Forest Restoration in India: Opportunities and Realities

Trisha Gopalakrishna



School of Geography and the Environment & Somerville College

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Supervised by Prof Yadvinder Malhi

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Abstract

There is an unprecedented urgency in mitigating the impacts of climate change and forest restoration is at the forefront. Global and national policy fora have championed the cause of forest restoration as a natural climate solution, culminating in the current UN Decade of Ecosystem Restoration. It has often been touted as a cost-effective and scalable panacea with the potential to deliver a variety of benefits beyond sequestration of carbon. However, the reality of this strategy is more complex, warranting careful scientific assessment targeted at informing effective policy and practice. In this thesis, I evaluate the opportunities and realities of forest restoration in India by undertaking three interlinked pieces of research.

In *Chapter 3*, I estimate where there is opportunity area for forest restoration and the resulting climate change mitigation potential in each of the 28 Indian states. A novel methodological approach, using India-specific data when possible, included field-collected points of different forest types, machine learning, spatial analyses, and national inventory data of carbon pools for different forest canopy densities. I find there is just 1.58 million hectares (Mha) opportunity area resulting in 61.3 TgC mitigation potential, with immense variation between states. Approximately half of this opportunity is in degraded, barren and scrub land. Having accounted for fine-scale variation in India's complex patterns of existing land uses and covers, these estimates are lower than India-specific estimates from global studies, suggesting that the potential of forest restoration to mitigate climate change in India has been overestimated. However, I estimate there is 14.67 Mha opportunity area for agroforestry, providing 98.1 TgC climate change mitigation potential at the pan- India scale, reflecting the importance of context-appropriate strategies such as agroforestry in countries with large smallholder agricultural footprints. Overall, the potential of forest restoration and agroforestry in India contributes minimally to India's pledge to the Paris Agreement 2015, underscoring the need for a diversified portfolio of climate change mitigation strategies.

Chapter 4 assesses the patterns of tree cover across India's savanna and forest biomes and its determinants. India's savanna biome is often forgotten and misunderstood considering its relationship to colonial land management practises and India's quest to meet its ambitious international climate pledges. Combining remotely sensed information about tree cover and climate with empirical evidence of endemic savanna plants, I revealed four distinct climatic zones of tree cover, with a clear 'no go' zone for afforestation. I then applied additional remotely sensed information about soil, fire and domestic livestock herbivory pressure to reach novel insights about the determinants of tree cover. Topography is a key regulator of tree cover, with anthropogenic activities and high herbivory pressure also limiting tree cover from reaching its maximum climatic potential. In contrast to evidence from South America, Africa and Australia, there is no clear evidence of the effect of fire disturbances on tree cover, potentially highlighting the different extent and intensities of fire regimes and historic and contemporary views on fire suppression, across South Asia. These new insights from South Asia help to fill a missing piece in the global puzzle of biome distribution. They also show the need to account for climatic, topographic and disturbance factors when planning forest restoration, moving beyond simplistic tree-planting initiatives.

Chapter 5 uses spatial prioritization methods to assess trade-offs in key environmental and social outcomes from single- and multi-objective forest restoration strategies. I focus on three outcomes- climate change mitigation, habitat creation for forest-dependent mammals and societal provision for human basic needs of energy, livelihoods, and housing construction material from naturally regenerating native forests across India. I find that multi-objective forest restoration strategies have the least trade-offs between the above environmental and societal outcomes and achieve most of the benefits of all single-objective strategies. The benefits from a multi-objective strategy were geographically distributed across India implying flexibility and options for on-the-ground implementation. Lastly, strategies focused on societal benefit or combined outcomes have the potential to deliver human basic needs to the highest fraction of socioeconomically disadvantaged people compared to forest restoration strategies aimed at climate change mitigation or biodiversity.

Overall, the thesis highlights the crucial need to consider contextual factors when planning forest restoration in India, including existing land uses and covers, distribution of human population density, natural disturbance regimes and priority areas delivering a variety of outcomes. Hence, the findings in this thesis have wider implications for other countries in the tropical biome. The novelty of this work includes (i) estimation of opportunity area and resulting climate change mitigation potential of forest restoration at the sub-jurisdiction spatial scale, crucial for informing policy and decision making; (ii) estimation of the immense potential of agroforestry as a strategic climate change mitigation action; (iii) determination of fresh insights about the factors that drive tree cover across forest and savannas; and (iv) assessment of the potential of multi-objective forest restoration strategies to deliver multiple environment and societal outcomes, for a future in which humans and nature thrive.

COVID 19 Impact Statement

Of the three and half years I have taken to complete this doctoral thesis, approximately two years of it has been under the conditions created by the COVID19 pandemic. I acknowledge that during this time I have been very lucky to have had good mental and physical health, have had good living conditions, supportive wider network of family and friends and crucially a vibrant, encouraging and helpful Ecosystem Lab to rely on. However, this does not mean that the COVID19 pandemic did not have any impacts on the development of this thesis, my productivity and motivation to complete it and my overall doctoral research journey.

The initial scope of my doctoral research included addressing three research questions (i) where and what is the climate change mitigation potential of forest restoration in India, (ii) which forest restoration techniques provide an optimum combination of multiple ecosystem services, with a focus on naturally regenerating native forests, mixed native plantations and monoculture plantations and (iii) what are the social and political barriers, specifically land tenure regimes, that constrain implementation of forest restoration schemes? Are there any opportunities for it despite identified barriers, such as removal of invasive, exotic *lantana* species that is problematic in the region? The first research question, which I completed and have included in this thesis *(Chapter 3 Research Paper 1)*, involved desk-based methodologies focused at the pan-India scale. However, the remainder two research questions included fieldwork-based methodologies in the central Indian state of Madhya Pradesh. Specifically, I had proposed to set up and monitor a plot-level experiment of different types of regeneration mentioned with data collection of key functional traits that would then be linked to ecosystem services of carbon sequestration, biodiversity metrics and water usage. For the last research question, I had proposed to include social science theory about land tenure coupled with semi structured interviews and focus groups of different stake holders such as local farmers, state forestry department and private companies. Hence, I cancelled the fieldwork component of my research in 2020 at the onset of the pandemic, and in 2021 when India became one of the worst hit countries of the world.

I changed the scope of two-thirds of this thesis to its current form because there was minimal chance of successfully completing even a tiny fraction of the required data collection, in the 3 years that I had received funding to complete this doctorate. Consequently, I made use of the weekly reading groups set up by the Ecosystems Lab, the weekly online seminars organized as part Oxford Centre for Tropical Forests and delved into the scientific and policy literature to rethink the scope of the remaining two research chapters of this thesis. I exchanged emails and had many introductory online calls with variety of practitioners and academics including fellow doctoral students, in India and different parts of the world to investigate the issues of afforestation and colonial narratives around savannas and grasslands of Asia, and the research gaps. This resulted in *Chapter 4 (Research Paper 2).*

I continued to broaden the scope of my doctoral research and decided to apply to the 2021 cohort of the Young Scientist Summer Program at the International Institute of Applied Systems Analyses' (IIASA). I was accepted into the program but due to the ongoing COVID19 restrictions in Austria I completed the short project remotely i.e. I was based in Oxford. With regular check-in calls with my supervisory team at IIASA and self-motivation and determination, I completed the preliminary research of what became *Chapter 5 (Research Paper 3)*. I am grateful to my supervisors at IIASA who welcomed me back, in person the following year of 2022, to complete the project. At IIASA, I learned the main methodology of spatial optimization as applied to the context of forest restoration and India.

Overall, I believe that I have showcased my abilities of innovation and flexibility to complete this thesis. As a result, I highlight the important issue of promoting forest restoration strategies in landscapes of forests and savannas in India, and the novel insights of different factors to be accounted in such landscapes (*Chapter 4, Research Paper 2)*. Additionally, I have used the methodology of spatial optimization that is primarily used in protected area delineation and network design, to the context of forest restoration in a first of its kind study in India (*Chapter 5, Research 3)*. For the entire doctoral research, I have built partnerships with academics and research groups in

India and those experienced working in South and Southeast Asia, as evidenced by the variety of co-authors of each of the research chapters in this thesis. Suffice to say that despite the changed scope of this thesis due to the COVID19 pandemic, I have done my best to develop this research focused on the understudied geography of India, on key issues of scientific and policy significance, using a variety of innovative desk based approaches.

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I take this opportunity to recognize those who have helped me complete this doctoral thesis and those who have contributed to this enriching journey.

Firstly, it is with great pride I acknowledge the big role that my supervisor Prof Yadvinder Malhi has played in my doctoral journey. From Yadvinder, I learned the important skill of not only being able to zoom into the minute details, but also stepping back and understanding the wider picture. Yadvinder opened many doors of opportunity within Oxford and beyond that I am very grateful for. Without his unwavering support I would not have been able to complete this thesis.

I would like to thank Dr Radhika Khosla, my college tutor at Somerville and the Oxford India Centre for Sustainable Development, for being a beacon of pragmatism and a solid sounding board throughout my studies at Oxford. I truly value the much needed reality checks that kept me grounded and going. I would also like to thank Dr Siddharth Arora from the Oxford India Centre for Sustainable Development, for lending an empathetic and kind ear from time to time and being a wholehearted champion of my work.

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When the going got tough, I was lucky enough to rely on the truly amazing Dr Susan Cook-Patton, my role model. Thank you for the US-UK online pep talk meetings! Similarly, I thank Dr Guillaume Delhaye for pushing me to get on with wrapping up this thesis in his distinct and quirky manner. Thanks to the both of them for pulling me out of the deep rabbit hole of burnout that I had fallen into towards the end of this doctorate.

This journey of completing a doctorate is often said to be a lonely one. But I had the good fortune to be surrounded by fellow doctorate students and friends Laura Picot, Tina Christmann, Carlota Segura Garcia and Huanyuan Zhang. Thank you for patiently listening to me moan and crib (it is indeed a skill), for pushing me to be the best I can be and for providing a much needed calm outlook at doing research.

Having moved to the city of Oxford in Sep 2019 and with the COVID19 pandemic following soon after in Feb 2020, I would not have survived without the good fortune of wonderful friends. Thank you to Isabela Nunez del Prado Nieto, Mrinalini Penumaka, Alex Midlen and Vinita Govindarajan for your friendship. And a shoutout to my housemates and friends at Furnace House – Hamish Burton, Gina Wren and Zoe Smallwood for creating a great atmosphere at home where I did the majority of this research. Lastly, having decided to move out of Oxford and having completed this thesis remotely, I thank my circle of friends in Exeter who made the transition easy and truly enjoyable.

