are not inclined to listen (18%, n=45), and that it is not an issue because forests belong to all local customary users (16%, n=45). Other reasons reported were that they were reluctant to make enemies in the neighborhood (4%), and that outsiders were aggressive (2%). This may indicate that despite higher awareness, committees do not take action to protect their forest resources. In all of these analyses, economic payments received was a significant predictor of outcome despite other variables such as age, gender, education and number of years in the committee also influencing outcome (Figure 5). Also, these differences cannot be attributed to differences in attitude upon receiving payments as there were no significant differences in concern about forest issues in villages that had received economic payments (proportional t-test, p-value=0.58), and equal proportions of committee members reported that forests were useless (proportional t-test, p-value=0.83), and that forests were good for the environment (proportional t-test, p-value=0.39).

3.2 Institutional Variables influencing canopy change

Variables associated with canopy change included institutional (whether payments were received, whether action was taken to stop outsiders, meeting frequency, whether people considered forest useful for the environment, and the gender ratio of committee) and socio-economic variables (literacy rate), controlling for landscape variables (distance matrix, distance to roads) (Figure 6).

Two measures of participation were significantly associated with changes in canopy cover: Committees where members reported that they stopped outsiders from using their forest were associated with positive change in forest canopy; and meeting frequency was associated with negative change in canopy. As expected, positive change in canopy is associated with action taken, however payments do not alter action taken (Section 3.1). Surprisingly, committees where members reported that they never held any meetings were associated with increasing forest canopy. This variable is correlated with committees where reportedly neither the Forest Department nor the Committee Chairperson calls the meeting, and where committee members voluntarily mentioned the presence of outside traders (S1). These committees also had higher incumbency for Committee Chairperson but average incumbency for other members (for a subset of villages for which we had data: Figure 7).

Other variables can be considered as controls in the model: gender ratio of the committee is correlated with gender ratio of the village (S1), and is thus an existing socio-economic parameter of the village, as is the literacy rate of a village. Distance matrix is correlated with distance to towns, which in turn is correlated with population densities, thus accounting for landscape and demographic variables. Distance to roads can also be considered a control, as canopy cover is associated with negative change with distance from roads. Further, differences in canopy change with institutional variables is not a result of values or awareness, as committees where members reported that the forest was useful for the environment was significant and is thus accounted for in the best model. As we could not test the impact of economic payments on change in canopy directly because economic payments necessarily follow harvests, economic payments can also be considered a control. Further, economic payments were correlated with available forest area, where available forest area was correlated with many biophysical variables such as slope, edge and fire radiative power (FRP) (S1). Therefore, positive change in forest canopy from 2002 to 2010 may be an artifact of correlations with biophysical variables, or result of post-harvest forest recovery, and therefore cannot be used to say anything conclusive about impact of payments. Therefore, at best we can say that economic payments are associated with increasing awareness, but no reported action on ground.

4. DISCUSSION

4.1 Impact of economic payments on participation

Many studies have examined the impact of payments on participation (Bowler et al., 2012) and find that it generally increases with payments (Barbier, 2012). This study finds that economic payments is associated with an increase in awareness, an increase in participation in committees as villagers probably realize the potential benefits of schemes for payments for forest protection, but there is little impact on self-reported participation in protection activities.

Previous studies suggest that non-participation can be a result of many reasons. One is a lack of a well-defined boundary of the resource over which a community is responsible (Agrawal, 2001; Gibson et al. 2005). This study suggests the same, as despite economic payments, there was no increase in awareness of the forest boundaries that the community was supposed to manage. Lack of consensus over rights and responsibilities is also known to reduce participation in community forest governance (Persha et al., 2011). This study demonstrates the same as many respondents felt that all neighboring villages should be able to use their forest as customary users of the forest, citing reasons such as plentiful resources in the forests, the forest's proximity to other villages, and that some resources were only available in their forest. Of the respondents, 16% specifically said that they do not stop users from other villages, as all customary forests users can use the resource. Additionally, 18% said that the outsiders do not listen because they do not agree with these forest boundaries. Further, 40% said that users from other villages do not come, or they come secretly, or at night. These respondents were in villages where other members claimed that outsiders did, in fact, come. Fieldwork in the area suggests it is not possible to visit the forest at night, as it is very dangerous due to wildlife and other reasons. Therefore, in suggesting that people from other villages do not come or only come secretly at night, the respondents may have been reluctant to tell me (an outsider) that they do nothing, as they felt they could not justify their actions. An additional 4% of the respondents claim that it was not worthwhile to stop outsiders as they did not want to make enemies in the neighborhood, and although few people explicitly said this, it is possible that other respondents felt the same. Therefore, these responses may be aggregated as support for reluctance to stop outsiders. Other studies have identified lack of equity, lack of long-term benefits and other utilitarian concerns for the failure of economic payments (Barbier, 2012), but this study suggests that reluctance to stop outsiders may also be an important class of interactions to examine as public support for payments for ecosystem services increases (Barbier, 2012).

4.2 Action taken to exclude outsiders

However, action taken to stop outsiders from using the forest is associated with positive change in canopy cover. Previous studies have found that enforcement is important in forest governance (Gibson et al., 2005; Chhatre, 2008), and this study finds the same. However, enforcement is not linked with payments (Section 3.1), and despite increased understanding and awareness, people may be reluctant to enforce the rules of forest governance (correlation: Understand payment scheme, action taken to stop outsiders, r=0.16, S1). Besides mutual monitoring, enforcement is also possible through hired temporary watchers who are paid for their work. However, the impact of hiring temporary watchers could not be tested explicitly, as it was correlated with distance matrix (r=0.41, and distance matrix was the most important predictor of change, S4), although there is a positive association between hiring temporary watchers and positive change in forest canopy. This suggests that action taken by committee members is associated with positive changes in forest canopy, but further studies need to investigate methods to motivate committee members to take action.

4.3 Meeting frequency

That villages that never have any committee meetings are associated with positive changes in forest canopy is counter-intuitive. Villages that never have any meetings are those where no one (neither the Forest Department nor the Committee Chairperson) calls a committee meeting (r=0.54). These are also villages where interviewees voluntarily mentioned the existence of outside traders (r=0.40). Higher incumbency of Committee Chairperson coupled with average incumbency of other members suggest that these villages were not very representative as the chairperson tends to stay the same through successive committees while other committee members are changed. These new committee members are then not included in committee decisions (as no one calls the meeting).

The importance of individuals with substantial leadership and other assets has been consistently shown to influence outcomes (Ostrom, 1991; Agrawal, 2001). Individuals who are incumbents on the committee may also represent a form of elite capture of resources. Not only have these committee chairpersons accumulated power by spending a longer time heading this institution, which gives them greater ability to exclude outsiders, but there are often few rivals during elections as local people have customarily voted in these individuals or their family members. Elite capture of resources in developing countries has been well documented (Barbier 2012), especially in areas with high income inequality (Platteau et al., 2002; Bardhan, 2000) due to de-legitimization of customary authorities (Barbier 2012). Yet, where local leaders are considered legitimate and representative, forests are able to support successful projects (Skutch et al., 2008). A long-term study of multiple CPR institutions finds that there is an increased tendency of grab (privatize) CPR land rather than manage and use it as a community asset (Jodha, 2008), and increase in resource is linked with changes in local faction politics where local actors seek to protect CPR from rivals rather than attempting to grab CPR (Jodha, 2008). Elections may then serve as a way of eliminating rivals within the village and establish legitimacy for the land grab. While several studies have documented the positive impact on resources upon elite capture (Skutch et al., 2008), this study provides quantitative evidence of elite capture of resources being beneficial for the forests even if not for the local people, as these individuals were effectively able to exclude other users as they did not face the stress of creating new hostilities due to their legacy of excluding other users. Further, many studies do not emphasize the importance of accretion of institutional capital (Ostrom, 1991). In committees with higher turnover of chairpersons, committee chairpersons may not have sufficient time to learn or to accumulate institutional capital since learning is an incremental, transformative process (Ostrom, 1991). Therefore, importance of individuals capable of leading committees may demonstrate the potential of institutional learning as well as legacy of management and excluding behavior.

4.4. Literacy Rates

Villages with higher literacy rates are also associated with increased canopy. Other studies have found that less educated populations are less likely to participate in governance (Chen et al., 2013) and regulations (Nielson and Meilby, 2013), but it is also likely that alternative livelihoods made possible with better education may reduce the forest dependence of local populations.

4.5. Institutional Variables Associated with Canopy Change

Where action is taken against outsiders, it is associated with positive impact on the forest. Yet, payments are not associated with action taken. In long-term relationships, such as those present in a community, people are motivated by friendship, love, status and a desire to impress others to look out for each other (de Graaf, 2008). Peers find whistle-blowers highly unlikable (Trevino, 1992) and sanctions against nonconformity include internal costs such as guilt, anxiety, and lower self-worth (Ostrom, 1991). In communities that have coexisted for a long time, enforcement and exclusion may become more difficult to develop.

Alternative mechanisms are needed to motivate communities to take action. Some possibilities include use of remote sensing as a low-cost mechanism of monitoring forest change, and committee activities. Use of remote sensing to monitor forest change may make committees more accountable for changes in the forests assigned to them, which may promote the development of mechanisms for preventing excessive use. Since higher literacy rates are also associated with positive change in forests, increasing literacy rates may be another way forward, either because people are less dependent on forests as they find alternative livelihoods or because they have greater agency in forest governance, or because they are educated to be careful with forest use.

5. CONCLUSIONS

Economic payments were associated with significant increases in awareness of Joint Forest Management, its attendant responsibilities to protect the forest, but not with action taken to protect the forest. Yet, action taken to exclude outsiders is associated with positive change in forest canopy. Therefore payments alone are not sufficient for communities to participate but other mechanisms need to be investigated.

Positive change in canopy is also associated with less representative forest committees, that may aid forest conservation as individuals accrete institutional capital and become better at excluding others. While the common property literature suggests that the way to overcome the problem of individuals valuing short-term individual gains over long-term community gains is to through greater representation and greater say in the functioning of forest governance, less representative governance and elite capture of resources are often the norm but are not always detrimental to forests.

Overall, this study assesses the role of economic incentives, participation and community homogeneity in promoting resource conservation. As support for community resource management continues to increase (Bowler et al., 2012), this study highlights the importance of factors other than payments in motivating community action.

ACKNOWLEDGEMENTS

We are grateful to assistance and data from the Wildlife Institute of India (WII), Madhya Pradesh Forest Department, PCCF (MP), CF (Jabalpur-Central Circle), DFO (Seoni), DFO (Balaghat) and Department of Animal Husbandry. NSF Grant Number 1029219 supported this research. This project was approved under IRB Protocol Number IRB-AAAI1677. We also thank K. Sivaramakrishnan, Pinki Mondal, Maria Uriarte, Kuldip Tekam, Dharmendra Tekam, Yamuna and Gyaani Marabi.

Figures

Figure 1: Study region. Numbers in bold indicate village, numbers in original indicate compartment. Numbers generated randomly to protect identity of village.

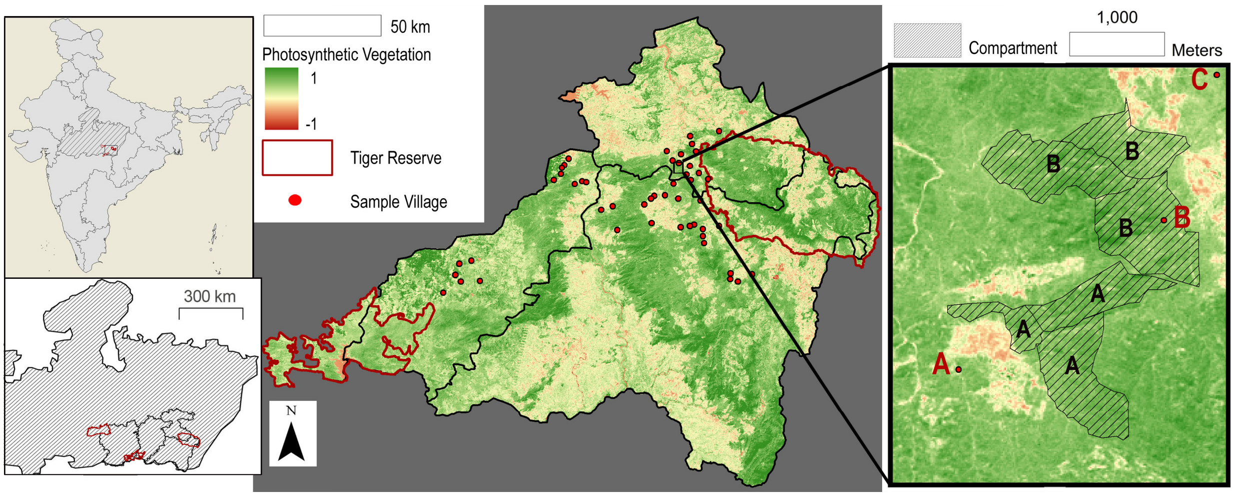


Figure 2: Effect of payments on understanding of JFM, understanding of the scheme for economic payments, and knowledge of forest boundaries and the extent of forest for which committees were responsible. For explanation on coded response, see Table 1.

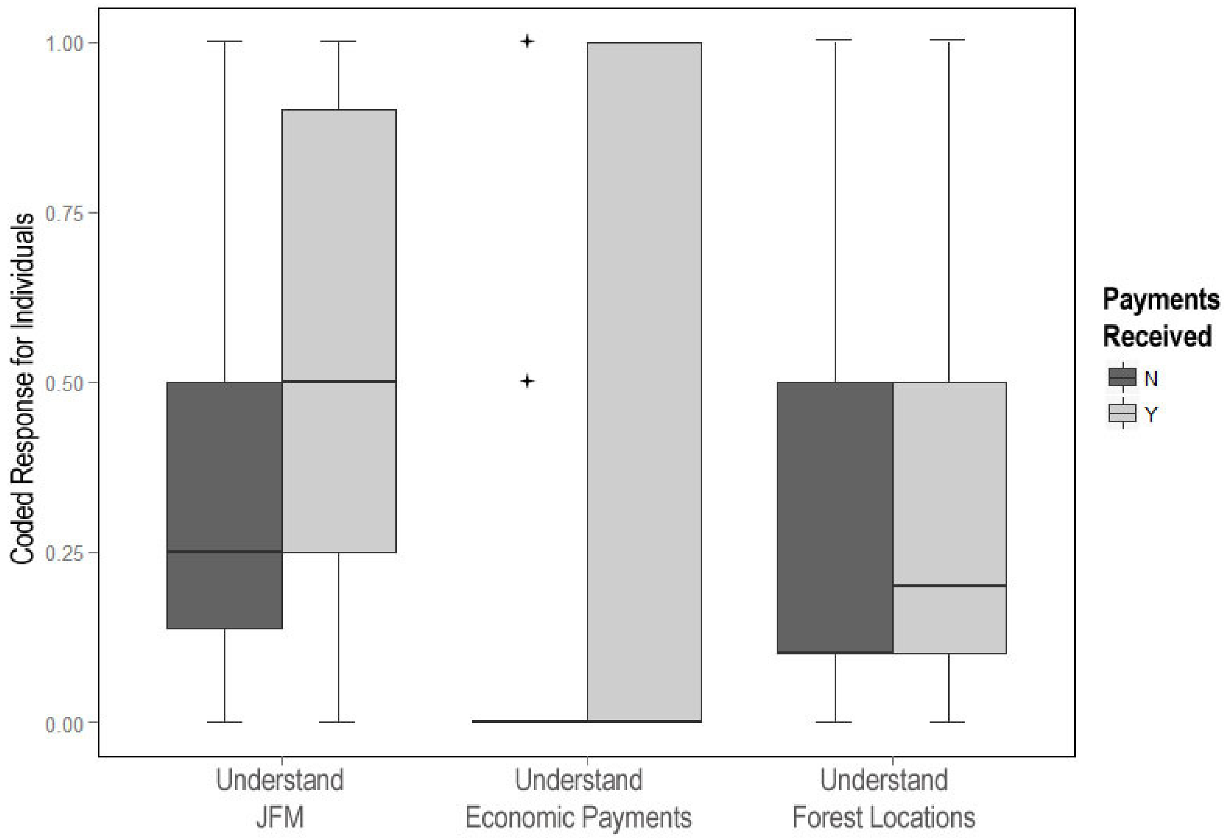


Figure 3: Knowledge of funding mechanisms for committee: Differences in (a) a belief that committee funds are generated from fines, (b) awareness that committee funds are generated from profits from protected forest, and (c) awareness that writing proposals was the mechanism for receiving funds, and (d) no information.

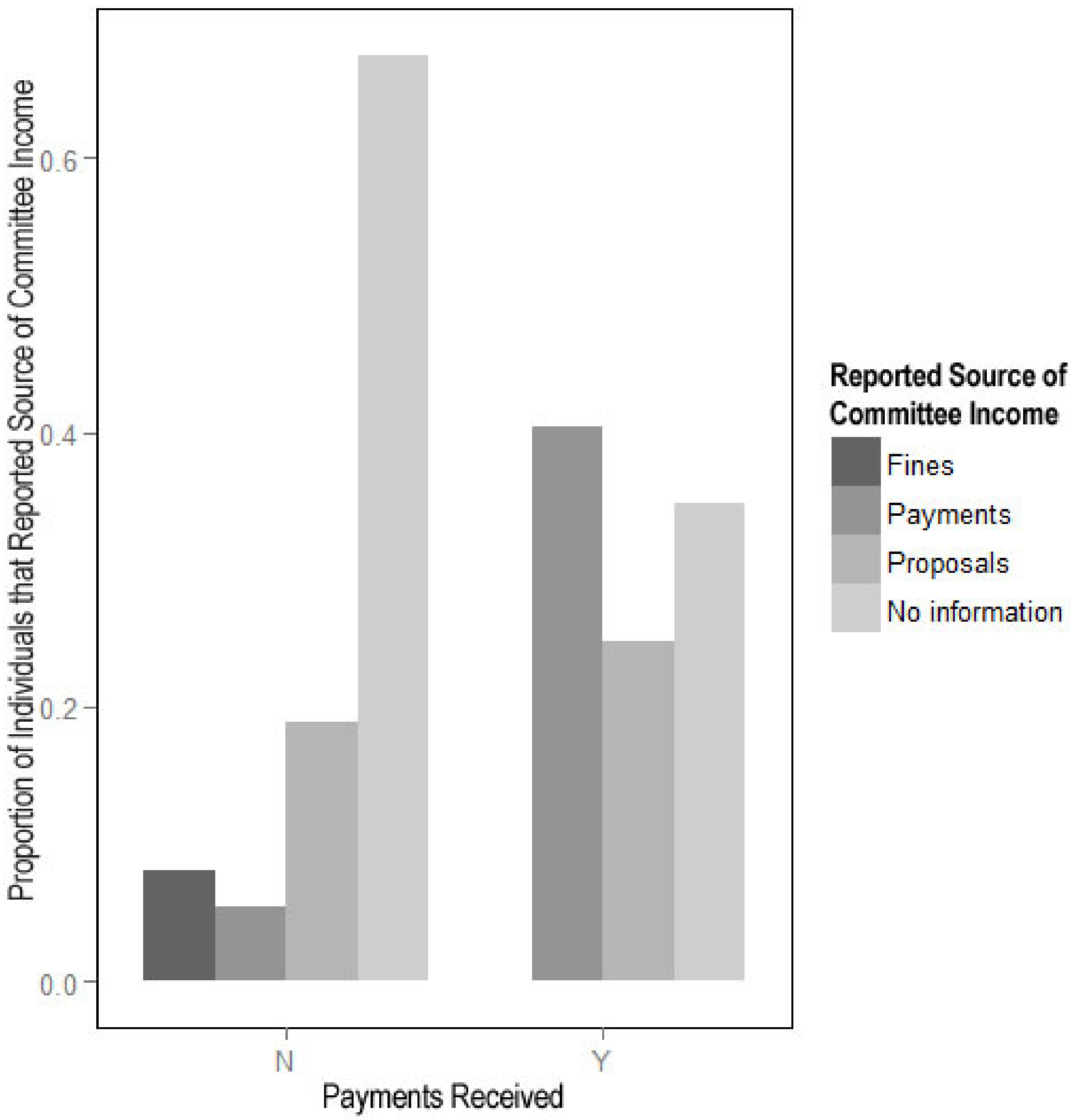


Figure 4: Effect of payments on institutional characteristics: (a) number of years spent in committee and education of committee members, and (b) proportion incumbency in committee, and proportion of committee members not selected by village.

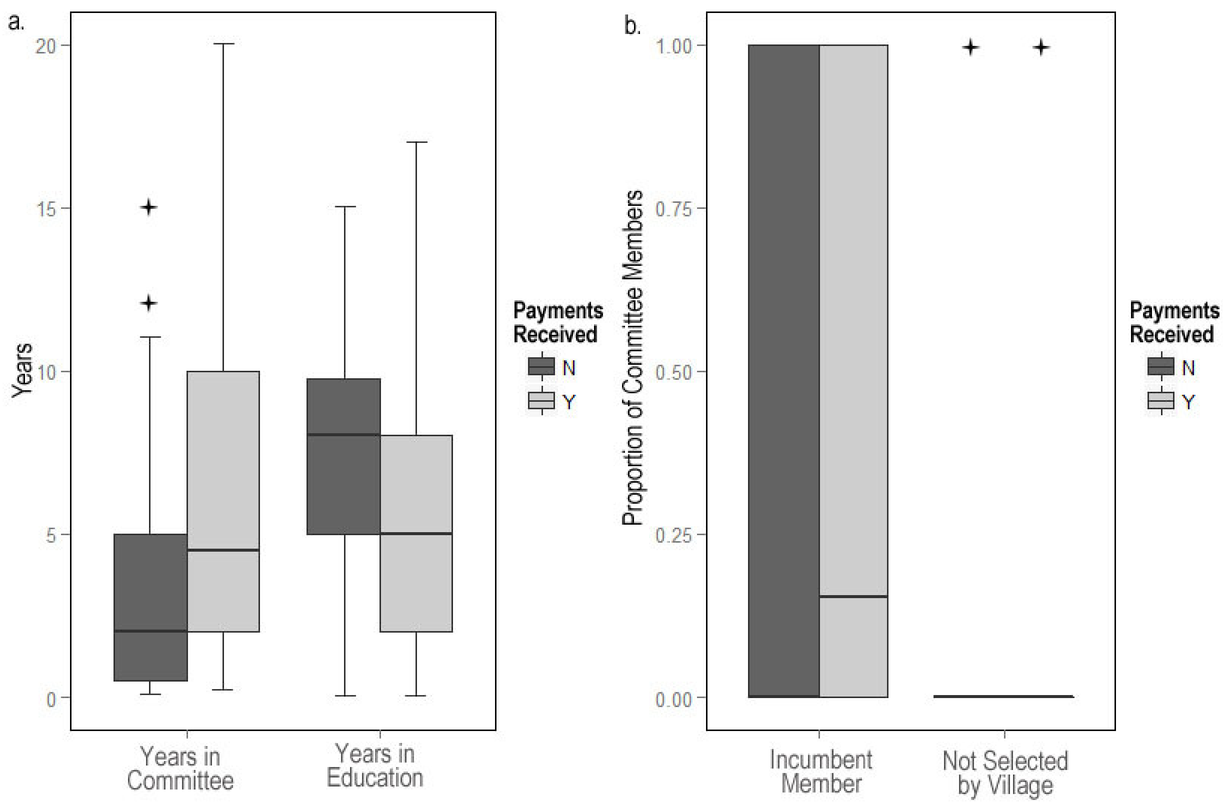


Figure 5: β-coefficients of predictors for effect of payments on institutional characteristics.

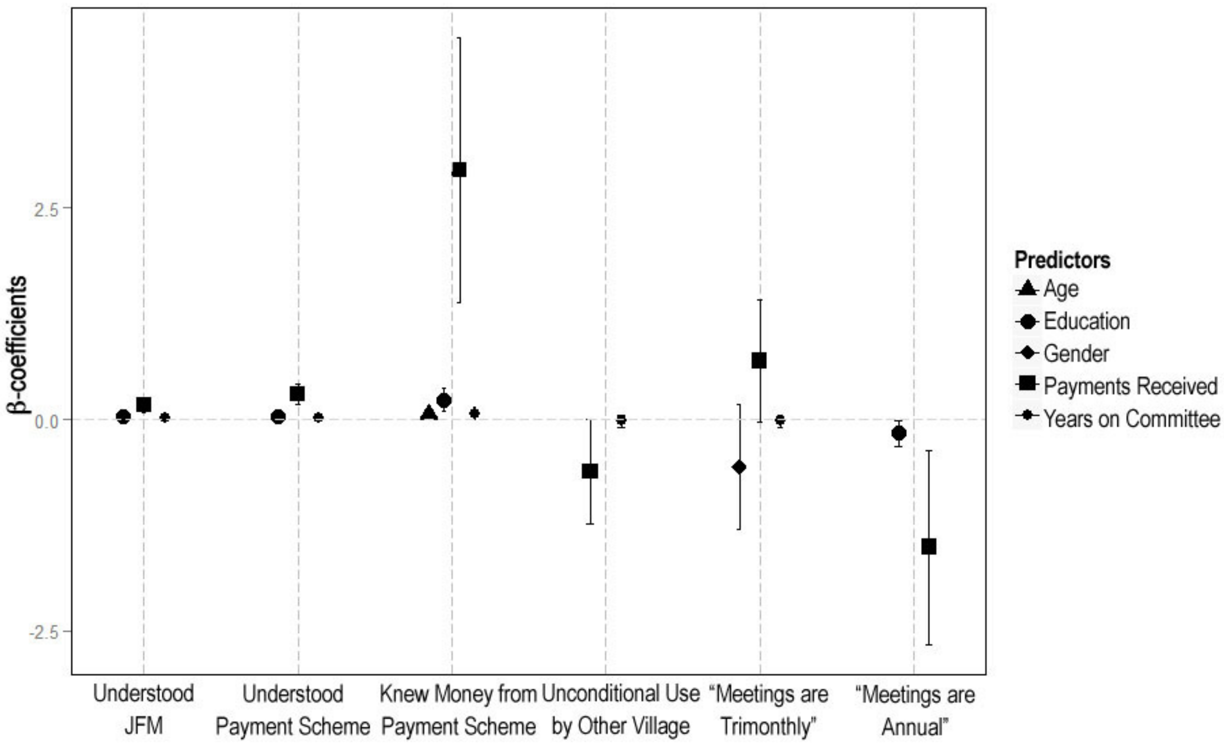


Figure 6: β-coefficients of predictors for institutional factors associated with differences in canopy change. Grayed out variables denote controls.