Of course, I would not have been able to complete this research without the support of my family in Bangalore. Thank you to my parents and brother for letting me pursue my interests, which led me to this doctorate. And thank you to my family-in-law-to-be in Oxford for the much needed breaks and reminder of life outside academia.

Lastly, thank you to my fiancé Guy. Words cannot express my feelings for you. From challenging me to be a critical thinker to being the most compassionate and understanding being, I thank you for standing by me always.

Trisha Gopalakrishna, 20th March 2023, Exeter

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Table of Contents

Forest Restoration in India: Opportunities and Realities 1
Abstract 1
COVID 19 Impact Statement 4
Acknowledgements 7
Funding Acknowledgement 9
Main List of Figures 14
Main List of Tables 17
Chapter 1 Introduction 20
1.1 Background 20
1.1.1 Forest restoration: a silver bullet or dilemma 20
1.1.2 Forest restoration in India 22
1.2 Knowledge Gaps 23
1.3 Research Questions 26
1.4 Thesis Structure 29
1.5 References 32
Chapter 2 Literature Review 40
2.1 India - an intriguing landscape for forest restoration 40
2.1.1 Brief overview of the historic and contemporary patterns of land uses and covers 40
2.1.2 Colonial management of land 41
2.1.3 Ambition to be a world leader in sustainable development 42
2.2 Forest restoration: an opportunistic 'Natural Climate Solution' 43
2.3 Forest restoration: the reality of the 'threat of afforestation and forest expansion' 47
2.3.1 Risks of afforestation and expansion of forest cover 47
2.3.2 Knowledge gaps of the ecological drivers of forest and savanna biome distribution 49
2.4 Forest restoration: opportunities and challenges beyond carbon 50
2.4.1 Trade-offs and synergies between ecosystem services from forest restoration 51
2.4.2 Application of spatial prioritization to assess wins and losses between ecosystem services 52
2.5 Summary of research gaps addressed in the thesis 54
2.6 References 57
Chapter 3 Existing land uses constrain climate change mitigation potential of forest restoration in India 66
3.1 Abstract 68
3.2 Introduction 69
3.3 Methods 71
3.3.1 Feasible Area of Opportunity 71

3.3.2 Assessment of carbon stock 73
3.4 Results 74
3.5 Discussion 79
3.5.1 Forest Restoration Opportunity 79
3.5.2 Agroforestry Opportunity 82
3.5.3 Climate policy implications 83
3.6 Acknowledgements 85
3.7 Author's Contributions 85
3.8 Data Accessibility Statement 85
3.9 Conflict of Interest 85
3.10 References 86
3.11 Supplementary Information 90
3.11.1 Supplementary Methods 90
3.11.2 Supplementary Tables 96
3.11.3 Supplementary Figures 103
3.12 Supplementary References 112
Chapter 4 The geography and drivers of tree cover across India's forest and savanna biomes 116
4.1 Structured Abstract 117
4.2 Introduction 119
4.3 Methods 122
4.3.1 Study area delineation and sampling strategy 122
4.3.2 Selection of environmental drivers to predict percentage tree cover 122
4.3.3 Analyses of distribution of tree cover and drivers that limit tree cover from reaching its climatically determined maximum potential 123
4.4 Results 124
4.5 Discussion 133
4.5.1 Seasonality and soil texture drive savanna and forest biome distribution 133
4.5.2 Novel insights of topography and disturbances on tree cover shortfall variation 134
4.5.3 Implications for ecosystem restoration and tree planting for climate change mitigation 136
4.6 Data Availability Statement 137
4.7 References 138
4.8 Supplementary Information 145
4.8.1 Supplementary Methods 145
4.8.2 Supplementary Tables 150
4.8.3 Supplementary Figures 155
4.9 Supplementary References 160

Chapter 5 Trade-offs in nature's contributions to people from multi and single objective forest restoration strategies in India 163
5.1 Abstract 165
5.2 Introduction 166
5.3 Methods 168
5.3.1 Area suitable for naturally regenerating native forests 168
5.3.2 NCP from natural regeneration of native forests in opportune area 168
5.3.3 Systematic conservation prioritization analyses considering different strategies 170
5.3.4 Distributional equity of the material NCP delivered 171
5.4 Results 171
5.5 Discussion 177
5.5.1 The case for multi-objective forest restoration strategies to deliver NCP 177
5.5.2 NCP trade-offs from single objective forest restoration strategies 178
5.6 Acknowledgements 180
5.7 Author Contributions 180
5.8 References 181
5.9 Supplementary Information 187
5.9.1 Supplementary Methods 187
5.9.2 Supplementary Tables 191
5.9.3 Supplementary Figures 194
5.10 Supplementary References 200
Chapter 6 Synthesis and Conclusion 203
6.1 Main conclusion, significance and novelty of this thesis 203
6.1.1 Conclusion 1- "Existing land uses constrain climate change mitigation potential of forest restoration in India" 203
6.1.2 Conclusion 2- "Novel factors such as topography and disturbance regimes are to be accounted for when delineating areas where forest is not the climax ecosystem" 205
6.1.3 Conclusion 3- "Multi-objective forest restoration strategies have the least trade-offs in environmental and societal outcomes with flexibility in options for on the ground implementation and are equitable" 206
6.2 Outlook 209
6.3 Future Research Steps 210
6.3.1 Where should forests be restored in India? What is the climate change mitigation potential of forest restoration in India? 210
6.3.2 What is the distribution of tree cover across the forest and savanna biomes in India? What drivers maintain the distribution of tree cover and hence the biomes? 211
6.3.3 What are the trends in environmental and societal benefits from single and multi-objective forest restoration strategies in India? What are the spatial patterns in the delivery of

these benefits from the different strategies? What are the equity consequences on different societal groups from the different strategies? 212
6.4 Concluding remarks..... 213
6.5 References..... 214

Main List of Figures

Figure 1.1 Research questions addressed in my thesis. The process of doing forest landscape restoration can be set along the principles of the Adaptive Management Cycle with primary stages of assessment, prioritization conceptualization, design, implementation, and evaluation. Each stage has a variety of key tasks and science advancements to be addressed for successful forest restoration as elaborated in detail in Marshall et al., 2023. My thesis focuses on the science advances highlighted in the 'Assess' and 'Prioritize' stages, with the three research questions stated for the country of India (background).

Figure 3.1 Opportunity (Mha) considering all LULCs that cannot be restored, by region (indicated in Fig 3.3 and listed in Table S3.5) arranged in decreasing order of total opportunity included in the title of each plot, left to right a)-f). Central states have the highest total opportunity of 0.53 Mha and western states have the least opportunity of 0.08 Mha. Within each plot, states are arranged in decreasing order of opportunity. Chhattisgarh has the highest opportunity of 0.26 Mha overall and within the central region while Goa has the least opportunity of 0.002 Mha overall and in the western region. Delhi and Tripura have no opportunity remaining after accounting for all unrestorable LULCs. The size of each bar is the bioclimatic envelope of forest cover in that state (Mha) while the remaining colours indicate the area of different LULCs that cannot be restored and the feasible area of opportunity. National estimate of opportunity (Mha) of 1.58 Mha considering all LULCs that cannot be restored is shown in g), follows the same interpretation as the remaining figure with a different scale. See Table S3.6 for detailed estimates of opportunity for all jurisdictions.

Figure 3.2 Assessment of current LULC of feasible area of opportunity. Proportion of top 15 current LULC classes (Roy et al., 2015) accounting for 97.6% of the estimated 1.58 Mha opportune areas, where the percentage is indicated by numbers at the end of each bar. 33.2% of the opportune area was classified as degraded forests, 28.8% was classified as scrub and 8.1% was classified as barren land. Examples of visual assessment of opportunity classified in the top three LULCs is shown in Meghalaya and Madhya Pradesh (top to bottom), where the teal dot is the centroid of the opportunity pixel and/or indicated by the black square (60m side). See Fig SS3.12 for more examples of visual assessment in remaining LULCs in other jurisdictions.

Figure 3.3 Mitigation potential of forest restoration normalized by total area of each state (MgC/ha) (no agroforestry). All areas in grey are not included in the analyses. Top five states with highest mitigation potential are indicated with units TgC. The highest potential is in the central Indian states of Madhya Pradesh and Chhattisgarh, totalling 23.5 TgC cumulative. See Table S3.7 for mitigation potential estimates of all jurisdictions.

Figure 4.1 Percentage tree cover across a gradient of maximum climate water deficit (MCWD) (black dots, n=8554). Points with occurrence of endemic savanna plants from Nerleker et al., 2022 are indicated as bright orange diamonds. We delineate four vegetation zones (1) a low maximum tree cover zone beyond 1300 mm deficit (uncoloured), a core savanna zone 930-1300 mm deficit (light mustard); a mixed forest-savanna zone 580-930 mm deficit (lavender) and a predominant forest zone 0-400 mm deficit (light green). Inset images, clockwise starting top left, are examples of the landscape in the core savanna and mixed savanna forest zones- MCWD 912 mm and one observed fire, MCWD 680 mm and no fire, MCWD 887 and no fire and MCWD 1059 mm and 7 observed fires. See Fig S4.8 for geographic locations of the coloured zones and Fig S4.9 for distribution of environmental drivers across the points in the coloured zones.

Figure 4.2 Climatic maximum potential tree cover (%) is the maximum tree cover based on the mean annual precipitation (MAP) and maximum climate water deficit (MCWD) regimes, fitted with a 95th percentile smooth additive quantile regression model. The climatic maximum potential tree cover is highest in north - eastern India and the stretch of the Western Ghats along with western coast of peninsular India (a). Potential tree cover shortfall (PTCS) is a measure of the convergence/divergence of the realized tree cover from the climatic maximum potential tree cover with range 0-1, where values close to 1 indicate divergence of realized tree cover from the climatic maximum potential tree cover or there is zero realized tree cover (shades of red), and values close to 0 indicate convergence (shades of blue). Note that all areas less than 1300mm MCWD has been excluded, predominantly north - western India, as these areas have zero tree cover and are areas of caution for tree planting activities (b). Study area (coloured) was delineated by excluding built-up land, water bodies, aquaculture, mangroves, salt pans, permanent wetlands, snow and ice and all forms of agriculture (croplands, shifting agriculture, irrigated croplands) and by excluding all land area greater than 1200m in elevation from terrestrial land area of India (grey) (Fig S4.5).

Figure 4.3 Partial effect plots of physical drivers of potential tree cover shortfall (PTCS) (Fig 4.2 b)) across sampled points in the core savanna and mixed forest savanna zones (n= 3118). Each plot shows the additive contribution of the respective driver on the linear component, which is exponentiated to obtain PTCS. Within each plot, the density plot (grey) shows the distribution of the respective driver in the data considered. There was a decreasing trend of shortfall with increase in sand fraction (%) (a). There was a steady increase in shortfall in cool north easterly areas (up to Heat Load Index = 0.87) after which shortfall decreased towards warm south westerly areas (b). Shortfall was the least in valleys but increased towards flat areas (up to Topographic Position Index = 0) and decreased towards ridges (c). Note that only significant relationships are shown, and the shaded area is the 95% confidence intervals.

Figure 4.4 Partial effect plots of disturbance drivers of potential tree cover shortfall (PTCS) (Fig 4.2 b)) across sampled points in the core savanna and mixed forest savanna zones (n= 3118). Each plot shows the additive contribution of the respective driver on the linear component, which is exponentiated to obtain PTCS. Within each plot, the density plot (grey) shows the distribution of the respective driver after log transformation. There was a steady decrease in shortfall as burn frequency increased, considering the highly skewed burn frequency across the data (a). Shortfall increased with increasing human population density (b). There was no significant trend between shortfall and sheep herbivory up to 1 tonne km-2 yr-1. However, beyond this threshold there was a strong linear increase in shortfall with sheep herbivory pressure (c). Note that only significant relationships are shown, and the shaded area is the 95% confidence intervals

Figure 5.1 Nature's Contribution to People (NCP) delivered across the opportunity area: (a) climate change mitigation, (b) percentage of biodiversity targets met for forest dependent mammals considered and (c) material NCP of average societal reliance for key needs of energy, housing construction material and livelihoods. Strategies aimed at maximizing a sole NCP, provides the highest respective NCP, while the multi-objective strategy provides the next best solution, implying the least trade-off across all strategies ((a), (b), (c)). There is a linear increase in climate change mitigation potential as more opportune areas are restored (a). All biodiversity targets for potential area of habitat were met within 17% of opportune area with no additional biodiversity benefits accrued from restoration of remainder opportunity area. Within 25% of the opportune area, a multi-objective strategy resulted in ~80% targets being met, a people centric strategy resulted in ~28% targets being met and a carbon centric strategy delivered the least proportion of biodiversity targets ~16% (b). The societal reliance benefits follow a concave down increasing trend with a people centric

and a multi-objective strategy, and a concave up increasing trend with a carbon centric strategy (c). There is an artefactual effect caused by the optimization method beyond 46% of the opportunity area, indicated by the dashed line in the biodiversity centric strategy response.

Figure 5.2 Spatial patterns of trade-offs between NCP, considering all optimization scenarios for each strategy . There is strong bias in spatial patterns particularly in the Western Ghats along the western coast of India and the north-eastern region of India (indicated by the shades of blue), when choosing the carbon centric and biodiversity centric strategies (a) and (b). There is no strong spatial pattern in delivery of NCP from a people-centric strategy due to the wide distribution of societal reliance for key needs (c). Similar evidence of no spatial pattern in delivery of NCP is seen when implementing a multi-objective strategy (d). Note all areas in grey were considered when delineating the study area.

Figure 5.3 Distributional equity of the NCP considered across 20% increments of total opportunity area. Each bar represents the average material NCP of societal reliance for key needs (people). The length of the bar is the total population to whom material NCP would be delivered and the darker shaded portion of each bar is the socioeconomically disadvantaged fraction of this population. Across each increment of total opportunity area, the people-centric strategy delivers material NCP to the highest number of socioeconomically disadvantaged people with negligible differences (shades of purple). A similar pattern is found in the multi-objective strategy (shades of grey). In the carbon-centric strategy: there is a steady increase in the total population and socioeconomically disadvantaged population to whom material NCP will be delivered as the priority area is increased (shades of orange). The biodiversity centric strategy delivered material NCP to the smallest total population and socioeconomically disadvantaged population (shades of green). The material NCP delivered using the biodiversity centric strategy between 20 & 100% of the priority area remained constant due to the artefactual effects of the same area being prioritized in the 17- 46% range of total opportune area.

Figure 6.1 Synthesis of *Chapters 4,5 & 6* of this thesis highlighting the main conclusions from each chapter.

Main List of Tables

Table 1.1 Summary of knowledge gaps in the priority science advancements addressed in this thesis. Further details of the state of knowledge, gaps that need to be addressed and the context of India is elaborated in *Chapter 2 Literature Review.*

Table 3.1 Comparison of estimates of feasible area of opportunity and mitigation potential estimated in this study against India specific estimates from global studies. Our estimates of mitigation potential are cumulative carbon stocks that would naturally regenerate in the opportunity, while some of the studies included provide a rate of carbon stock accumulation, not allowing for direct comparison.

Better a cruel truth than a comfortable delusion
-*Edward Abbey*

Chapter 1 Introduction

1.1 Background

Protection of ecosystems, in their current extent and function, is insufficient to meet global conservation and societal goals: we must also restore ecosystems to remedy past degradation (Gann et al., 2019; Leclère et al., 2020). The importance of focusing on natural ecosystems as a key strategy for mitigation, adaptation, and resilience in a rapidly changing climate, has gained prominence as 'Nature based Solutions' (Chausson et al., 2020; Seddon, Sengupta, et al., 2020). Specifically, the solution of forest restoration is being touted as a silver bullet for mitigation of climate change due to its relatively low costs, multiple co-benefits including biodiversity and scalability (Bastin et al., 2019; Brancalion & Holl, 2020; Busch et al., 2019; Griscom et al., 2017). However, poorly planned forest restoration efforts, be they in science, policy or practise, can have deleterious impacts to all ecosystems and the people that depend on them (Di Sacco et al., 2021; Holl & Brancalion, 2020; Le et al., 2012; Locatelli et al., 2015; Seddon, Chausson, et al., 2020).

1.1.1 Forest restoration: a silver bullet or dilemma

There is an unprecedent need to recover degraded, damaged and destroyed ecosystems for their intrinsic values and to provide important goods and services to people (Di Sacco et al., 2021; Fischer et al., 2021; Marshall et al., 2023; Martin, 2017). Forest restoration has gained prominence as an important strategy to mitigate climate change, providing the highest mitigation out of a number of strategies focused on the potential of the natural world, needed to limit global temperature rise to 1.5°C by 2030 (Griscom et al., 2017). The case for forest restoration is further bolstered by evidence of improved biodiversity outcomes, such as improved connectivity between forest fragments for species movements (Newmark et al., 2017) and congruence of potential area for forest restoration and biodiversity hotspots (Leadley, Gonzalez, et al., 2022; Soto-Navarro et al., 2020; Strassburg et al., 2020). There are additional benefits of improved water related services including supply and quality (Filoso et al., 2017; Pires et al., 2017). Lastly, there is immense potential of forest restoration schemes to contribute to important human wellbeing and societal outcomes such as income

generation and various dimensions of livelihoods (Bradbury et al., 2021; Brancalion et al., 2022) and consequent equity aspects across different societal groups (Wells et al., 2021).

However, forest restoration is inherently a complex strategy with inevitable trade-offs and synergies, uncertainties and challenges in outcomes to different stakeholders at various stages of science, implementation and monitoring (Brancalion & Holl, 2020; Di Sacco et al., 2021; Holl & Brancalion, 2020; Marshall et al., 2023). On a broad conceptual level, it can be misused as a justification for 'business-as-usual' fossil-fuel combustion and deferment of the monumental task of rapidly decarbonizing our economy (Anderson et al., 2019; Baldocchi & Penuelas, 2019). On the science front, evidence of overestimates of the climate change mitigation potential of forest restoration, including area available has led to over ambitious policy development (Doelman & Stehfest, 2022; Lewis, Mitchard, et al., 2019). Regarding area available for forest restoration, many non-forest ecosystems, such as savannas and grasslands, are being threatened by afforestation, a forest restoration strategy of restoring forests in areas that do not support forests as the climax state (Joshi et al., 2018; Parr et al., 2014; Temperton et al., 2019; Veldman et al., 2015, 2019). Large scale plantations, another forest restoration strategy, has been proven to have reduced overall long term mitigation potential and has been proven to be detrimental to biodiversity (Fagan et al., 2020; Lewis, Wheeler, et al., 2019). Furthermore, there is increased uncertainty in the success of forest restoration schemes due to various environmental and socio-economic factors (Banin et al., 2023; Le et al., 2012). Lastly, there can be contrasting outcomes of other benefits including potential reduction in water supply (Bonnesoeur et al., 2019). From the societal perspective, there are equally complex consequences that requires careful planning and implementation. Forest restoration can result in increased inequity (Schultz et al., 2022) and marginalization of local communities, especially those reliant on agriculture related livelihoods (Erbaugh et al., 2020; Erbaugh & Oldekop, 2018; Fleischman et al., 2022).

1.1.2 Forest restoration in India

The evolution of forest restoration in India can be categorized into pre-colonial, colonial and post-colonial periods to its current metamorphosis (Roy & Fleischman, 2022). Forest restoration methods largely derived from sacred groves (Gadgil & Vartak, 1976). Subsequent rising agrarian mindset and prominence of hunting in forests (Parpia, 2018), in the pre-colonial period, then made way towards large scale afforestation for timber revenue, in the colonial times (Grove & Grove, 1996). In the post-colonial period, broadly, the involvement of forest-dependent people in forest restoration had reduced mainly due to the continued legacy of the afforestation-based industry of timber production (Roy & Fleischman, 2022). However, since then, the Joint Forest Management program under India's Forest Rights Act 2006, aims to restore degraded forests with people's participation (Macura et al., 2011).