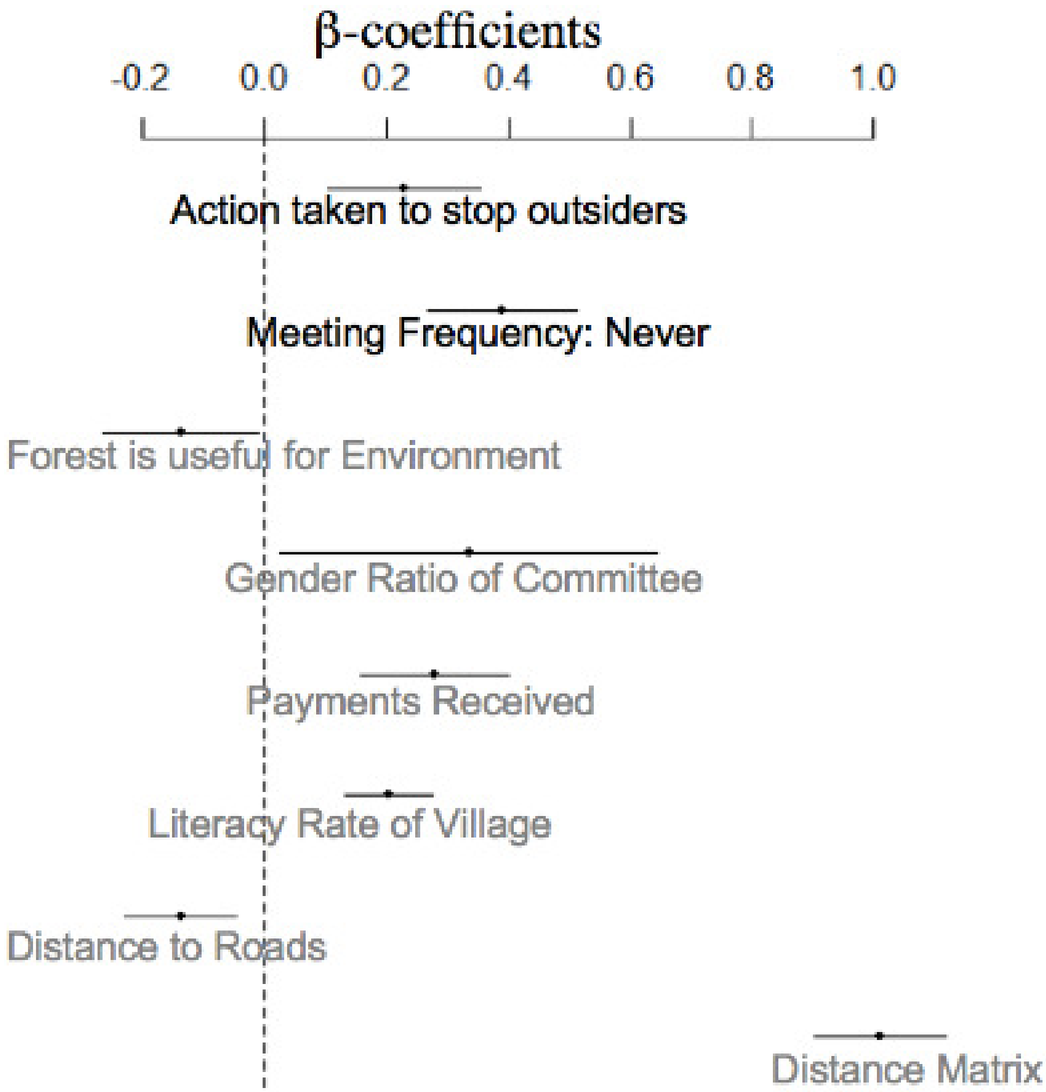
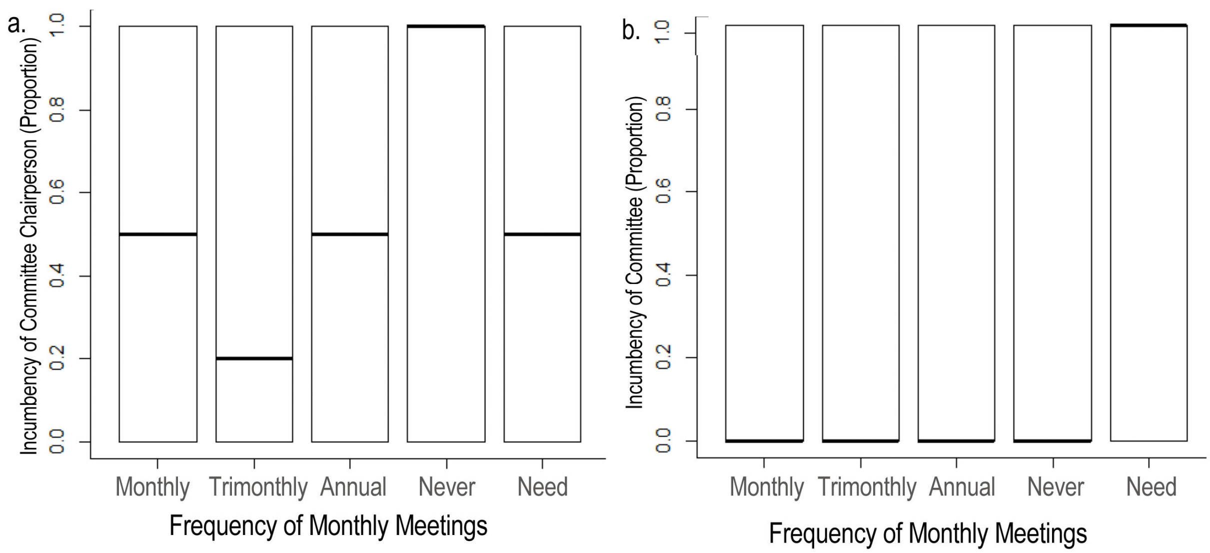


Figure 7: Differences in (a) Incumbency of Committee Chairperson, (b) Incumbency of Committee.



Tables

Table 1: Predictors used in Full model

Section	Level	Predictors	Data Source	Metric
1	Biophysical Variables	Temperature Precipitation Elevation Slope Fire FRP	MODIS 11A2 (250-meter resolution)* (reverb.echo.nasa.gov) TRMM 3B43 (1-km resolution)* (trmm.gsfc.nasa.gov) ASTER-DEM (30-meter resolution) (reverb.echo.nasa.gov) ASTER-DEM (30-meter resolution) (reverb.echo.nasa.gov) MODIS 14A1 (250-meter resolution)* (reverb.echo.nasa.gov)	Mean (8-day mean daily land temperature, Nov-Jan: 2002-2010-11) Mean (8-day mean precipitation, May-Oct: 2002-2010) Slope calculated from DEM using ArcGIS 9.3 Mean (8-day fire radiative power, Jan-June:2002-2010) Years since last fire Number of fires from 2002-2010
2	Landscape Variables	Available Forest Area Edge Forest Distance to Road Distance by Road to Market Area of Compartment Distance Matrix	Landsat Imagery (glovis.usgs.gov) Landsat Imagery (glovis.usgs.gov) [http://download.geofabrik.de /asia.html](http://download.geofabrik.de/asia.html) Wildlife Institute of India, 2011 Madhya Pradesh Forest Department, 2011 Madhya Pradesh Forest Department, 2011	Average forest cover (within a 1.5 km radius). Mean value for each compartment Average distance to non-forest for each compartment. Distance to road calculated using ArcGIS 9.3 Distance by road to nearest town reported for each village, and interpolated to pixel resolution. Calculated using ArcGIS 9.3 (square meters) Calculated from centroids of forest compartments using R package spdep
3	Demographic Variables	Human Population Density Livestock Population Density	(Wildlife Institute of India, 2011) Department of Animal Husbandry, 2011	Human populations reported from 2001 census for each village. Livestock populations reported from 2005 censusfor each village.
4	Socio-economic Variables	Sex Ratio Proportion of literate population Non-working population Proportion Non-working Proportion Scheduled	Wildlife Institute of India, 2011	Female Population/Total Village Population Total Literate Population/Total Village Population Reported in dataset Non-working Population/Total Village Population ST Population/Total Village Population

		Tribe (ST)		
5	Committee characteristics	Number of Years in Committee Gender ratio Mean Age Mean Education Proportion not selected by village* Incumbency*	Interview Interview Interview Interview Interview Interview	Female committee members/5 Question: how did you become a committee member? Answer code: 0 if members responded that they were elected or selected by the village; 1 for other means. Question: Were you on last committee Answer code: 1, Yes; 0, No
	Committee Values	Concern for Forest Forest Use (None) Forest Use (Environment)	Interview Interview Interview	Question: What do you hope for the future? Answer code: 1 if they voluntarily mentioned concern for environment, 0 otherwise Question: What is the use of forest Answer code: 1 if they said forest has no use, 0 otherwise Answer code: 1 if they said forest useful for environment, 0 otherwise
6	Community Awareness and Consent	Know and understand JFM Know they have to protect forest* Know and locate compartments	Interview Interview Interview	Question: What is JFM? Answer code: 0 (never heard of scheme), 0.25 (knew of JFM in the village, and knew that it was responsible for protecting the forest but not their own responsibility of protecting the forest) or (it brought Forest Department work such as digging trenches and fire-lines to their village), 0.40 (knew both protection of forest and related forest department work), 0.75 (knew that they were responsible for protecting the forest), 1 (knew the location of the forest assigned to them and that protection of forest led to economic payments in the future). Question: Where is your forest? Answer code: 0 if they answered that the forest surrounding the village was assigned to them, 0.5 for more specific locations such as forest up to that river or up to that village road, and 1 if they knew the exact forest locations or the compartment numbers. Question: Where does the money

		Awareness of source of funds (Fines, Proposals, Payments, No information)* Believe forest for village use Believe forest for other village as well Awareness of rights* Believe no rights on forest Believe all rights on forest	Interview Interview Interview Interview Interview Interview	come from? Question: Who can use the forest? Question: What are your rights on the forest?
7	Community Participation	Watchman (official) Watchman (local temporary) "Everyone looks after the forest" "No one looks after the forest" Stood for election this time Will stand for election next time Meeting frequency (Monthly, Trimonthly, Yearly, Never) Meeting caller (Not FD or Adhyaksh or None) Meeting talk (Proposal, None) Action (Stop outsiders, explain to outsiders, Nothing)	Interview Interview Interview Interview Interview Interview Interview Interview Interview Interview	Question: Who looks after the forest? Question: Did you stand for election? Question: Will you stand for election next time? Question: How often does the meeting happen? Question: Who calls the meeting? Question: What happens in the meetings? Question (only to those who said outsiders cannot use forest): What do you do when outsiders come?
8	External Factors	Economic payments received Traders mentioned voluntarily	Interview/Madhya Pradesh Forest Department Interview	Mentioned voluntarily: 1 if they volunteered information on outside traders, 0 otherwise.

* Pixels resampled to 30-meter resolution using bilinear resampling.

**Not included in generalized linear model because data not collected for all 50 villages or because irrelevant to impact on forest.

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Supporting information

S1: Correlation Matrix for predictors for impact of institutional variables on canopy change

Table S1: Correlation Matrix for predictors for impact of institutional variables on canopy change.