The Green India Mission, one of eight missions launched as part of India' National Action Plan on Climate Change is the flagship policy driving forest restoration for climate change mitigation (Ravindranath & Murthy, 2010). Additionally, the Compensatory Afforestation Fund Management and Planning Authority (CAMPA), which is a mechanism for offsetting by industry, has also gained prominence in India. However, this latter financial instrument has widely been criticized for promoting monoculture plantations with 50% or more non-native species and overall has been declared to be unsuccessful (Aggrawal, 2019; Roy & Fleischman, 2022). Under the Paris Agreement 2015, India has ambitious goals as part of its Nationally Determined Contribution, which includes "Additional (cumulative) carbon sink of 2.5-3 $GtCO_2e$ by 2030" in the Land Use Land Use Change and Forestry (LULUCF) category, with the goal of increasing forest cover area from 23% to 33% of its land area, by 2030 (Singh et al., 2021; Union Environment Ministry, 2015). Also, India had pledged 21 Mha to be restored to forests by 2030, as part of the Bonn Challenge. This target was further increased to 26 Mha under the UN Convention on Combating Desertification Conference 2019, making India's pledge the most ambitious of all South Asian countries (Burnwal, Kundan, Bharat, 2020).

India is the six largest economy in the world (in terms of Gross Domestic Product) and is on track to be the third largest economy, only after the United States of America (USA) and China (Ying Shan, 2022). India also has ambitious plans for its agenda on sustainable development goals including goals for biodiversity, poverty alleviation and reducing hunger (United Nations, 2023). This makes India a compelling and strategic case for filling important knowledge gaps related to forest restoration (Singh et al., 2021).

1.2 Knowledge Gaps

Despite the prominence of forest restoration strategies especially for climate change action, there are still many knowledge gaps yet to be addressed in its science, policy, and practise. For the case of many developing countries in the tropical biome, such as India, the key science advances that need to be made for impactful policy and practise range from better understanding of the biophysical/environmental/ecological factors for successful forest restoration to the relationship between forest restoration and environmental and societal benefits (Marshall et al., 2023). In this thesis, I focus on three primary science advancements needed (Table 1.1) :- (1) where should forests be restored? (2) what are the consequences of forest restoration on non-forest ecosystems? Are there disturbance regimes that need to be managed and restored as opposed to simplistic tree-planting schemes? (3) how can forest restoration best be planned to achieve multiple objectives?

There are various global studies that provide estimates of the area suitable for forest restoration and the potential climate change mitigation (Bastin et al., 2019; Cook-Patton, Leavitt, et al., 2020; Griscom et al., 2017). Such global studies only highlight broad scale patterns with limited to no information about locally specific contexts, that is imperative for place- based informed decision making (Cook-Patton, Gopalakrishna, et al., 2020). Consequently, there is concern of overestimates of the mitigation potential from forest restoration (Doelman & Stehfest, 2022; Friedlingstein et al., 2019; Grainger et al., 2019; Skidmore et al., 2019). Secondly, there is disputed evidence of the areas delineated to be suitable for forest restoration in global studies (Bond et al., 2019; Griffith et al., 2017; Veldman et al., 2019). There is limited information about how to delineate areas for forest

restoration such that open ecosystems, which include savannas, grasslands and woodlands are not threatened by afforestation (Buisson et al., 2020; Dudley et al., 2020; Temperton et al., 2019). This issue takes centre stage when doing forest restoration in mosaic landscapes with forests and savannas, a common landscape in India. There is evidence of the drivers of tree cover across forest and savanna biomes and in Africa, South America and Australia, with limited to no information from Southern Asia (Lehmann et al., 2014; Staver et al., 2011). Lastly, there is limited information about how landscapes/regions are to be prioritized such that multiple goals of society and environment are met from forest restoration schemes (Table 1.1). Further details of the state of knowledge and research gaps that need addressing is developed in *Chapter 2 Literature Review*.

Science advancements	Knowledge gap	Brief details	Key references used to understand the knowledge gaps
Where should forests be restored?	Lack of locally specific data and knowledge, with coarse scale assumptions	Coarse scale data lacking detailed information of current land uses and covers suitable to be restored to forests. Consequently, lack of appropriate accounting of non-forest ecosystems such as agricultural and pasture lands, and open ecosystems.	Bastin et al., 2019; Basuki et al., 2022; Drever et al., 2021; Fargione et al., 2018; Griscom et al., 2017; Zeng et al., 2020
	Overestimated climate change mitigation potential	Global data about biomass stocks and/or sequestration rates have been used. This limits the use of national inventory data and other nuanced datasets such as potential forest type restored, potential stocks and sequestration rates at different canopy densities and/or different stand ages.	Bastin et al., 2019; Cook-Patton, Leavitt, et al., 2020; Griscom et al., 2017; Strassburg et al., 2020. See replies and comments to Bastin et al., 2019 and Doelman & Stehfest, 2022
What are the consequences on non-forest ecosystems? Are there disturbance regimes that need to be managed and restored as opposed to simplistic tree-planting schemes?	Inclusion of areas that do not biophysically support forest as the climax ecosystem	Limited exclusion or no exclusion of savannas and grasslands from mapping forest restoration opportunity area is a serious threat to open ecosystems, such as savannas. Hence, detailed information of biome distribution is needed.	Bastin et al., 2019; Joshi et al., 2018; Parr et al., 2014; Ratnam et al., 2011; Temperton et al., 2019; Veldman et al., 2015
	Limited knowledge of drivers that maintain tree cover and hence maintain savannas, that in turn should not be afforested	Information of drivers of tree cover and hence biome distribution of savannas and forests is vastly available in Africa, South America and Australia, with limited insights from Southeast Asia and no insights from South Asia. South Asian savannas are routinely misclassified as 'degraded forests' due to colonial management of land making these areas incorrectly key for forest restoration i.e. afforestation, thereby aggravating the issue.	Lehmann et al., 2014; Pletcher et al., 2022; Ratnam et al., 2016; Singh et al., 2022; Staal et al., 2018; Staver et al., 2011
How can forest restoration best be planned to meet multiple objectives?	Lack of information to prioritize landscapes for forest restoration to meet multiple environmental and societal outcomes	Lack of information to design forest restoration policy instruments to meet multiple outcomes. Additionally, information about which landscapes/regions/sub jurisdictions are to be prioritized to obtain maximum forest restoration impact, considering limited resources, is imperative for on-the-ground implementation activities.	Brancalion et al., 2019; Chazdon & Brancalion, 2019; Donatti et al., 2022; Jung et al., 2021; Soto-Navarro et al., 2020; Strassburg et al., 2020
	Lack of information of consequences of prioritizing a landscape for forest restoration, on different societal groups	Limited information about where in the landscape, societal needs including livelihoods, energy, housing construction are met from forest restoration. Also, there is limited knowledge about equity among different societal groups from outcomes achievable from forest restoration.	Erbaugh et al., 2020; Erbaugh & Oldekop, 2018; Fleischman et al., 2020, 2022; Schultz et al., 2022

Table 1.1 Summary of knowledge gaps in the priority science advancements addressed in this thesis. Further details of the state of knowledge, research gaps that need to be addressed and the context of India is elaborated in *Chapter 2 Literature Review*.

1.3 Research Questions

The overarching objective of this thesis is to better understand the complexities of forest restoration as a climate change mitigation strategy for informed policy and decision- making (Fig 1.1). Specifically, I address the three scientific advancements elaborated in the previous section (and detailed in *Chapter 2 Literature Review*), as applied to the country of India –

I. Where should forests be restored in India? What is the climate change mitigation potential of forest restoration in India?
II. What is the distribution of tree cover across the forest and savanna biomes in India? What drivers maintain the distribution of tree cover and hence the biomes?
III. What are the trends in environmental and societal benefits from single and multi-objective forest restoration strategies in India? What are the spatial patterns in the delivery of these benefits from the different strategies? What are the equity consequences on different societal groups from the different strategies?

I tested the following hypotheses-

Hypothesis for Research Question I: After accounting for fine scale land uses and covers that are not suitable for forest restoration, area of opportunity and resulting climate change mitigation potential in India is lower than India specific estimates from global studies.

Hypothesis for Research Question II: Firstly, there are distinct zones of low and high tree cover in areas that are savannas and forests respectively. Secondly, resource based drivers of climate and soil determine the maximum tree cover potential across India's forest and savanna biomes. Disturbance based drivers of fire limits tree cover, followed by herbivory pressure, considering India's mesic savanna system.

Hypothesis for Research Question III: Single objective forest restoration strategies will have the largest trade-offs in environmental and societal outcomes, prioritizing specific regions for action. There will be large inequities in delivery of outcomes from sole objective strategies.

In this thesis, I focus on naturally regenerating native forest types as the forest restoration technique. I define forest restoration as the strategy to increase tree cover, only in areas where forests are the climax ecosystem, considering the natural disturbance regimes that maintain a forest ecosystem. It is a strategy that delivers multiple environmental and societal outcomes.

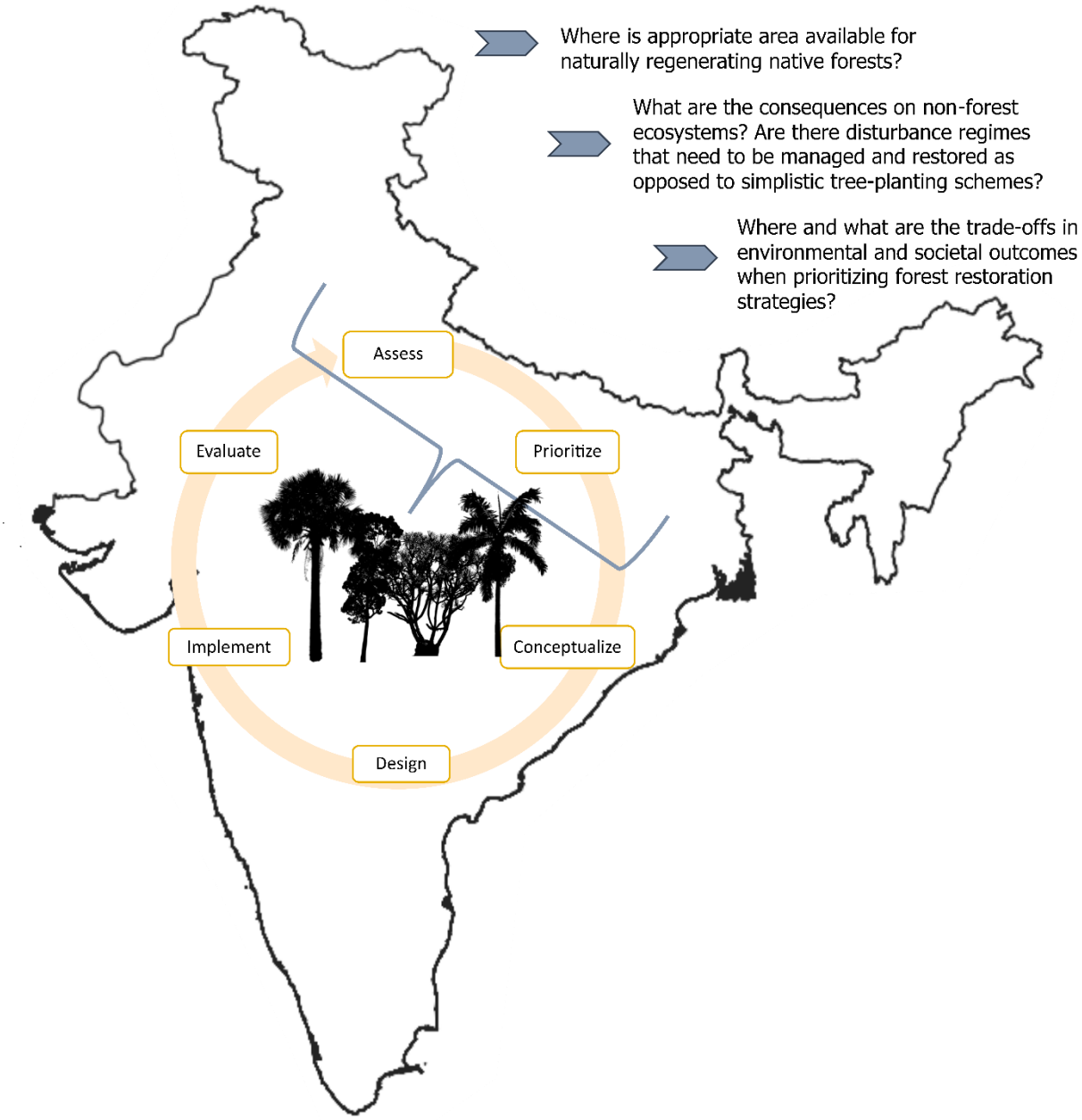


Figure 1.1 Research questions addressed in this thesis. The process of doing forest landscape restoration can be set along the principles of the Adaptive Management Cycle with primary stages of assessment, prioritization conceptualization, design, implementation, and evaluation. Each stage has a variety of key tasks and science advancements to be addressed for successful forest restoration as elaborated in detail in Marshall et al., (2023). My thesis focuses on the science advances highlighted in the 'Assess' and 'Prioritize' stages, with the three research questions stated for the country of India (background). Silhouette images are by Mason McNair (*Pandanus tectorius, Sabal causiarum, Veitchia arecina*) and T. Michael Keesey, from a photo by Bernard Dupont (*Parashorea malaanonan*). Indian map shown has not been drawn to scale and is only a nominal illustration. Refer to *Chapters 4,5 & 6* for detailed information about study area delineated. Designed by Trisha Gopalakrishna.

1.4 Thesis Structure

This thesis is presented according to the requirements for the University of Oxford's degree of Doctor of Philosophy in Geography and the Environment and follows the research article format. The thesis is comprised of six chapters.

Chapter 1 Introduction provides the background information of forest restoration as an important climate change mitigation strategy gaining momentum in global policy fora. It provides an overview of the context of forest restoration in India- origins, policies, pledges, and ambitions. It provides a summary of the knowledge gaps that are addressed. Lastly, this chapter sets the research questions and the associated hypotheses tested in the thesis.

Chapter 2 Literature Review develops the background information and elaborates on the knowledge gaps underpinning the research questions addressed in the thesis, focusing on the global and Indian contexts. The chapter includes background information about the context of India that supports this thesis. The remainder of the chapter is structured into three sections, each section focused on each of the research questions that form three separate research papers detailed in *Chapters 3, 4, and 5*.

Chapter 3 Existing land uses constrain climate change mitigation potential of forest restoration in India (Research Paper 1) evaluates the area of opportunity and the climate change mitigation potential of naturally regenerating native forests across India. The analyses includes (1) estimation of area of opportunity by first developing the biophysical envelope of native natural forests followed by sequential exclusion of land uses and covers unsuitable for restoration and (2) usage of national inventory data of carbon stocks of different native natural forest types at various canopy densities to estimate climate change mitigation potential, for each of the 28 Indian states (and six of eight Union Territories). Also, I estimate the climate change mitigation potential of agroforestry at the pan-India scale. I discuss the reduced estimates when compared to India specific estimates from global studies, having used fine scale resolution data and refined assumptions especially about the inclusion of agricultural lands. I highlight the opportunity of

agroforestry as an important climate change mitigation strategy in India. Lastly, I elaborate on the limited contribution of forest restoration as a strategy that India is aggressively pursuing to meet its ambitious international climate pledges. This research paper was published in *Conservation Letters.*

Chapter 4 The geography and drivers of tree cover across India's forest and savanna biomes (Research Paper 2) estimates the natural tree cover across India's forest and savanna biomes and its drivers, to guide appropriate implementation of forest restoration schemes. I use remote sensing based data of tree cover, resource based drivers of climate and soil and disturbance based drivers of fire and herbivory pressure together with empirical data of location of savanna understorey plants in this study. The methodology I use includes (1) delineation of zones of tree cover with distinct determinants and (2) assessment of the key resource and disturbance drivers, using a generalized additive modelling framework. I discuss that there are four distinct zones of tree cover- two in which climate clearly drives tree cover, a core savanna zone consisting of savanna plants and where climate limits maximum tree cover and a mixed forest – savanna zone with savanna plants and where tree cover is not limited by climate. I discuss how topography is a key regulator of tree cover in India, in addition to precipitation seasonality and soil sand fraction. Also, I discuss that tree cover is limited by anthropogenic activity and high herbivory pressure. Contrary to global paradigms, I elaborate on the unclear evidence of fire reducing tree cover from its maximum potential, suggestive of the effects of historic fire suppression in this highly populated and agricultural country. Lastly, I discuss 'no go' areas of afforestation based on the delineated zones and restoration strategies that need to account for additional factors that are beyond simplistic tree-planting schemes. This research paper is in review in *Global Ecology and Biogeography.*

Chapter 5 Trade-offs in nature's contributions to people from single and multi- objective forest restoration strategies in India (Research Paper 3) uses a spatial prioritization approach to estimate the trade-offs in climate change mitigation, habitat created for forest dependent

mammals and societal reliance for human basic needs of energy, livelihoods, and housing construction material from naturally regenerating native forests across India. I focus on strategies aimed at single objectives listed above, versus a multi-objective strategy that weights all objectives equally. Additionally, I estimate the distributional equity of the societal outcomes delivered to socioeconomically disadvantaged groups across India from sole and multi-objective forest restoration strategies. I discuss the main findings of this chapter – (1) multi-objective forest restoration strategies have the least trade-offs in the above outcomes (2) multi- objective strategies have no spatial patterns in delivery of above outcomes, implying flexibility and options for on-the-ground implementation and (3) multi-objective strategies deliver societal outcomes to the highest number of socioeconomically disadvantaged people, when compared to forest restoration strategies aimed at climate change mitigation or biodiversity. This research paper is being prepared to submit to peer review.

Please note that *Chapter 3,4 and 5* have been formatted according to the peer- reviewed journal that the studies have been published in or are in review currently or are being finalized for submission.

Chapter 6 Synthesis and Conclusion integrates the overall opportunities and realities addressed in the previous three chapters. I provide an outlook on the findings of this thesis. Lastly, I provide potential future research that can be done to advance the science of forest restoration and end with concluding remarks.

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Chapter 2 Literature Review

The science, policy and practice of forest restoration still lack key information about (i) where to restore forests, (ii) what environmental drivers maintain a forest and its consequences on non-forest ecosystems such as savannas and (iii) the trade-offs between environmental and societal outcomes when prioritizing areas for forest restoration. There is immense variation in information about these knowledge gaps globally, with significant gaps for the country of India.

In this chapter, I start by elaborating the Indian environmental and policy context, which provides nuanced information to support the scholarship in this thesis. The remainder of this chapter is divided into three sections, each developing the case for the three research papers in *Chapters 3, 4* and *5*. In each section, I elaborate on the state of knowledge and the research gaps that have been addressed in my thesis, focusing on the global and Indian contexts. I conclude by summarising the research gaps addressed in this thesis.

2.1 India - an intriguing landscape for forest restoration

2.1.1 Brief overview of the historic and contemporary patterns of land uses and covers

Various historians have characterized the change in India's environmental resources, especially native forests, during different periods of its history. Gadgil (1985) argued that there was an 'equilibrium' between people and nature up to 1800 A.D in India. This harmony was disrupted during the colonial period due to largescale colonial forestry, mainly for timber (Guha & Gadgil, 1989). However, post-Independence, starting in the 1960s, India's Green Revolution made food security for its growing population a primary economic objective (Yadav & Anand, 2022). Since then, agricultural land area has had the sharpest increase relative to remaining land uses and covers. The increase in extent and intensity of agriculture-related land uses and covers has

included increase in crop and pasture land (by approximately 52% according to Tian et al., 2014), agroforestry (Roy et al., 2015) and irrigated cropland (Ambika et al., 2016; Moulds et al., 2018).

The pervasiveness of agriculture, including small settlements around agricultural lands, is evidenced by noted difficulties in estimation of areas where agricultural land uses (current or former) are interspersed with forests and open ecosystems (Roy et al., 2015; Moulds et al., 2018). In addition, the evidence concerning different types of shifting agriculture practices is still limited, apart from preliminary estimates of *jhum,* a shifting agriculture practice common in northeastern India (Roy et al. 2015). Furthermore, while India's growing population has led to an approximate 300% increase in built-up area (Tian et al., 2014), rural-to-urban migration overall has been slower than expected (Kundu, 2014), with an expansion of suburban land comprising mixed smallholder agriculture and built up area. Hence, the mosaicked landscapes of mixed land uses continues to support the high reliance of Indian people on nature for basic needs (Fedele et al., 2021). Indeed, India is one of the top-ranked countries considering the proportion of population living in close proximity to a forest patch (Newton et al., 2020). Hence, it is clear that anthropogenic activities, including different forms of agriculture and urbanisation, have caused an indelible transformation of India's natural environment (Choksi et al., 2021). This intimate relationship between human land use and nature in India is a key factor in all chapters in this thesis, especially supporting the findings in *Chapter 3* (*Research Paper 1*)**.**

2.1.2 Colonial management of land

In addition to agricultural land uses and covers, land in India is formally classed as 'wastelands' and 'degraded forests'. These intriguing categories have a unique history in India, and are among the areas being most actively pursued for climate outcomes, especially for expansion of renewable energy capacity and afforestation (Madhusudan & Vanak, 2022). India, as in the majority of the Asian tropics, has strong ties between its socio-political history and its vegetation classification (Ratnam et al., 2016). During the colonial period, formal government entities imposed numerous land management practices, derived from European systems. For

example, the Indian Forest Department, operating across erstwhile Indian states, came to own a fifth of India's land area (Rangarajan, 1994) and managed it for timber production (Guha & Gadgil, 1989).