(on following pages)

SNo		Change in Canopy	Elevation (DEM)	Slope (DEM)	Precipitation	Edge	Available Forest Area	fire frequency	number of years since fire	Distance to Roads	Distance to Town	Livestock Population (interpolated)	Human Population (interpolated)	FRP (mean)	Distance Matrix
1	Change in Canopy	1.000	0.103	0.228	0.101	-0.001	0.218	0.060	-0.078	-0.112	0.305	-0.018	-0.054	0.041	0.710
2	Elevation (DEM)	0.103	1.000	0.051	-0.508	0.302	0.138	0.121	-0.018	0.136	-0.246	0.292	-0.124	0.250	0.123
3	Slope (DEM)	0.228	0.051	1.000	-0.094	0.418	0.562	0.360	-0.439	-0.107	0.476	-0.104	-0.088	0.481	0.294
4	Precipitation	0.101	-0.508	-0.094	1.000	-0.222	-0.063	-0.012	-0.031	-0.041	0.115	-0.096	-0.138	-0.089	0.072
5	Edge	-0.001	0.302	0.418	-0.222	1.000	0.700	0.459	-0.311	0.032	0.172	0.089	-0.181	0.459	-0.034
6	Available Forest Area	0.218	0.138	0.562	-0.063	0.700	1.000	0.375	-0.324	0.099	0.550	0.055	-0.378	0.400	0.174
7	fire frequency	0.060	0.121	0.360	-0.012	0.459	0.375	1.000	-0.876	-0.018	0.222	0.123	-0.044	0.848	0.060
8	number of years since fire	-0.078	-0.018	-0.439	-0.031	-0.311	-0.324	-0.876	1.000	0.052	-0.277	-0.011	0.004	-0.823	-0.126
9	Distance to Roads	-0.112	0.136	-0.107	-0.041	0.032	0.099	-0.018	0.052	1.000	0.125	0.021	-0.298	-0.075	0.062
10	Distance to Town	0.305	-0.246	0.476	0.115	0.172	0.550	0.222	-0.277	0.125	1.000	-0.028	-0.037	0.157	0.409
11	Livestock Population (interpolate	-0.018	0.292	-0.104	-0.096	0.089	0.055	0.123	-0.011	0.021	-0.028	1.000	0.271	0.231	-0.162
12	Human Population (interpolated	-0.054	-0.124	-0.088	-0.138	-0.181	-0.378	-0.044	0.004	-0.298	-0.037	0.271	1.000	-0.015	-0.051
13	FRP (mean)	0.041	0.250	0.481	-0.089	0.459	0.400	0.848	-0.823	-0.075	0.157	0.231	-0.015	1.000	0.034
14	Distance Matrix	0.710	0.123	0.294	0.072	-0.034	0.174	0.060	-0.126	0.062	0.409	-0.162	-0.051	0.034	1.000
15	Livestock Population	-0.190	0.407	-0.265	-0.149	0.096	-0.059	0.027	0.133	0.095	-0.314	0.466	-0.086	0.115	-0.336
16	Human Population	0.027	0.202	-0.341	0.158	-0.279	-0.401	-0.112	0.150	-0.018	-0.455	0.114	0.134	-0.096	-0.072
17	FRP (sum)	0.041	0.250	0.481	-0.089	0.459	0.400	0.848	-0.823	-0.075	0.157	0.231	-0.015	1.000	0.034
18	Number of years on committee (	0.259	-0.030	0.259	-0.043	0.167	0.252	0.007	-0.113	0.044	0.310	-0.213	-0.042	-0.025	0.343
19	Literacy representation	-0.304	0.063	-0.237	-0.149	-0.103	-0.053	-0.160	0.151	0.323	-0.270	-0.035	-0.238	-0.153	-0.194
20	Non working population	0.017	-0.069	0.175	0.160	-0.002	-0.021	0.081	-0.108	-0.587	-0.026	0.052	0.112	0.130	-0.157
21	Village Gender Ratio	-0.213	0.365	-0.149	-0.115	0.185	0.123	-0.019	0.074	0.117	-0.100	0.290	-0.087	0.075	-0.283
22	Non working proportion	0.042	0.174	-0.241	0.216	-0.233	-0.354	-0.075	0.095	-0.215	-0.419	0.097	0.142	-0.038	-0.067
23	Forest Use None	0.045	0.136	-0.074	0.221	-0.078	-0.152	0.099	-0.036	-0.028	-0.215	0.072	0.002	0.081	-0.036
24	Forest use Environment	0.092	0.353	0.082	-0.092	0.230	0.112	0.113	-0.026	-0.093	-0.201	0.166	-0.012	0.184	0.052
25	Meeting frequency	0.092	0.418	-0.171	0.048	-0.191	-0.213	-0.117	0.131	0.095	-0.442	0.162	-0.292	0.010	-0.020
26	Meeting caller other	-0.190	0.085	-0.150	-0.025	0.149	0.020	0.116	-0.063	-0.168	0.014	0.206	0.011	0.155	-0.200
27	Action Taken: Stop	0.144	0.005	0.113	-0.046	0.143	0.262	0.018	0.007	0.282	0.287	-0.032	-0.233	-0.034	0.157
28	Action Taken: Nothing	-0.042	0.115	-0.041	0.071	0.051	-0.037	0.019	-0.020	-0.202	-0.069	0.296	0.190	0.079	-0.060
29	Action Taken: explain	0.107	-0.305	0.130	0.061	0.067	0.169	0.056	-0.161	0.019	0.305	-0.266	-0.039	-0.020	0.111

SNo		Change in Canopy	Elevation (DEM)	Slope (DEM)	Precipitation	Edge	Available Forest Area	fire frequency	number of years since fire	Distance to Roads	Distance to Town	Livestock Population (interpolated)	Human Population (interpolated)	FRP (mean)	Distance Matrix
30	Money no information on source	0.135	0.021	0.116	0.103	-0.162	-0.055	-0.085	-0.007	0.308	0.114	-0.165	-0.170	-0.115	0.206
31	Understand Labhans	0.166	-0.239	0.458	0.154	0.332	0.421	0.176	-0.269	-0.256	0.385	-0.061	0.084	0.232	0.216
32	Payments Received	0.266	-0.183	0.358	0.201	0.238	0.414	0.144	-0.196	-0.238	0.317	0.058	-0.050	0.195	0.176
33	Meeting caller none	0.186	0.386	-0.163	-0.176	-0.157	-0.284	-0.146	0.118	-0.065	-0.369	-0.155	-0.160	-0.144	0.141
34	Meeting talk proposal	-0.167	-0.173	-0.047	-0.041	0.056	0.077	0.073	-0.119	0.101	-0.059	-0.239	-0.080	-0.066	-0.222
35	Meeting talk none	-0.006	0.214	0.072	0.200	0.065	-0.066	0.031	-0.019	0.206	-0.247	0.055	-0.319	0.181	0.043
36	Traders Mentioned	0.220	0.346	-0.242	0.030	-0.153	-0.107	-0.156	0.191	0.092	-0.123	-0.104	-0.124	-0.123	0.311
37	No one looks after forest	0.163	-0.088	0.219	0.156	-0.015	0.032	0.193	-0.170	-0.121	0.193	-0.154	-0.203	0.113	0.171
38	Committee mean education	-0.104	0.019	-0.223	-0.126	0.001	-0.123	-0.099	0.163	0.178	-0.240	-0.055	-0.010	-0.199	-0.169
39	Committee gender ratio	0.080	0.156	0.178	0.011	0.040	0.159	0.132	-0.169	-0.014	0.169	0.221	0.018	0.213	0.063
40	Concern Forest	0.102	0.102	-0.035	-0.290	-0.039	-0.088	-0.237	0.152	0.090	-0.042	-0.141	0.210	-0.228	0.261
41	Did contest election this time	-0.039	0.061	0.060	-0.044	-0.080	-0.018	0.002	-0.008	0.104	0.042	0.010	-0.026	0.102	0.012
42	Will contest election next time	0.097	0.031	0.046	-0.156	-0.111	-0.085	-0.037	0.057	-0.036	0.162	0.142	0.247	-0.061	0.165
43	Hire temporary watchers	0.328	-0.007	0.422	0.277	0.010	0.317	0.171	-0.226	0.079	0.517	0.031	-0.050	0.264	0.409
44	Literacy rate	0.180	-0.234	-0.096	0.256	0.005	-0.077	0.036	0.003	-0.281	0.077	-0.137	0.239	-0.144	0.038
45	Proportion of ST	-0.230	-0.128	0.142	-0.204	0.111	0.211	0.042	-0.022	0.255	0.091	-0.014	-0.201	0.133	-0.203
46	Mean age of Committee	0.033	-0.033	-0.193	0.173	-0.064	-0.269	0.031	0.012	-0.426	-0.392	-0.014	-0.021	-0.063	-0.118

SNo	Livestock Population	Human Population	Number of years on committee (mean)	Literacy representation	Non working population	Village Gender Ratio	Non working proportion	Forest Use None	Forest use Environment	Meeting frequency	Meeting caller other	Action Taken: Stop	Action Taken: Nothing	Action Taken: explain	Money no information on source	Understand Labhans
1	-0.190	0.027	0.259	-0.304	0.017	-0.213	0.042	0.045	0.092	0.092	-0.190	0.144	-0.042	0.107	0.135	0.166
2	0.407	0.202	-0.030	0.063	-0.069	0.365	0.174	0.136	0.353	0.418	0.085	0.005	0.115	-0.305	0.021	-0.239
3	-0.265	-0.341	0.259	-0.237	0.175	-0.149	-0.241	-0.074	0.082	-0.171	-0.150	0.113	-0.041	0.130	0.116	0.458
4	-0.149	0.158	-0.043	-0.149	0.160	-0.115	0.216	0.221	-0.092	0.048	-0.025	-0.046	0.071	0.061	0.103	0.154
5	0.096	-0.279	0.167	-0.103	-0.002	0.185	-0.233	-0.078	0.230	-0.191	0.149	0.143	0.051	0.067	-0.162	0.332
6	-0.059	-0.401	0.252	-0.053	-0.021	0.123	-0.354	-0.152	0.112	-0.213	0.020	0.262	-0.037	0.169	-0.055	0.421
7	0.027	-0.112	0.007	-0.160	0.081	-0.019	-0.075	0.099	0.113	-0.117	0.116	0.018	0.019	0.056	-0.085	0.176
8	0.133	0.150	-0.113	0.151	-0.108	0.074	0.095	-0.036	-0.026	0.131	-0.063	0.007	-0.020	-0.161	-0.007	-0.269
9	0.095	-0.018	0.044	0.323	-0.587	0.117	-0.215	-0.028	-0.093	0.095	-0.168	0.282	-0.202	0.019	0.308	-0.256
10	-0.314	-0.455	0.310	-0.270	-0.026	-0.100	-0.419	-0.215	-0.201	-0.442	0.014	0.287	-0.069	0.305	0.114	0.385
11	0.466	0.114	-0.213	-0.035	0.052	0.290	0.097	0.072	0.166	0.162	0.206	-0.032	0.296	-0.266	-0.165	-0.061
12	-0.086	0.134	-0.042	-0.238	0.112	-0.087	0.142	0.002	-0.012	-0.292	0.011	-0.233	0.190	-0.039	-0.170	0.084
13	0.115	-0.096	-0.025	-0.153	0.130	0.075	-0.038	0.081	0.184	0.010	0.155	-0.034	0.079	-0.020	-0.115	0.232
14	-0.336	-0.072	0.343	-0.194	-0.157	-0.283	-0.067	-0.036	0.052	-0.020	-0.200	0.157	-0.060	0.111	0.206	0.216
15	1.000	0.569	-0.337	0.103	0.059	0.506	0.537	0.334	0.166	0.368	0.318	0.029	0.228	-0.375	-0.152	-0.343
16	0.569	1.000	-0.316	-0.099	0.046	0.268	0.939	0.412	0.056	0.387	-0.135	-0.235	0.221	-0.382	0.013	-0.405
17	0.115	-0.096	-0.025	-0.153	0.130	0.075	-0.038	0.081	0.184	0.010	0.155	-0.034	0.079	-0.020	-0.115	0.232
18	-0.337	-0.316	1.000	0.052	-0.303	-0.107	-0.355	-0.124	-0.033	-0.062	-0.060	0.145	-0.065	0.350	0.249	0.549
19	0.103	-0.099	0.052	1.000	-0.317	0.204	-0.185	-0.084	-0.088	0.178	0.006	0.055	0.022	-0.214	-0.117	-0.186
20	0.059	0.046	-0.303	-0.317	1.000	-0.092	0.362	0.131	0.003	-0.047	0.191	-0.132	0.266	-0.054	-0.116	0.068
21	0.506	0.268	-0.107	0.204	-0.092	1.000	0.229	0.281	0.250	0.220	0.233	0.019	0.353	-0.215	-0.211	-0.044
22	0.537	0.939	-0.355	-0.185	0.362	0.229	1.000	0.429	0.061	0.331	-0.062	-0.246	0.304	-0.381	-0.005	-0.318
23	0.334	0.412	-0.124	-0.084	0.131	0.281	0.429	1.000	0.157	0.306	0.268	-0.194	0.276	-0.238	0.134	-0.097
24	0.166	0.056	-0.033	-0.088	0.003	0.250	0.061	0.157	1.000	0.210	0.007	0.042	-0.016	-0.029	0.014	0.184
25	0.368	0.387	-0.062	0.178	-0.047	0.220	0.331	0.306	0.210	1.000	0.013	-0.244	0.223	-0.252	0.190	-0.256
26	0.318	-0.135	-0.060	0.006	0.191	0.233	-0.062	0.268	0.007	0.013	1.000	-0.194	0.273	0.007	-0.259	-0.044
27	0.029	-0.235	0.145	0.055	-0.132	0.019	-0.246	-0.194	0.042	-0.244	-0.194	1.000	-0.537	0.372	0.135	0.168
28	0.228	0.221	-0.065	0.022	0.266	0.353	0.304	0.276	-0.016	0.223	0.273	-0.537	1.000	-0.445	-0.159	0.044
29	-0.375	-0.382	0.350	-0.214	-0.054	-0.215	-0.381	-0.238	-0.029	-0.252	0.007	0.372	-0.445	1.000	0.127	0.483