Consequently there was a tripartite classification of land: agricultural lands that were taxed, forested lands that were managed and other 'wastelands' (Balooni & Singh, 2003), with India's tropical grassy biomes falling in all three categories. First, most of India's grassland area was converted to agricultural land. Second, India's savanna landscapes, especially land area with mosaics of forest and savanna, was classified as 'degraded forests', within the forest land category overall. Lastly, the remaining grasslands and other lands were classified as 'wastelands' (Lahiri et al., 2022).

Furthermore, land management practices including suppression of natural fire regimes (Wanthongchai et al., 2011), which are necessary for maintenance of the savanna biome (Bond, 2005), have contributed to the current confused and degraded state of these lands. Consequently, this legacy and misclassification of India's savannas as 'degraded forests', or denoting a secondary successional stage of a forest biome, persisted post-independence (Kumar et al., 2020), thereby supporting the idea for the need for forest restoration in these lands (Vanak et al., 2017). Hence, this contextual information and the dominance of agriculture as a land use detailed in the previous section, explains the findings of *Chapter 4* (*Research Paper 2)***.**

2.1.3 Ambition to be a world leader in sustainable development

As I prepare this thesis, India has surpassed China to be the most populous country in the world (Silver et al., 2023), and is projected to be the third biggest economy, after China and the USA, by 2030 (Ying Shan, 2022). Nevertheless, India continues to support remarkably high biodiversity, having four biodiversity hotspots of the world (Myers et al., 2000) with 5% of its area under different forms of protection (Dinerstein et al., 2017). Post-independence, India has a strong legislative history of protecting its rich biodiversity (Ghosh-Harihar et al., 2019). Currently, India consists of 104 National Parks and 551 Wildlife Sanctuaries, with the former having the

highest protection status and the latter allowing limited human use. Additionally, India has Conservation Reserves in public land and Community Reserves on private lands (Ghosh-Harihar et al., 2019). Clearly, India's conservation challenge is different from other sparsely populated countries of the USA and Brazil.

In addition, India transitioned from championing the need for the Global North to take more responsibility for climate change action towards stepping up as a leader in international climate dialogues (Dubash et al., 2018; Lele, 2019), as explained in section *1.1.2*. However, there is a need for realignment of its domestic climate action agendas with its pledges at international climate policy arenas (Mohan & Wehnert, 2019).

In theory, post-independence India has made steady strides in formally acknowledging the role and importance of indigenous communities and local peoples in the stewardship of its natural environment through the historic passing of the Forest Rights Act 2006. For example, the Joint Forest Management programme, under the Forest Rights Act 2006, aims to decentralize governance of natural resources, though there is much left to be desired on this front (Bhattacharya Prodyut et al., 2010; Kumar et al., 2017). In this vein, the Indian environmental policy context has slowly shifted to an integrated view of linking climate change mitigation and adaptation, livelihoods, water related services, biodiversity conservation and agricultural production (Dubash et al., 2018; Lele, 2019). This integrated context echoes international climate and biodiversity policy dialogues (Donatti et al., 2022; Leadley, Archer, et al., 2022; Leadley, Gonzalez, et al., 2022). Hence, now is a critical window of opportunity to design equitable and just practises for the conservation, restoration and improved management of India's natural biomes such that multiple ecosystem benefits are delivered, while accounting for the wide variety of values underpinning human-nature interactions, as shown in *Chapter 5* (*Research Paper 3*).

2.2 Forest restoration: an opportunistic 'Natural Climate Solution'

Forest restoration as a climate change mitigation strategy is a 'Natural Climate Solution' (Griscom et al., 2017) or a 'Nature based Solution for mitigation' (UNEP & IUCN, 2021). Globally, a

seminal study by Griscom et al., (2017) estimated that 'Natural Climate Solutions' can provide one-third of the climate change mitigation needed to limit global temperatures to 1.5°C by 2030, with forest restoration, specifically reforestation, having the highest contribution of all the solutions. It was estimated that reforesting the maximum biophysical potential area of 678 million hectares (Mha) could deliver 10,124 $TgCO_2eyr^{-1}$ globally (474 Mha and 8025 $TgCO_2eyr^{-1}$ in tropical and subtropical regions). These area estimates were modified from the Atlas of Forest Landscape Restoration Opportunities (Potapov, Laestadius, Minnemeyer, 2011), such that terrestrial areas that cannot be restored to forests were excluded. The land uses and covers excluded included densely populated areas, open ecosystems, agricultural and pasture lands and wetlands (forested peatlands and mangrove forests). The additionality criteria was met by excluding all land area currently classified as forests. The carbon flux information was derived from an extensive literature review including above and belowground sequestration and soil organic carbon rates.

Soon after, Bastin et al., (2019) identified 900 Mha of reforestation area available globally (accounting for current forests and other land uses and covers that cannot be converted to natural forests) with a cumulative long-term mitigation potential of 205 PgC (752 $PgCO_2$). The interesting advancement made by this study was the usage of data of tree cover from recently undisturbed forests (i.e., protected forests globally) in a machine learning framework against a variety of edaphic, climatic and topographic variables, to map the tree cover that could be recovered. Again, the carbon stocks data were biome level information from a limited literature review of two studies.

Such global studies are valuable because they highlight the broad scale trends and patterns as a product of global environmental drivers of change. However, they lack contextual and locally specific information, with possible inaccuracies when applied at smaller scales. Furthermore, these estimates have been reported at country-level, with no additional details of the variation of forest restoration potential and area available within the country. Lastly, such global studies use

data at coarse resolutions and rely on assumptions that could over- or underestimate the potential of forest restoration. For example, by the inclusion or limited exclusion of grassland and savannas, the climate change mitigation potential of forest restoration has been overestimated in Bastin et al., (2019) (Friedlingstein et al., 2019; Grainger et al., 2019; Veldman et al., 2019). By limited exclusion of agricultural lands, there is overestimation of forest restoration potential with unintended consequences to biodiversity and food security (Skidmore et al., 2019). Lastly, carbon flux information from a literature review, can be biased to cover only certain regions, forest types, ages and canopy densities with focus on specific carbon pools, thereby over/underestimating carbon stocks that could be recovered (Grainger et al., 2019; Lewis, Mitchard et al., 2019).

Since then, as expected, there has been a slew of country- and sub-jurisdiction specific studies that have estimated the potential of forest restoration as a 'Natural Climate Solution', with advancements made to address the limitations of global studies. Fargione et al., (2018) estimated that there is 63 Mha and 307 $TgCO_2eyr^{-1}$ carbon sequestration potential from reforestation in the lower 48 states of the USA. This USA-wide estimate was further disaggregated to each of the lower 48 states, by land use and cover, and co-benefits such as biodiversity corridors that can be reforested to support sub-jurisdictional policy formulation (Cook-Patton, Gopalakrishna et al., 2020). Similarly, Drever et al., (2021) estimated that there is 3.8 Mha of opportunity available with the annual mitigation potential of 0.05 $TgCO_2eyr^{-1}$ (2030 timeline) in Canada, the least mitigation potential when compared to other Natural Climate Solutions assessed in the study, at the Canadian province spatial scale. After accounting for economic and social constraints, Zeng et al., (2020) concluded that although there is 121 Mha of degraded land available for reforestation in Southeast Asia, only 0.3-18% of it is feasible when considering on-the-ground financial, land use and operational constraints. Basuki et al. (2022) used Indonesian specific land cover data and estimated that reforestation of unproductive land (shrub, open land) could deliver up to 247 $TgCO_2eyr^{-1}$ mitigation potential across Indonesia. Lastly, Wills et al., (2023) used aboveground biomass benchmarks, to delineate areas suitable for

forest restoration in the central south-west region of Tanzania. Their primary conclusion was that maximum opportunity was in degraded moist forests in protected areas and in savanna woodlands.

Collectively, each of these studies have varying definitions of forest restoration in terms of expected recovered natural canopy cover, recovered biomass and composition of expected natural forests. These studies also consider various forest restoration techniques, including natural regeneration and active planting of native seedling stock. However, these country- and region-specific studies often refine the coarse assumptions made in global studies, such as the impact of albedo on the mitigation potential of forest restoration in temperate and boreal ecosystems (addressed in Canada by Drever et al. (2021)). Country-level studies also tend to make use of locally produced or tailored datasets rich in contextual and local information, which are often more relevant and trusted, especially for country and sub jurisdiction policy making (such as Basuki et al. (2022) in Indonesia). Lastly, there is a wide range of methodologies used in each of the studies combining ground truth data of plot measurements of forest type, canopy cover, biomass, spatial analyses including land use and cover information at various spatial scales, predictive analyses using machine learning and data from literature and social science surveys. The use of such diverse methods exemplifies the contextual information that needs to be accounted for at fine spatial scales.

At the time of conception of the research questions for my thesis, there were limited such country/region-specific studies, with no information about the area suitable and the climate change mitigation potential of forest restoration for India. Hence, this key research gap led to the development of *Chapter 3* (*Research Paper 1).* Apart from *Chapter 3*, there is only one other study that has assessed forest restoration potential at the country scale in India. The Restoration Opportunities Atlas of India, by the World Resources Institute India program, determined that there is 192 Mha of opportunity for 'wide-scale' and 'mosaic' reforestation (Chaturvedi et al., 2018). It is a novel analysis in that it identified potential canopy densities recoverable in the

opportunity areas, like Bastin et al., (2019). Also, it used refined rates of carbon sequestration of naturally regenerating forests by forest type for different carbon pools, derived from extensive national carbon inventory data published by the Forest Survey of India. However, it failed to evaluate the potential area available in degraded, waste and fallow lands, which may include genuine forest restoration opportunity as well as ancient and degraded savannas. This is a debated topic because of the continued misconception of Indian grasslands and savannas as areas suitable for forests, due to colonial era legacies of forestry operations (see sections *2.1.2*, *2.3* and *Chapter 5* (*Research Paper 2*)). Another crucial assumption made in this study is the inclusion of croplands with less than 40% canopy cover density, raising potential conflicts with food supply and agriculture dependent livelihoods in India.

2.3 Forest restoration: the reality of the 'threat of afforestation and forest expansion'

Recent years have seen increased momentum behind global policies and initiatives to sequester carbon and mitigate climate change impacts, as well as a broader interest in ecological restoration culminating in the UN Decade on Ecosystem Restoration (Dudley et al., 2020). These factors have driven interest in forest restoration and a proliferation of forest restoration targets announced by countries around the world.

2.3.1 Risks of afforestation and expansion of forest cover

The drive for ambitious forest expansion has created an underlying threat that non-forest terrestrial ecosystems or open ecosystems such as grasslands, savannas and woodlands will be converted to closed canopy forests (plantations or secondary growth natural forests), i.e., afforestation to meet ambitious climate change mitigation goals (Bond et al., 2019; Buisson et al., 2019; Temperton et al., 2019). Hence, careful scientific assessments are needed to address where *not* to restore forests, and to identify those areas where ecological and other factors are not suitable for conversion to forest. Such information could support a wider concept of ecosystem

restoration that includes native savannas requiring management of disturbance drivers that maintain tree cover across forest and non-forest systems, in addition to tree planting.

One of the main critiques of many studies that map area available for forest restoration is that savannas are not excluded properly. For example, Bastin et al., (2019) included afforestation of open ecosystems in their estimates of area available for forest restoration and climate change mitigation potential (Grainger et al., 2019; Veldman et al., 2019). Similarly, in the Restoration Opportunities Atlas of India, only the terrestrial grassland ecosystem was excluded from the area suitable for the 'wide-scale' and 'mosaic' area suitable for forest restoration, with no information or additional analyses considering India's savannas and woodlands. These inconsistencies in addressing open ecosystems have aggravated the threat of afforestation globally.

Tropical mesic savannas, such as in India, are predominantly characterised by a mix of a continuous layer of C_4 grasses and varying densities of fire-tolerant and shade-intolerant tree species, while forests lack C_4 grasses and are dominated by fire-intolerant and shade-tolerant tree species (Ratnam et al., 2011). Hence, tree cover is commonly used as a differentiating feature between forest area and savanna area, especially when using remotely sensed imagery and geospatial data, with evidence of savanna land having low tree cover and forested lands having high tree cover.

In South and Southeast Asia, tropical savannas are widely under-recognized as a distinct ecosystem and are frequently mislabelled as 'degraded forests', as previously explained (Pletcher et al., 2022; Ratnam et al., 2016). In India particularly, the many mesic savannas share physiognomies that are very similar to closed canopy forests, contrasting the grassy open landscapes that characterise African and South American savannas that are widely known. This characteristic further supports the narrative of Indian savannas being degraded forests. Furthermore, the legacy of colonial practices of managing land for timber revenue (Roy & Fleischman, 2022), have persisted to current vegetation classification maps that classify Indian open ecosystems to be degraded lands (Madhusudan & Vanak, 2022). With the target of restoring

26 Mha, by 2030, India's pledges to the Bonn Challenge are among the most ambitious among the southern Asian countries (Burnwal, Kundan, Bharat, 2020). Consequently, there is persistent threat that many of India's savanna lands ("degraded forests"), are becoming easy targets for afforestation and conversion to grid-scale solar energy farms (Madhusudan & Vanak, 2022; Vanak et al., 2017).

2.3.2 Knowledge gaps of the ecological drivers of forest and savanna biome distribution

A key challenge for delineating between tropical forest and savanna lands in India, and the majority of South and Southeast Asia, is that there is limited knowledge about the drivers of tree cover and hence biome distribution. The majority of the literature of the drivers of forest and savanna biome distribution is largely from Africa, South America and Australia (Lehmann et al., 2014; Staver et al., 2011), which is a key research gap I address in *Chapter 4* (*Research Paper 2).*

The current theory of forest and savanna biome distribution highlights the role of 'resource'-based drivers of climate and soil and 'disturbance'-based drivers of herbivory pressure and fire regimes in controlling tree cover (Sankaran et al., 2004; 2005; 2008). From the biogeographic and macroecological perspectives, at the global spatial scale and in Africa, climate, specifically rainfall and rainfall seasonality, determines maximum potential tree cover by regulating tree growth and mortality (Bucini & Hanan, 2007; Staver et al., 2011; Zeng et al., 2014). There is a clear dichotomy between water use-related physiological processes that maintain trees and those that maintain grasses, which is dependent on total precipitation (Hirota et al., 2011), seasonality (Staal et al., 2016) and interannual variability in precipitation (Holmgren et al., 2013). However, there are few such insights from the Indian subcontinent considering its intense monsoonal season.

Precipitation variables affect vegetation primarily by controlling the availability of water in soil, which in turn determines the co-existence/existence of trees and/or grasses. The differing response of trees and grasses to rainfall and soil moisture is explained by classic root niche

theory, with the root zones of trees accessing deeper soil layers versus grasses using shallow layers (Walter & Burnett, 1971). However, there is disputed evidence of overlapping root niches, primarily from African savannas (Hipondoka et al., 2003; Verweij et al., 2011). *Chapter 4 (Research Paper 2)* informs this debate considering the Indian context.

Disturbance-based drivers limit tree cover from reaching its maximum climatic potential, hence maintaining savannas (Bond, 2005; Bond, 2008; Pausas & Bond, 2020; 2022). Fires are extensive in the tropical mesic savanna biome due to high flammability and connectivity of the C_4 grassy fuel layer (Bond, 2005; Ratnam et al., 2011). Fire regulates tree growth at various stages, for example, preventing saplings from escaping the 'fire trap' (Oliveras & Malhi, 2016). Again, while the role of fire in maintaining the savanna biome is widely studied in Africa, South America and Australia (Bond et al., 2003; Lehmann et al., 2009; Van Langevelde et al., 2003; Zeng et al., 2014), there is limited evidence from regions that have a long history of fire suppression, such as India (Wanthongchai et al., 2011).

Like fire, herbivory pressure also limits tree cover, hence maintaining a savanna. Experimental evidence, primarily from Africa, shows that wild grazing increases tree cover by suppressing grasses, while browsing and wild mixed feeding reduces tree cover due to the consumption of tree saplings (Sankaran et al., 2008; Staver et al., 2021; Staver & Bond, 2014). However, there is relatively less information about the effects of domestic livestock, which are the dominant herbivores in many regions of the world, including India. Additionally, evaluation of herbivory pressure has been limited, especially in remote sensed product based studies, due to the unavailability of comprehensive spatial data on herbivory (Staver et al., 2011). Hence, I address the role of fire regimes and domestic livestock herbivory on controlling tree cover in *Chapter 4 (Research Paper 2)*.

2.4 Forest restoration: opportunities and challenges beyond carbon

There has never been a more urgent time to address the global challenges of climate change, biodiversity loss and societal needs of livelihoods and human well-being. Hence,

conservation actions including protection, restoration and improved management of ecosystems need to be designed such that multiple objectives, goals, services and benefits are delivered, at various spatial and temporal scales (Marshall et al., 2023). Indeed, there is a pressing need for 'Natural Climate Solutions' or 'Nature based Solutions for climate change mitigation' to also include additional benefits of biodiversity and human well-being (Chazdon & Brancalion, 2019; Donatti et al., 2022). Consequently, forest restoration is an inherently complex activity leading to inevitable trade-offs and synergies between targeted outcomes that vary spatially (Brancalion & Holl, 2020; Holl & Brancalion, 2020). Hence, improved information about these wins and losses in outcomes and their locations would be useful for advancing decision and policy making.

2.4.1 Trade-offs and synergies between ecosystem services from forest restoration

Evidence from experimental and simulation based studies, at various spatial scales, suggest a complex set of trade-offs and synergies between multiple benefits from forest restoration. For example, targeted forest restoration activities along biodiversity corridors can promote climate change mitigation and seasonal migration paths for movement of forest dependent birds in the Atlantic forests of Brazil (Newmark et al., 2017). Similarly, forest restoration can improve habitat connectivity for tigers, a flagship species, in Central India (Dutta et al., 2018).

However, the synergies between biodiversity and climate change mitigation and adaptation are nuanced, as these synergies are highly dependent on the type of forest restoration technique being employed. Globally, afforestation (restoring forests in areas where forest is not the climax ecosystem, for example in savannas) can lead to reduced climate change mitigation and adverse effects on savanna specific biodiversity (Bond et al., 2019; Veldman et al., 2015). Indeed, restoration of fast growing timber species in monoculture plantations does lead to high climate change mitigation in the short term, with a distinct trade-off with provision of habitat for biodiversity, and ultimately long term negative impacts on biodiversity and carbon (Lewis, Wheeler et al., 2019; Wheeler et al., 2016).

Similarly, the relationship between carbon and local benefits to people is not straightforward due to various social, cultural and institutional factors that lead to trade-offs between climate change action and people. Rule-making autonomy and land ownership are institutional factors that are related to synergies between carbon storage and livelihoods from forests (Chhatre & Agrawal, 2009). However, conversion of current agricultural lands to forests, as suggested by some modelling studies described in section *2.2,* can result in loss of livelihoods and high probability of rejection of forest restoration schemes by the local communities (Fleischman et al., 2020). Hence, it has been identified that forest landscape restoration strategies need to include social, economic and political outcomes on local communities, thereby accounting for equity and justice (Erbaugh et al., 2020; Erbaugh & Oldekop, 2018).

There are only a handful of simulation-based global scale studies that address the issue of designing forest restoration studies by accounting for the trade-offs and synergies between multiple environmental and social outcomes. For example, Brancalion et al. (2019) found key priority areas in the tropical biome, defined to be areas that have the highest return of benefits from being restored to forests. The benefits included climate change mitigation, adaptation, number of range restricted vertebrate species, and spatial variation of water security risks. This study employed a simple methodology of a spatial inventory approach, i.e., stacking of geospatial information of the various benefits, to identify the priority restoration hotspots. However, this methodology is vulnerable to biases and data gaps in the spatial information about the benefits considered and may not truly identify areas where the returns on investment are high.