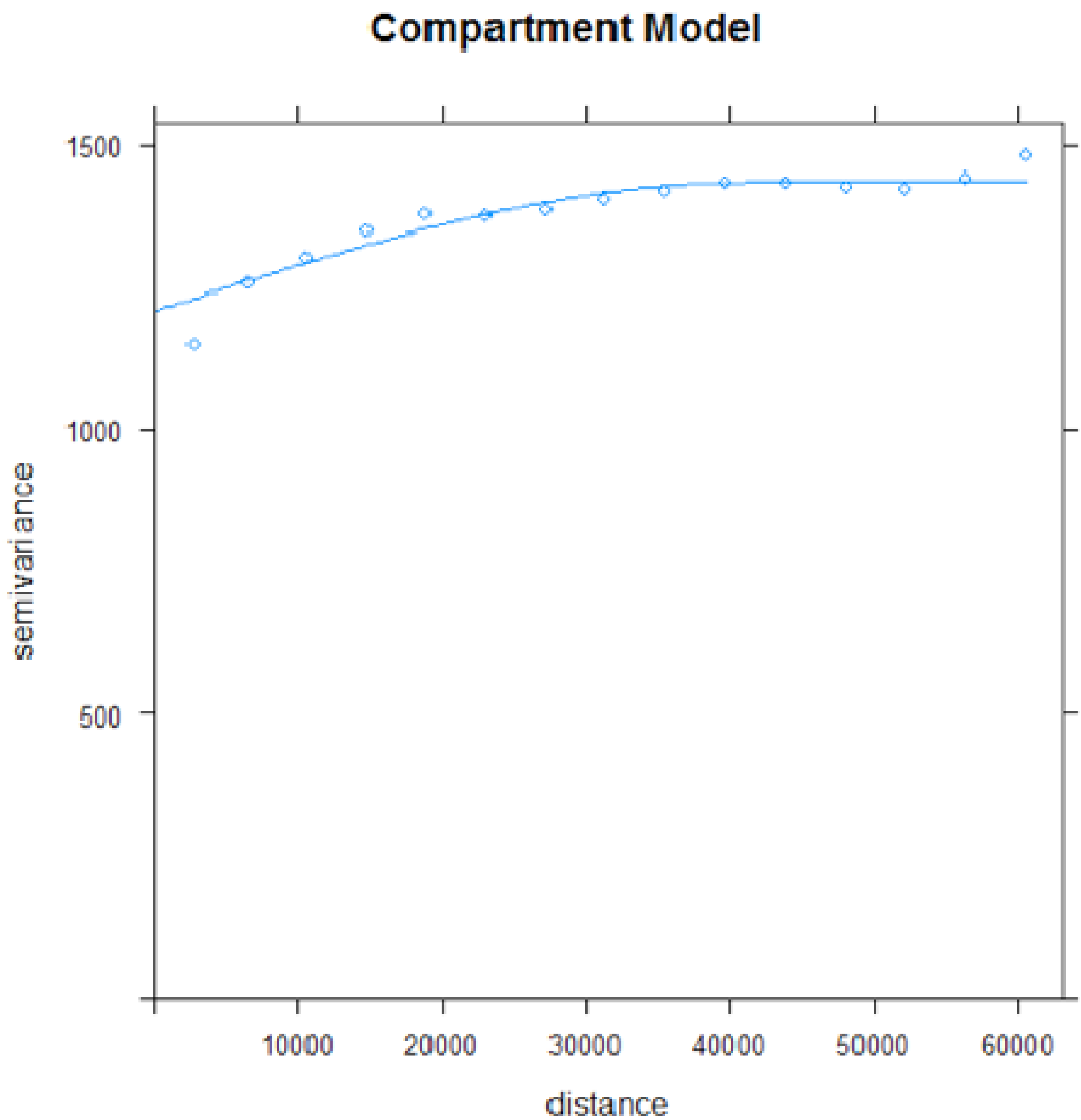
SNo	Livestock Population	Human Population	Number of years on committee (mean)	Literacy representation	Non working population	Village Gender Ratio	Non working proportion	Forest Use None	Forest use Environment	Meeting frequency	Meeting caller other	Action Taken: Stop	Action Taken: Nothing	Action Taken: explain	Money no information on source	Understand Labhans
30	-0.152	0.013	0.249	-0.117	-0.116	-0.211	-0.005	0.134	0.014	0.190	-0.259	0.135	-0.159	0.127	1.000	-0.017
31	-0.343	-0.405	0.549	-0.186	0.068	-0.044	-0.318	-0.097	0.184	-0.256	-0.044	0.168	0.044	0.483	-0.017	1.000
32	-0.293	-0.211	0.354	-0.206	0.104	0.104	-0.138	-0.028	0.263	-0.049	0.008	-0.110	0.177	0.157	0.013	0.583
33	0.031	0.154	0.172	0.121	-0.013	0.062	0.131	0.212	0.063	0.547	-0.063	-0.104	0.120	-0.151	0.123	-0.210
34	-0.270	-0.221	0.088	0.120	-0.205	-0.081	-0.294	0.082	-0.029	-0.078	-0.018	0.008	-0.155	0.318	0.098	0.139
35	0.199	0.223	-0.112	-0.038	0.079	0.045	0.255	0.284	0.258	0.359	-0.083	0.075	-0.057	-0.202	0.245	-0.037
36	0.260	0.473	0.066	0.085	-0.120	0.122	0.430	0.280	-0.145	0.404	0.057	-0.133	0.210	-0.306	-0.053	-0.340
37	-0.003	0.175	-0.206	-0.340	0.339	-0.141	0.293	0.206	-0.005	0.009	-0.031	-0.221	0.178	-0.133	0.299	-0.246
38	0.205	0.112	0.143	0.477	-0.321	0.097	-0.010	0.005	0.062	0.025	-0.200	0.160	0.064	-0.098	-0.024	-0.083
39	0.031	0.111	-0.238	-0.147	0.086	0.362	0.141	0.033	0.009	0.004	0.091	-0.049	0.173	-0.070	-0.025	-0.106
40	-0.243	-0.067	0.499	0.101	-0.280	-0.091	-0.136	-0.237	0.044	0.126	-0.123	-0.038	-0.004	0.169	0.171	0.040
41	-0.043	-0.112	-0.120	0.092	0.005	-0.072	-0.121	0.173	-0.072	0.228	0.329	-0.337	-0.042	0.069	-0.035	-0.074
42	-0.163	-0.186	-0.099	-0.090	0.078	0.086	-0.172	0.137	-0.025	-0.097	0.159	-0.235	0.278	-0.076	-0.120	-0.115
43	-0.100	-0.030	0.096	-0.160	-0.039	0.063	-0.011	-0.027	0.194	0.052	-0.117	0.072	0.111	-0.001	0.313	0.292
44	-0.091	0.125	0.029	-0.492	0.270	-0.183	0.187	0.140	0.090	-0.328	-0.081	0.099	-0.044	0.255	-0.005	0.190
45	-0.202	-0.431	-0.130	0.260	-0.290	-0.030	-0.519	-0.401	-0.280	-0.139	-0.053	0.264	-0.352	0.149	-0.282	-0.024
46	0.016	0.062	0.006	-0.201	0.288	-0.232	0.148	0.251	0.079	0.010	0.171	-0.154	-0.106	-0.021	0.056	-0.076

SNo	Payments Received	Meeting caller none	Meeting talk proposal	Meeting talk none	Traders Mentioned	No one looks after forest	Committee mean education	Committee gender ratio	Concern Forest	Did contest election this time	Will contest election next time	Hire temporary watchers	Literacy rate	Proportion of ST	Mean age of Committee
1	0.266	0.186	-0.167	-0.006	0.220	0.163	-0.104	0.080	0.102	-0.039	0.097	0.328	0.180	-0.230	0.033
2	-0.183	0.386	-0.173	0.214	0.346	-0.088	0.019	0.156	0.102	0.061	0.031	-0.007	-0.234	-0.128	-0.033
3	0.358	-0.163	-0.047	0.072	-0.242	0.219	-0.223	0.178	-0.035	0.060	0.046	0.422	-0.096	0.142	-0.193
4	0.201	-0.176	-0.041	0.200	0.030	0.156	-0.126	0.011	-0.290	-0.044	-0.156	0.277	0.256	-0.204	0.173
5	0.238	-0.157	0.056	0.065	-0.153	-0.015	0.001	0.040	-0.039	-0.080	-0.111	0.010	0.005	0.111	-0.064
6	0.414	-0.284	0.077	-0.066	-0.107	0.032	-0.123	0.159	-0.088	-0.018	-0.085	0.317	-0.077	0.211	-0.269
7	0.144	-0.146	0.073	0.031	-0.156	0.193	-0.099	0.132	-0.237	0.002	-0.037	0.171	0.036	0.042	0.031
8	-0.196	0.118	-0.119	-0.019	0.191	-0.170	0.163	-0.169	0.152	-0.008	0.057	-0.226	0.003	-0.022	0.012
9	-0.238	-0.065	0.101	0.206	0.092	-0.121	0.178	-0.014	0.090	0.104	-0.036	0.079	-0.281	0.255	-0.426
10	0.317	-0.369	-0.059	-0.247	-0.123	0.193	-0.240	0.169	-0.042	0.042	0.162	0.517	0.077	0.091	-0.392
11	0.058	-0.155	-0.239	0.055	-0.104	-0.154	-0.055	0.221	-0.141	0.010	0.142	0.031	-0.137	-0.014	-0.014
12	-0.050	-0.160	-0.080	-0.319	-0.124	-0.203	-0.010	0.018	0.210	-0.026	0.247	-0.050	0.239	-0.201	-0.021
13	0.195	-0.144	-0.066	0.181	-0.123	0.113	-0.199	0.213	-0.228	0.102	-0.061	0.264	-0.144	0.133	-0.063
14	0.176	0.141	-0.222	0.043	0.311	0.171	-0.169	0.063	0.261	0.012	0.165	0.409	0.038	-0.203	-0.118
15	-0.293	0.031	-0.270	0.199	0.260	-0.003	0.205	0.031	-0.243	-0.043	-0.163	-0.100	-0.091	-0.202	0.016
16	-0.211	0.154	-0.221	0.223	0.473	0.175	0.112	0.111	-0.067	-0.112	-0.186	-0.030	0.125	-0.431	0.062
17	0.195	-0.144	-0.066	0.181	-0.123	0.113	-0.199	0.213	-0.228	0.102	-0.061	0.264	-0.144	0.133	-0.063
18	0.354	0.172	0.088	-0.112	0.066	-0.206	0.143	-0.238	0.499	-0.120	-0.099	0.096	0.029	-0.130	0.006
19	-0.206	0.121	0.120	-0.038	0.085	-0.340	0.477	-0.147	0.101	0.092	-0.090	-0.160	-0.492	0.260	-0.201
20	0.104	-0.013	-0.205	0.079	-0.120	0.339	-0.321	0.086	-0.280	0.005	0.078	-0.039	0.270	-0.290	0.288
21	0.104	0.062	-0.081	0.045	0.122	-0.141	0.097	0.362	-0.091	-0.072	0.086	0.063	-0.183	-0.030	-0.232
22	-0.138	0.131	-0.294	0.255	0.430	0.293	-0.010	0.141	-0.136	-0.121	-0.172	-0.011	0.187	-0.519	0.148
23	-0.028	0.212	0.082	0.284	0.280	0.206	0.005	0.033	-0.237	0.173	0.137	-0.027	0.140	-0.401	0.251
24	0.263	0.063	-0.029	0.258	-0.145	-0.005	0.062	0.009	0.044	-0.072	-0.025	0.194	0.090	-0.280	0.079
25	-0.049	0.547	-0.078	0.359	0.404	0.009	0.025	0.004	0.126	0.228	-0.097	0.052	-0.328	-0.139	0.010
26	0.008	-0.063	-0.018	-0.083	0.057	-0.031	-0.200	0.091	-0.123	0.329	0.159	-0.117	-0.081	-0.053	0.171
27	-0.110	-0.104	0.008	0.075	-0.133	-0.221	0.160	-0.049	-0.038	-0.337	-0.235	0.072	0.099	0.264	-0.154
28	0.177	0.120	-0.155	-0.057	0.210	0.178	0.064	0.173	-0.004	-0.042	0.278	0.111	-0.044	-0.352	-0.106
29	0.157	-0.151	0.318	-0.202	-0.306	-0.133	-0.098	-0.070	0.169	0.069	-0.076	-0.001	0.255	0.149	-0.021

SNo	Payments Received	Meeting caller none	Meeting talk proposal	Meeting talk none	Traders Mentioned	No one looks after forest	Committee mean education	Committee gender ratio	Concern Forest	Did contest election this time	Will contest election next time	Hire temporary watchers	Literacy rate	Proportion of ST	Mean age of Committee
30	0.013	0.123	0.098	0.245	-0.053	0.299	-0.024	-0.025	0.171	-0.035	-0.120	0.313	-0.005	-0.282	0.056
31	0.583	-0.210	0.139	-0.037	-0.340	-0.246	-0.083	-0.106	0.040	-0.074	-0.115	0.292	0.190	-0.024	-0.076
32	1.000	-0.270	0.096	0.023	-0.177	0.127	-0.367	0.169	0.030	0.030	-0.055	0.313	-0.068	0.029	0.019
33	-0.270	1.000	-0.087	0.144	0.349	-0.024	0.264	-0.108	0.173	-0.011	0.141	-0.197	0.106	-0.254	0.288
34	0.096	-0.087	1.000	-0.171	-0.217	-0.226	0.078	-0.217	-0.050	0.035	-0.174	-0.219	0.070	0.109	0.130
35	0.023	0.144	-0.171	1.000	0.129	0.176	-0.126	0.053	-0.175	0.057	-0.287	0.048	-0.191	-0.034	0.085
36	-0.177	0.349	-0.217	0.129	1.000	0.063	-0.016	-0.031	0.159	0.118	-0.082	-0.019	-0.151	-0.229	-0.086
37	0.127	-0.024	-0.226	0.176	0.063	1.000	-0.210	0.200	-0.175	-0.001	0.175	0.156	0.075	-0.279	0.179
38	-0.367	0.264	0.078	-0.126	-0.016	-0.210	1.000	-0.396	0.182	-0.319	-0.159	-0.180	0.280	-0.198	-0.034
39	0.169	-0.108	-0.217	0.053	-0.031	0.200	-0.396	1.000	-0.174	0.032	0.088	0.280	-0.272	0.177	-0.261
40	0.030	0.173	-0.050	-0.175	0.159	-0.175	0.182	-0.174	1.000	0.022	0.059	-0.033	-0.064	-0.136	-0.224
41	0.030	-0.011	0.035	0.057	0.118	-0.001	-0.319	0.032	0.022	1.000	0.132	0.162	-0.254	0.193	-0.081
42	-0.055	0.141	-0.174	-0.287	-0.082	0.175	-0.159	0.088	0.059	0.132	1.000	-0.024	0.029	-0.011	-0.043
43	0.313	-0.197	-0.219	0.048	-0.019	0.156	-0.180	0.280	-0.033	0.162	-0.024	1.000	-0.076	-0.026	-0.352
44	-0.068	0.106	0.070	-0.191	-0.151	0.075	0.280	-0.272	-0.064	-0.254	0.029	-0.076	1.000	-0.492	0.364
45	0.029	-0.254	0.109	-0.034	-0.229	-0.279	-0.198	0.177	-0.136	0.193	-0.011	-0.026	-0.492	1.000	-0.338
46	0.019	0.288	0.130	0.085	-0.086	0.179	-0.034	-0.261	-0.224	-0.081	-0.043	-0.352	0.364	-0.338	1.000

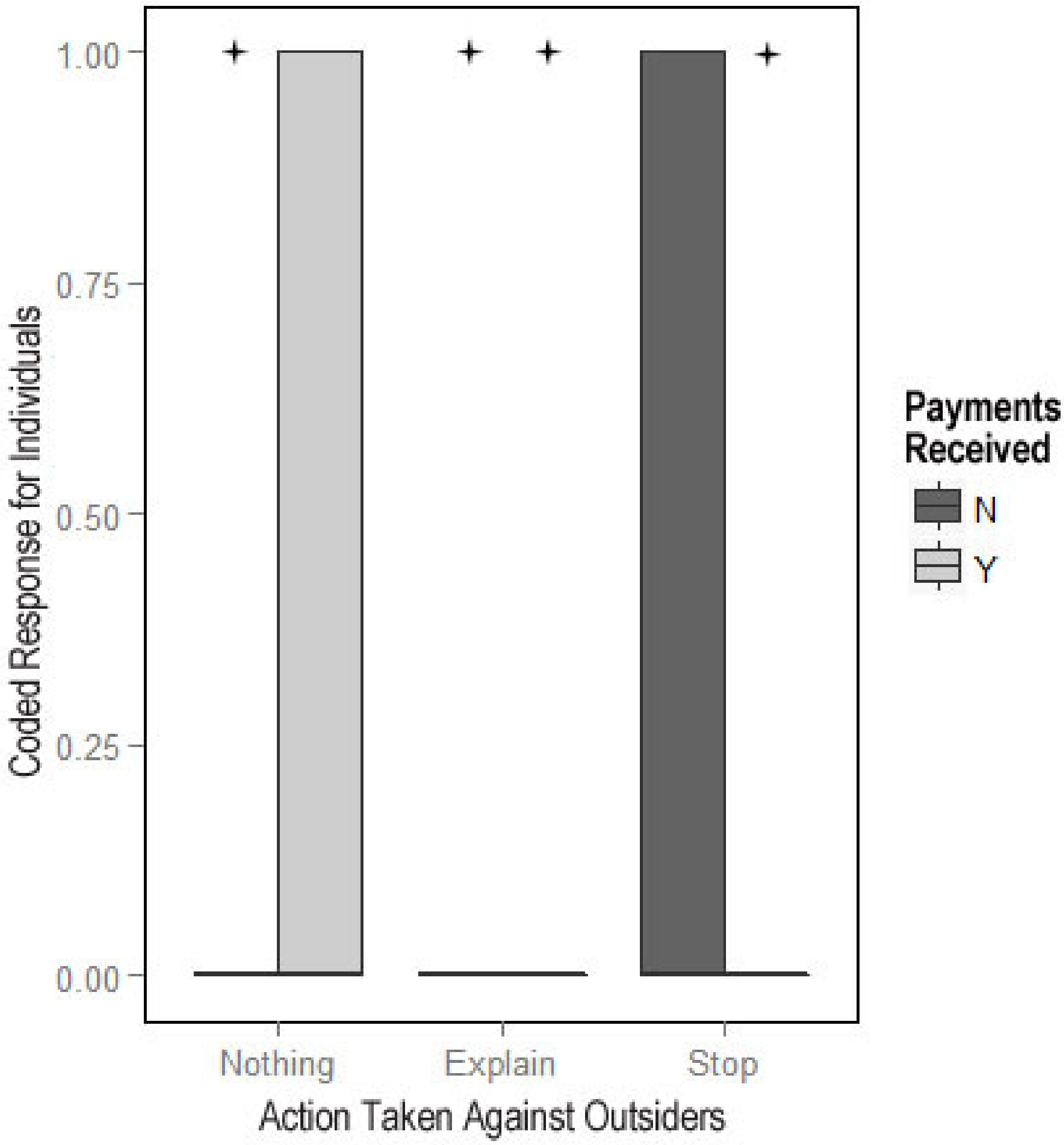
S2: Accounting for spatial autocorrelation

Figure S2: Semi-variance using generalized linear model before including distance matrix.



S3: Impact of Economic Payments on Action taken against outsiders

Figure S3: Impact of Economic Payments on Action taken against outsiders



S4: Model Selection

Table S4: Selecting best model using Akaike Information Criterion (AIC).

SNo	Model	AIC
1	**Elevation**+Slope+Distance Matrix +Dist to Roads+Population Density+ Number of Years ono Committee+ Literacy representation	171.2

	+Action Taken to Stop Outsiders+Meeting Frequency+Meeting caller other+Forests useful for Environment+Gender Ratio of Committee +Non-working Proportion+No one looks after the forest+Meeting talk proposal+Meeting talk none+Election this time+Election Next time	
2	**Cattle Density**+Slope+Distance Matrix +Dist to Roads+Population Density+ Number of Years ono Committee+ Literacy representation +Action Taken to Stop Outsiders+Meeting Frequency+Meeting caller other+Forests useful for Environment+Gender Ratio of Committee +Non-working Proportion+No one looks after the forest+Meeting talk proposal+Meeting talk none+Election this time+Election Next time	171.4
3	**Precipitation**+Slope+Distance Matrix +Dist to Roads+Population Density+ Number of Years ono Committee+ Literacy representation +Action Taken to Stop Outsiders+Meeting Frequency+Meeting caller other+Forests useful for Environment+Gender Ratio of Committee +Non-working Proportion+No one looks after the forest+Meeting talk proposal+Meeting talk none+Election this time+Election Next time	170.3
4	Elevation+Edge+Distance Matrix +Dist to Roads+Population Density+ Number of Years ono Committee+ Literacy representation +Action Taken to Stop Outsiders+Meeting Frequency+Meeting caller other+Forests useful for Environment+Gender Ratio of Committee +Non-working Proportion+No one looks after the forest+Meeting talk proposal+Meeting talk none+Election this time+Election Next time	169.6
5	Elevation+Available Forest+Distance Matrix +Dist to Roads+Population Density+ Number of Years ono Committee+ Literacy representation +Action Taken to Stop Outsiders+Meeting Frequency+Meeting caller other+Forests useful for Environment+Gender Ratio of Committee +Non-working Proportion+No one looks after the forest+Meeting talk proposal+Meeting talk none+Election this time+Election Next time	164.1
6	Elevation+FRP+Distance Matrix +Dist to Roads+Population Density+ Number of Years ono Committee+ Literacy representation +Action Taken to Stop Outsiders+Meeting Frequency+Meeting caller other+Forests useful for Environment+Gender Ratio of Committee +Non-working Proportion+No one looks after the forest+Meeting talk proposal+Meeting talk none+Election this time+Election Next time	171.2
7	Elevation+Distance to Towns+Distance Matrix +Dist to Roads+Population Density+ Number of Years ono Committee+ Literacy representation +Action Taken to Stop Outsiders+Meeting Frequency+Meeting caller other+Forests useful for Environment+Gender Ratio of Committee +Non-working Proportion+No one looks after the forest+Meeting talk proposal+Meeting talk none+Election this time+Election Next time	170.2
8	Elevation+Payments Understand+Distance Matrix +Dist to Roads+Population Density+ Number of Years ono Committee+ Literacy representation +Action Taken to Stop Outsiders+Meeting Frequency+Meeting caller other+Forests useful for	171

	Environment+Gender Ratio of Committee +Non-working Proportion+No one looks after the forest+Meeting talk proposal+Meeting talk none+Election this time+Election Next time	
9	Elevation+Temporary Watchers+Distance Matrix +Dist to Roads+Population Density+ Number of Years ono Committee+ Literacy representation +Action Taken to Stop Outsiders+Meeting Frequency+Meeting caller other+Forests useful for Environment+Gender Ratio of Committee +Non-working Proportion+No one looks after the forest+Meeting talk proposal+Meeting talk none+Election this time+Election Next time	171.1
10	Elevation+Edge+Distance Matrix +Non-working Population+Population Density+ Number of Years ono Committee+ Literacy representation +Action Taken to Stop Outsiders+Meeting Frequency+Meeting caller other+Forests useful for Environment+Gender Ratio of Committee +Non-working Proportion+No one looks after the forest+Meeting talk proposal+Meeting talk none+Election this time+Election Next time	166
12	Elevation+Edge+Temporary Watchers +Dist to Roads+Population Density+ Number of Years ono Committee+ Literacy representation +Action Taken to Stop Outsiders+Meeting Frequency+Meeting caller other+Forests useful for Environment+Gender Ratio of Committee +Non-working Proportion+No one looks after the forest+Meeting talk proposal+Meeting talk none+Election this time+Election Next time	211.6
13	Elevation+Edge+Distance Matrix +Dist to Roads+Cattle Density+ Number of Years on Committee+ Literacy representation +Action Taken to Stop Outsiders+Meeting Frequency+Meeting caller other+Forests useful for Environment+Gender Ratio of Committee +Non-working Proportion+No one looks after the forest+Meeting talk proposal+Meeting talk none+Election this time+Election Next time	170.3
14	Elevation+Edge+Distance Matrix +Dist to Roads+Population Density+ Payments Understand+ Literacy representation +Action Taken to Stop Outsiders+Meeting Frequency+Meeting caller other+Forests useful for Environment+Gender Ratio of Committee +Non-working Proportion+No one looks after the forest+Meeting talk proposal+Meeting talk none+Election this time+Election Next time	172.6
15	Elevation+Edge+Distance Matrix +Dist to Roads+Population Density+ Payments Received+ Literacy representation +Action Taken to Stop Outsiders+Meeting Frequency+Meeting caller other+Forests useful for Environment+Gender Ratio of Committee +Non-working Proportion+No one looks after the forest+Meeting talk proposal+Meeting talk none+Election this time+Election Next time	167.3
16	Elevation+Edge+Distance Matrix +Dist to Roads+Population Density+ Concern for Forest+ Literacy representation +Action Taken to Stop Outsiders+Meeting Frequency+Meeting caller other+Forests useful for Environment+Gender Ratio of Committee +Non-working Proportion+No one looks after the forest+Meeting talk	171.5

	proposal+Meeting talk none+Election this time+Election Next time	
17	Elevation+Edge+Distance Matrix +Dist to Roads+Population Density+ Number of Years ono Committee+ Mean Education +Action Taken to Stop Outsiders+Meeting Frequency+Meeting caller other+Forests useful for Environment+Gender Ratio of Committee +Non-working Proportion+No one looks after the forest+Meeting talk proposal+Meeting talk none+Election this time+Election Next time	173.2
18	Elevation+Edge+Distance Matrix +Dist to Roads+Population Density+ Number of Years ono Committee+ Literacy Rate +Action Taken to Stop Outsiders+Meeting Frequency+Meeting caller other+Forests useful for Environment+Gender Ratio of Committee +Non-working Proportion+No one looks after the forest+Meeting talk proposal+Meeting talk none+Election this time+Election Next time	167.9
19	Elevation+Edge+Distance Matrix +Dist to Roads+Population Density+ Number of Years ono Committee+ Literacy representation +Action Taken to do Nothing+Meeting Frequency+Meeting caller other+Forests useful for Environment+Gender Ratio of Committee +Non-working Proportion+No one looks after the forest+Meeting talk proposal+Meeting talk none+Election this time+Election Next time	174.4
20	Elevation+Edge+Distance Matrix +Dist to Roads+Population Density+ Number of Years ono Committee+ Literacy representation +Action Taken to Explain to Outsiders+Meeting Frequency+Meeting caller other+Forests useful for Environment+Gender Ratio of Committee +Non-working Proportion+No one looks after the forest+Meeting talk proposal+Meeting talk none+Election this time+Election Next time	174.5
21	Elevation+Edge+Distance Matrix +Dist to Roads+Population Density+ Number of Years ono Committee+ Literacy representation +Action Taken to Stop Outsiders+Meeting Caller None+Meeting caller other+Forests useful for Environment+Gender Ratio of Committee +Non-working Proportion+No one looks after the forest+Meeting talk proposal+Meeting talk none+Election this time+Election Next time	171.6
22	Elevation+Edge+Distance Matrix +Dist to Roads+Population Density+ Number of Years ono Committee+ Literacy representation +Action Taken to Stop Outsiders+Meeting Frequency+Meeting caller other+Forests useful for Environment+Gender Ratio of Committee +Traders Mentioned+No one looks after the forest+Meeting talk proposal+Meeting talk none+Election this time+Election Next time	171.5
23	Precipitation +Distance Matrix +Dist to Roads+Available Forest+Literacy Rate+Action Taken to Stop Outsiders+Meeting Frequency+Forests useful for Environment+Gender Ratio of Committee +Non-working Proportion+No one looks after the forest+Meeting talk proposal+Meeting talk none+Election this time+Election Next time	155.5
24	Distance Matrix +Dist to Roads+Available Forest+Literacy	154.2

	Rate+Action Taken to Stop Outsiders+Meeting Frequency+Forests useful for Environment+Gender Ratio of Committee +Non-working Proportion+No one looks after the forest+Meeting talk proposal+Meeting talk none+Election this time+Election Next time	
25	Distance Matrix +Dist to Roads+Available Forest+Literacy Rate+Action Taken to Stop Outsiders+Meeting Frequency+Forests useful for Environment+Gender Ratio of Committee +Non-working Proportion+No one looks after the forest+Meeting talk proposal+Meeting talk none	151.7
26	Distance Matrix +Dist to Roads+Available Forest+Literacy Rate+Action Taken to Stop Outsiders+Meeting Frequency+Forests useful for Environment+Gender Ratio of Committee +Non-working Proportion+No one looks after the forest	149.9
27	Distance Matrix +Dist to Roads+Available Forest+Literacy Rate+Action Taken to Stop Outsiders+Meeting Frequency+Forests useful for Environment+Gender Ratio of Committee +Non-working Proportion	150.8
28	Distance Matrix +Dist to Roads+Payments Received+Literacy Rate+Action Taken to Stop Outsiders+Meeting Frequency+Forests useful for Environment+Gender Ratio of Committee +Population Density	148.4
29	Distance Matrix +Dist to Roads+Payments Received+Literacy Rate+Action Taken to Stop Outsiders+Meeting Frequency+Forests useful for Environment+Gender Ratio of Committee +Non-working Proportion	148
30	Distance Matrix +Payments Received+Literacy Rate+Action Taken to Stop Outsiders+Meeting Frequency+Forests useful for Environment+Gender Ratio of Committee +Non-working Proportion	149.2
31	Distance to Roads+Payments Received+Literacy Rate+Action Taken to Stop Outsiders+Meeting Frequency+Forests useful for Environment+Gender Ratio of Committee +Non-working Proportion	209.2
32	Distance Matrix+Distance to Roads +Literacy Rate+Action Taken to Stop Outsiders+Meeting Frequency+Forests useful for Environment+Gender Ratio of Committee +Non-working Proportion	154
33	Distance Matrix+Distance to Roads+Payments Received +Action Taken to Stop Outsiders+Meeting Frequency+Forests useful for Environment+Gender Ratio of Committee +Non-working Proportion	156.2
34	Distance Matrix+Distance to Roads+Payments Received+Literacy Rate +Meeting Frequency+Forests useful for Environment+Gender Ratio of Committee +Non-working Proportion	149.1
35	Distance Matrix+Distance to Roads+Payments Received+Literacy Rate+Action Taken to Stop Outsiders +Forests useful for Environment+Gender Ratio of Committee +Non-working Proportion	154.2
36	Distance Matrix+Distance to Roads+Payments Received+Literacy Rate+Action Taken to Stop Outsiders+Meeting Frequency+ Gender Ratio of Committee +Non-working Proportion	148.2

37	Distance Matrix+Distance to Roads+Payments Received+Literacy Rate+Action Taken to Stop Outsiders+Meeting Frequency+Forests useful for Environment +Non-working Proportion	148.5
38	Distance Matrix+Distance to Roads+Payments Received+Literacy Rate+Action Taken to Stop Outsiders+Meeting Frequency+Forests useful for Environment+Gender Ratio of Committee +Non-working Proportion	148
39	**Distance Matrix+Distance to Roads+Payments Received+Literacy Rate+Action Taken to Stop Outsiders+Meeting Frequency+Forests useful for Environment+Gender Ratio of Committee**	**144.5**
40	Distance Matrix+Distance to Roads+Payments Received+%ST+Action Taken to Stop Outsiders+Meeting Frequency+Forests useful for Environment+Gender Ratio of Committee	150.7
41	Distance Matrix+Mean Age of Committee+Payments Received+Literacy Rate+Action Taken to Stop Outsiders+Meeting Frequency+Forests useful for Environment+Gender Ratio of Committee	148.3
42	Distance Matrix+Distance to Roads+Payments Received+Literacy Rate+Action Taken to Do Nothing+Meeting Frequency+Forests useful for Environment+Gender Ratio of Committee	146.5
43	Distance Matrix+Distance to Roads+Payments Received+Literacy Rate+Action Taken to Explain to Outsiders+Meeting Frequency+Forests useful for Environment+Gender Ratio of Committee	146.4
44	Distance Matrix+Distance to Roads+Slope+Literacy Rate+Action Taken to Stop Outsiders+Meeting Frequency+Forests useful for Environment+Gender Ratio of Committee	152.5
45	Distance Matrix+Distance to Roads+Edge+Literacy Rate+Action Taken to Stop Outsiders+Meeting Frequency+Forests useful for Environment+Gender Ratio of Committee	152.4
46	Distance Matrix+Distance to Roads+Available Forest+Literacy Rate+Action Taken to Stop Outsiders+Meeting Frequency+Forests useful for Environment+Gender Ratio of Committee	147.2
47	Distance Matrix+Distance to Roads+FRP+Literacy Rate+Action Taken to Stop Outsiders+Meeting Frequency+Forests useful for Environment+Gender Ratio of Committee	153.1
48	Distance Matrix+Distance to Roads+Payments Understand+Literacy Rate+Action Taken to Stop Outsiders+Meeting Frequency+Forests useful for Environment+Gender Ratio of Committee	152.9
49	Distance Matrix+Distance to Roads+Temporary Watchers+Literacy Rate+Action Taken to Stop Outsiders+Meeting Frequency+Forests useful for Environment+Gender Ratio of Committee	152.5
50	Distance Matrix+Distance to Roads+Total Population Density+Literacy Rate+Action Taken to Stop Outsiders+Meeting	152.8

	Frequency+Forests useful for Environment+Gender Ratio of Committee	
51	Distance Matrix+Distance to Roads+Non-working Proportion+Literacy Rate+Action Taken to Stop Outsiders+Meeting Frequency+Forests useful for Environment+Gender Ratio of Committee	152.1

Order of Importance of Variables (In decreasing rank): Distance Matrix, Literacy Rate, Meeting Frequency, Distance to Roads, Payments Received, Gender Ratio, Forest Use Environment, Action Taken to Stop Outsiders

CHAPTER 5

Conclusions and Synthesis

5.1 Conclusions

Although the chapters in this dissertation deal with two separate themes: community governance and forest degradation, they are united by a need for understanding the impact of human activities on forests at different scales. It is important to understand both when designing and implementing large-scale conservation projects, especially as they occur simultaneously and are rarely studied as such. This is especially important in South Asia, where there are competing demands for forests from wildlife, local people, government agencies and local people, and where analysis is further complicated by simultaneous enactment of conservationist agenda such as wildlife conservation, utilitarian agenda such as forest management for timber, and agendas for social justice and equity such as decentralization of forest resources to local communities. Practical limitations to such studies include difficulty in obtaining accurate on-ground data for studies that need large sample sizes and an inability to quantify changes in forests besides deforestation. This is particularly important in India, where forest conversion is largely outlawed, and forests are tightly managed and controlled. To address these questions comprehensively, I used a multi-site large sample size approach, incorporating analyses of satellite imagery, ecological field-work, political ecology, and collection of fine resolution, large scale datasets.

In Chapter 2, I examined the impact of human action on forests at a local scale and found that human use had already altered the biomass, understory, tree density and canopy cover, and that regeneration of certain species within the forest were impacted, which could alter the long-term species composition of the forest. Therefore, this study establishes that, at a local scale, in addition to static changes in the forest such as structure and biomass, human activities also alter long-term future of forests. In previous studies examining the impact of harvest and forest use for sustainable forestry, studies are restricted to a few species that are known for their commercial value (Schmidt, 2011). This study highlights the importance of extending analysis to other forest species, as their frequencies may be changing, thus altering long-term forest composition and the ability of forests to support local livelihoods as well as other ecosystem services.

Results from this chapter are particularly relevant for other forests such as the dry tropical forests in Asia and Africa, which are a highly threatened ecosystem due to high human population densities and continuous use (Miles et al., 2006). Further, while many studies focus on impacts of industrial use or industrial-scale conversion (Olander, 2008; Rudel et al., 2009; Houghton, 2012), this study focuses on impacts of subsistence use and finds that the patterns and impacts in subsistence-use tropical forests may differ widely from other types of forests (such as Ahrends et al., 2010; Young et al., 1994).

This chapter further unearths some important processes that may lead to lack of sustainability in these forests, and highlights some impacts that may be measurable in other forests similar to the study area. For instance, livestock density may be a more important driver of degradation in these forests than human use for fuel-wood, construction and commerce, as cattle can prevent species from acquiring reproductive age (as they do in this region). Further, it demonstrates increasing survival of species that are able to grow in human-modified forests, and establishes the importance of analyzing long-term impact on forest composition (Schmidt, 2011).

In Chapter 3, I aimed to quantify forest degradation and use it to understand landscape drivers of forest degradation in Central India. For this, I tested the ability of different sensors in quantifying forest biomass, and was able to quantify forest biomass with acceptable accuracy in tropical deciduous forests. ALOS-PALSAR (FBD) -based HV scatter was best able to quantify forest biomass, followed by Landsat-based spectral fractions, whose predictive ability was ~10% lower and still acceptable. However, MODIS-based EVI, which might be logistically easiest for continuous monitoring, had low accuracy and may not be able to quantify changes in forest biomass. These results suggest that ALOS-PALSAR may be the most appropriate sensor for quantifying change in forest components in the study region. In the absence of such data, Landsat can provide useful results with publicly-available data.

This chapter also identified factors associated with loss in forest biomass and found that fires, population densities and distance to town were associated with loss in forest biomass. The importance of population densities underscores that local pressures, and not only market demand, may drive change in forests. However, contrary to studies examining drivers of deforestation (Young et al., 1994; Ahrends et al., 2010) but similar to studies examining fires (Uriarte et al., 2012), this study identified that forests that are located away from towns are vulnerable to forest degradation.

The study recommends that managers should develop remote sensing capabilities, including use of ALOS-PALSAR, to continuously monitor changes in forest biomass at an appropriate temporal resolution as this will help them identify vulnerable forests and focus on them. Results indicate that it is especially important for managers to focus on vulnerable forests that are located away from towns as these are repositories of biodiversity and contain essential products to meet local needs. Although, the results focus on a particular study region, the methods and conclusions are more broadly applicable to dry tropical forests throughout the world.

In Chapter 4, I used the findings of Chapter 2 and 3, and added an interview-based political ecology component, to understand the impact of economic payments on participation in forest governance, and to understand how participation and representation in community governance is associated with forest degradation. The study found that economic payments were associated with significant increases in awareness of Joint Forest Management, its attendant responsibilities to protect the forest, but not with action taken to protect the forest. Yet, action taken to exclude outsiders was associated with positive change in forest canopy. Therefore payments alone are not sufficient for communities to participate but other mechanisms need to be investigated.

Positive change in canopy is also associated with less representative forest committees, that may aid forest conservation as individuals accrete institutional capital and become better at excluding others (Ostrom, 1990). While the common property literature suggests that the way to overcome the problem of individuals valuing short-term individual gains over long-term community gains is to through greater representation and greater say in the functioning of forest governance (Ostrom, 1990), less representative governance and elite capture of resources are often the norm but are not always detrimental to forests (although not ideal for local populations). A major contribution of this study was to provide a quantitative example for results that had been observed in qualitative field studies that found that elite capture of forests often had a positive impact on forests (Jodha, 2008; Skutsch et al., 2008), thus validating and strengthening the claims of these studies.

Overall, the chapter assessed the role of economic incentives, participation and community homogeneity in promoting resource conservation. As support for community resource management continues to increase (Bowler et al., 2012), the chapter emphasizes the role of institutional variables in engendering forest conservation, and identifies that payments alone cannot motivate community action.

5.2. Limitations of the Study

The work conducted in this thesis suffered from a few limitations:

I was not able to use remote sensing techniques and RADAR-based sensors to quantify certain forest components such as understory biomass and species composition. This was critical as cattle grazing was an important driver at the local scale but did not show up at larger scales, possibly due to our inability to map understory change. However, the work in Chapter 2 and 3 are part of a continuing investigation to quantify understory and species composition using RADAR. Upon completion, the results will be used for a landscape-level analysis throughout Central India, and further into the tropical dry forests in Eastern Africa, where historical processes and ecology are similar, and can be used to devise more generalizable theories across this biome.

Secondly, my use of MODIS-based fire radiative power (FRP) and fire incidence as metrics representing fire underestimated the occurrence of fires. This was evident in the number of fires detected on-site in the field but not identified by the MODIS sensor used to estimate fire frequency. This may have influenced the results of this dissertation as it potentially underestimates the role of fire in reducing forest biomass. Therefore, it is critical to devise more accurate measurements for quantifying forest fires.

Next, time limitations led to my focusing on certain temporal and spatial scales for analysis. Expanding the mandate to a wider range of temporal and spatial scales may help us better understand several observations that could not be explained. This is because both scale (both temporal and spatial) emerged as a key factor with different results emerging at different scales. For instance, fire led to forest gain over shorter periods and forest loss over longer periods, while harvest of forests by the Forest Department led to the opposite trend. Potential mechanisms behind these phenomena could include feedback loops between fire and vegetation, or interactions of long-term forest trajectories with the environment. Further research into this phenomenon would be important as managers continue to invest resource in fire management and harvests. Similarly, my results also suggest that local subsistence use has a strong impact on forests. Yet, this was for a relatively short time period with less variation in climatic variables. With changing climate, such static conditions cannot be expected over longer time frames. Therefore, it would be important to understand impact on forests when subsistence use is coupled with the changing climate.

Finally, there were certain limitations associated with using Joint Forest Management (JFM) to understand community governance because JFM did not delegate all decision-making power to the community. Further, the JFM in the study area was top-down, influenced by ICDPs (Integrated Conservation Development Projects), and initiated to aid in forest protection and not community empowerment. Therefore, the incentives of communities may not have aligned with those theoretically expected for community governance. However, these limitations are widespread in areas where such schemes were initiated and may provide critical information on such programs as they exist today.

5.3. Contributions of multiple disciplines on this study

The thesis combined the ideas, methods, and analyses from three different disciplines: ecology, remote sensing and political ecology. Whereas political ecology deals with spatial scale through chains of explanation, whereby researchers begin with analyzing a system at its smallest scale of a village or community and then scale up and out towards global processes (Vayda and Walters, 1999; Robbins, 1998), remote sensing is able to examine a much larger area with fine resolution (DeFries, 2008) but its understanding of underlying processes is naturally weaker. Similarly, ecology provides detailed understanding of species behavior and interactions, but it is still limited by scales at which they can make meaningful ecological observations (Urban, 2005). However, most processes, whether political, ecological or related to land use change occur at different scales, with different processes often being significant drivers at each scale. For example, a study in the interior Columbia Basin, USA, found that biophysical explanations for change were significant at finer scales while socio-economic factors were significant at a coarser scale (Black et al., 2003). Therefore, a comprehensive understanding of forest degradation and governance necessarily requires the use of these different disciplines.

Some studies have already used the scales of observation possible in one discipline to inform other disciples. The impact of wild boars on forest regeneration in

Indonesia could only be observed at the larger spatial scales possible through remote sensing (Curran et al., 1999). Conservation planning efforts also increasingly rely on spatial data of land cover and vegetation derived from remotely sensed data sets (Bergen et al., 2009), and it is expected that further improvements in resolution of the new sensors will more closely mimic ecological observations. At the other end, the community level unit of field work in political ecology, and the resulting difficulty in replicating observations, may be mitigated by remote sensing observations. For instance, Robbins (2003) used satellite images to find that the same forests were considered degradation by local communities and afforestation by the Forest Department. Similarly, this study was able to combine remote sensing and political ecology to generate a much larger sample size, and thus use hypothesis testing to establish trends in forest governance that previous researchers had only found qualitatively.

The issue of scale is also relevant in the temporal dimension. Political ecology, particularly environmental history, has informed us of the long term land use and land cover at different sites and shown that many sites have been managed over a long time period, and some of these have also been produced by human use (Neumann; Heckenberger et al., 2007). Limited historical availability of satellite imagery, has led researchers to recommend that historical data on land management be used to reconstruct spatially explicit data on land cover change (DeFries, 2008). Political ecology's emphasis on deep history, and questioning of what is natural, has also led ecology to pay more attention to deep history. Paleontological and historical records have established the dynamic nature of ecosystems, and have helped conservation biologists decide what is natural and assess the impact of recent human activities on this natural state (Willis and

Birks, 2006). This has also led to a greater emphasis on ecosystem resilience instead of ecosystem stasis (Folke et al., 2004), and has shed light on many human practices previously considered degrading. For example, long term remote sensing data in the Sahel was used to show that desertification in the Sahel was climate induced (Tucker et al., 1985) and not due to human practices such as overgrazing (Anyamba and Tucker, 2005), although these results have been contested. Both political ecology and conservation biology have been helped by the synoptic views and repeated observations available through remote sensing (DeFries, 2008; Ustin and Gamon, 2010). This study capitalized on this by using remote sensing to establish baseline resource quantity and quality with which change could be compared. As remote sensing can fail to establish detailed on ground processes and mechanisms, my ecological field-work strengthened the claims made by my remote sensing results by establishing that local human use does, in fact, reduce biomass and alter forest composition and structure, and impact long-term forest composition.

Data from each of these disciplines can also bolster research in the other fields. Conservation biology's claim that protected areas are able to prevent deforestation is supported by remote sensing data (DeFries et al., 2005; Oliviera et al., 2007). Political ecology's claim that communities are able to conserve resources is given credence through a similar absence of land cover change in areas managed by them (Nepstad et al., 2006). Changes in land cover documented by remote sensing are explained by cause-to-change drivers (Turner et al., 1994) provided by ecology and political processes, such as conversion to oil palm plantations and pasture (Rudel et al., 2009) and land abandonment (Rudel et al., 2005). Also, despite the acrimony between conservation biology and political ecology (Ehrlich and Ehrlich, 1996), researchers in the two disciplines have learnt several lessons from each other. Political ecology has re-initiated its earlier practice of using ecological concepts and biophysical parameters (Forsyth, 2003; Biersack and Greenberg, 2006). Conservation biology has learnt to acknowledge the needs and agency of local communities (West et al., 2006), that globalization may drive biodiversity depletion (Rudel et al., 2009), and that externally produced concepts may result in hostility to local conservation (West et al., 2006). Conservation-as-development projects have also been informed by the inequalities within communities and the differences in local understandings of biodiversity and conservation (West et al., 2006). This study, too, was able to establish local subsistence use and reluctance to stop outsiders as impediments to forest conservation in the study area, thus providing critical information to researchers, policy makers and managers.

In combining ideas from these three disciplines to inform the questions addressed in my thesis and provide me with the tools to answer them, I was able to establish that local human use impacts forest degradation, but not all of the changes can be seen using remote sensing. Where remote sensing can quantify changes in forest degradation (through quantifying biomass), I established that local communities are not able to manage resources unless they take specific action against outsiders. I was also able to quantitatively establish that elite capture of resources is associated with positive changes in the resource, a finding that small sample size case-studies that used political ecology and field ecology were unable to establish due to their sample size.

5.4. Implications for Management

The study identified fire as a key driver of degradation in the landscape. At a local scale, it led to changes in forest composition due to increased growth rate of fire-resistant species in comparison with other species. At the landscape scale, it was associated with loss of forest biomass, particularly at a distance from towns. Because the Forest Department invests heavily in fire management, the implications of the impacts of fire on landscape need further investigation. For instance, it is debatable whether the change in forests due to fire should be labelled as degradation, as historical studies suggest that the landscape was formed by fire, either through swidden agriculture, or through a natural fire regime.

The thesis also identified cattle as important in altering forest composition at the local scale, as species more resistant to cattle grazing and trampling are likely to increase in the future. The impact of cattle at the landscape scale could not be investigated due to our (as yet) inability to map understory accurately, the class size at which cattle impact forests. This would be an important driver to examine in the future.

Despite local impacts on forests due to fire and cattle grazing, at a landscape scale, forests that are at a distance from towns and roads are more likely to be impacted. Therefore, it is not local impacts that are impacting forest degradation at the local scale, as forest use is restricted to ~2 km surrounding the villagers. Therefore, some other mechanism is impacting forests located at a distance from major towns, and managers should concentrate their efforts in these forest areas.

The thesis also provided information that could add to the debate about use of forests for wildlife and people, as it found that communities, on their own, were unable to prevent canopy loss in the forest they managed. The primary reasons for this were their reluctance to stop outsiders despite their awareness of its need. Instead, we found that forest management committees where the elite had captured the resource were more likely to do well. Management implications of this result suggests that managers need to make a stronger case for protection of the forests that the committees managed, as just providing environmental awareness is not enough. On a positive note, the study did find that there is a positive impact on forests where committees take action against outsiders. Therefore, managers should work on methods that would further motivate committees to stop outsiders from using their forest.

Overall, this study suggests that managers do well in focusing on fire prevention and spreading awareness about their schemes, but also need to focus their attention on drivers that may be previously underestimated such as cattle use of forests, forests located at a distance from towns and roads, and in making a stronger case for excluding outsiders from forests assigned to a village. Managers can also invest in remote sensing capabilities for quantifying and monitoring degradation. This would help them understand the patterns and drivers of changes in forest components, and aid in monitoring the impacts of their interventions. Additionally, managers will also be able to monitor the activities of forest management committees, which may make the committees more accountable for the forests they manage, and help them develop mechanisms and institutions that would prevent forest degradation.

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