2.4.2 Application of spatial prioritization to assess wins and losses between ecosystem services

Spatial optimization, also known as spatial prioritization and systematic conservation planning, is a framework that was developed to delineate areas where protection strategies could lead to maximum biodiversity gains with minimal financial costs (Kukkala & Moilanen, 2013; Moilanen et al., s2009). The underlying theory of this framework is that an objective function is

maximized or minimized considering a set of input features, decision variables and constraints (Beyer et al., 2016). Simply put, the objective function is the value that is being optimized, either by maximizing or minimizing it. The variables in the objective function that can be modified correspond to the decision variables and the constraints are applied to decision variables. For the case of forest restoration, the objective could be to maximize the area available for restoration with area wholly or partially included as the decision variable. This process considers a variety of environmental and societal outcomes as input features and targets for each outcome that need to be met as the constraints.

Recently, this framework has started to be used not only for protection strategies but also restoration and improved management (Tallis et al., 2021; Villarreal-Rosas et al., 2020). However, there are still relatively few studies that use this methodology in the context of restoration, and fewer that use it to assess trade-offs and synergies between different features spatially (Villarreal-Rosas et al., 2020).

Strassburg et al. (2020) is a key global study that used spatial optimization to identify key priority areas and the wins and losses between a variety of environmental benefits from forest restoration. The key priority areas included majority of developing countries in the tropical biome with emphasis on Southeast Asia, the western African coastal areas and the Caribbean. This study concluded that by restoring the estimated priority areas, there will be abatement of 60% of the expected biodiversity extinctions and mitigation of 30% of total emissions. There are two primary reasons for the novelty of this study. First, the study used the framework of systematic conservation planning to evaluate the trade-offs and synergies between targeted environmental outcomes. Secondly, the biodiversity metric developed in the study is the probability of species extinction rates for all mammals, birds, reptiles, amphibians and tree species, making it a comprehensive assessment of biodiversity benefits from forest restoration, that goes beyond area based biodiversity metrics. However, this study has been critiqued heavily for inadequately considering equity and justice issues associated with restoring the priority areas identified

(Fleischman et al., 2022). As priority areas identified are in developing regions of the tropical biome, it also implies that the burden and responsibility of doing forest restoration for multiple environmental and societal goals will fall on these countries/regions and not that of the relatively developed nations of temperate and boreal biomes in North America and Europe (Fleischman et al., 2022; Schultz et al., 2022).

As of now, there are limited country- or region-wide analyses that estimate the trade-offs and synergies from forest restoration particularly using spatial optimization methodologies and accounting for equity aspects. To the best of my knowledge, there is no such study that has been done in India, which is the research gap I address in *Chapter 5 (Research Paper 3).* I use the systematic conservation planning framework, underpinned by the theory and practise of spatial optimization. I assess trade-offs and synergies between two environmental outcomes of climate change mitigation potential, habitat that would be created for forest dependent mammals and one societal outcome of reliance on naturally regenerating native forests to meet human basic needs of energy, housing construction material and livelihoods. Lastly, I address the crucial critique of inequities that may arise from the design of forest restoration strategies by evaluating the proportion of people to whom the societal outcomes will be delivered to, that are classified as "socioeconomically backward" or challenged in India.

2.5 Summary of research gaps addressed in the thesis

Both the opportunities and challenges of doing forest restoration are immense. To ensure that the potential benefits of forest restoration can be realised, nuanced and locally tailored scientific knowledge will be needed (Marshall et al., 2023), as detailed in this chapter and summarised in *Table 1.1 Chapter 1*. In my thesis, I specifically focus on the following research gaps, considering the case of India:

Chapter 3 (Research Paper 1)

1) Global studies tend to overestimate the opportunity area available and the resulting climate change mitigation from naturally regenerating native forests. These overestimates are largely due to the use of coarse scale data that lack locally specific and contextual information that would benefit policy and practise at finer spatial scales.
2) Consequently, there are conceptual assumptions such as inclusion or partial exclusion of agricultural lands that might lead to tensions with food security and supply.
3) The use of data about carbon sequestration rates from literature reviews is a large source of uncertainty and lacks nuanced information such as rates for different forest types, stand ages, biomass and canopy cover densities. This aggravates the key problem of overestimation of the forest restoration as a viable climate change mitigation strategy.

Chapter 4 (Research Paper 2)

4) There are great threats of afforestation and forest cover expansion to land areas where forests are not the naturally occurring ecosystem. These non-forest ecosystems include grasslands, savannas and woodlands. However, there is limited information of the natural distribution of these biomes across India.
5) Much literature focuses on tree cover being controlled by resource-based drivers of climate and soil and disturbance-based drivers of herbivory pressure and fire. However, most of this literature focuses on savannas of Africa, South America and Australia, with limited evidence from South and Southeast Asia.
6) Relatedly, there are outstanding knowledge gaps about drivers of tree cover across forests and savannas in areas with distinct monsoonal seasonality patterns and areas where there is a long history of fire suppression, such as the case of India.

Chapter 5 (Research Paper 3)

7) Apart from Strassburg et al., (2020), there are no studies that employ the framework of systematic conservation planning to identify priority areas for forest restoration and the resulting trade-offs in environmental and social objectives considered.

8) While there is research on trade-offs and synergies between multiple environmental and societal objectives from forest restoration strategies at the scale of individual projects, there is limited evidence comparing restoration strategies at the country or regional spatial scale.

9) A major critique of Strassburg et al., (2020) was the consideration of social inequity and injustice issues, and consequences for marginalized communities, resulting from the identification of priority areas for restoration. To the best of my knowledge, there are no studies that address equity issues when assessing trade-offs between multiple objectives using the framework of systematic conservation planning.

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Chapter 3 Existing land uses constrain climate change mitigation potential of forest restoration in India

Linking Statement: I wanted to first explore where is there opportunity for forest restoration in India and the resulting climate change mitigation potential. Hence, in this chapter, I estimate the opportunity available for natural regeneration of native forests for each of the 28 Indian states (including 6/8 Union Territories). I develop the biophysical envelop of natural forests using >10000 GPS gathered points of different natural forest types across India, and sequentially exclude land uses and covers that cannot be restored to forests. Using national forest inventory data, I calculate the climate change mitigation potential as the cumulative carbon stocks that would regenerate in the opportunity area. The striking findings are that forest restoration as a climate change mitigation strategy in India has been overestimated in global studies. Instead, agroforestry is a climate change mitigation strategy with promising potential, considering India's extensive foot print of small-holder agriculture. Lastly, forest restoration and agroforestry collectively contribute to a small sliver of India's targets in its pledge to the Paris Agreement 2015, underscoring the need for India to focus on eliminating fossil fuel usage.

This chapter titled *"Existing land uses constrain climate change mitigation potential of forest restoration in India"* has been published in the peer-reviewed journal *Conservation Letters* on 18th January 2022. This study was covered by *Mongabay India- "India's climate change mitigation potential in forests overestimated, finds study"*. Also, I was invited to co-author a guest post about this research piece in *CarbonBrief -"How much could restoring forests reduce India's emission?"*.

Contribution Statement: I conducted the conceptualization, methodology development and formal analyses of this research. I investigated and visualized the results and wrote the original draft and edited many versions of the manuscript. Lastly, I responded to all reviewer comments and reviews during the peer review process. Co-authors Dr. Parth Sarthi Roy and Dr Pawan K. Joshi provided the data of the GPS gathered points of locations of different natural forest types

across India. Guy Lomax supported the methodology development and the investigation of the analyses. Dr. David Bauman and Dr. Jesús Aguirre-Gutiérrez helped in the methodology development. Prof Yadvinder Malhi provided overall supervision and was involved in all steps of analyses. All co-authors helped in edition of the manuscript drafts.

3.1 Abstract

Many countries have made ambitious pledges to increase forest areas to mitigate climate change. However, the availability of land to meet these goals is not well understood. Global studies indicate substantial potential, but do not account for local land-use and regional variation, crucial for policy making. Using India as a case study, we use a machine learning framework to define the bioclimatic envelope of forest cover and map this against current land-uses with varying suitability for restoration. We estimate the additional feasible area for restoration to be only 1.58 Mha, cumulatively sequestering 61.3 TgC, which is substantially less than estimates derived from global studies. However, we also find up to 14.67 Mha of opportunity for agroforestry in current agricultural land, delivering up to 98.1 TgC nationally. In the UN Decade of Restoration, we recommend developing forest restoration strategies that are compatible with existing land-uses such as agroforestry, especially in countries that have large smallholder agriculture holdings.

3.2 Introduction

To limit global average temperature rise to 1.5°C, annual net emissions need to be 34 $GtCO_2e$ lower than estimates accounting for current policies (United Nations, 2020). Previous research has highlighted restoration of forests as a key contribution to a net zero goal, sequestering carbon from the atmosphere (Griscom et al., 2017). Forest restoration seems to be a promising land-based option because of its relatively low costs, multiple co-benefits and scalability (Brancalion & Holl, 2020). Griscom et al. (2017) estimated a maximum biophysical potential of reforestation globally to be 678 million hectares (Mha), yielding 2.8 $PgCyr^{-1}$ in annual mitigation. Using the same area estimates, Cook-Patton et al. (2020) revised this estimate to 1.6 $PgCyr^{-1}$ of mitigation potential. Bastin et al., (2019) identified 4400 Mha of reforestation area available globally with a cumulative long-term mitigation potential of 205 PgC.

Such global studies are valuable in highlighting broad-scale patterns, driven by global scale processes, but are limited in their ability to account for locally specific information in regions or countries, which can easily deviate from global estimates. Additionally, these global estimates can overestimate true potential due to inclusion of areas that are ecologically inappropriate for forest restoration, such as natural grasslands and savannas (Veldman et al., 2019), and inclusion (or limited exclusion) of agricultural and pasture lands where forest restoration may endanger future food security (Skidmore et al., 2019). If these caveats are overcome, it could lead to better-informed decision and policy making at the national and subnational scales (Cook-Patton, Gopalakrishna, et al., 2020).

Various countries have made national and international pledges to restore forests in order to limit global rise in temperatures (FAO, 2017). India has ambitious goals as part of its Nationally Determined Contribution to the Paris Agreement, which includes “additional (cumulative) carbon sink of 2.5-3 $GtCO_2e$ by 2030” in the Land Use, Land Use Change and Forestry (LULUCF) category. To meet its international commitments, India aims to expand its forest cover area from 23% to

33% by 2030 (Pandve, 2009). However, there has been limited assessment of the feasibility of these targets and which regions are most appropriate to expand forest and tree cover area.

The only existing India-specific study estimated the opportunity for forest and tree cover restoration to be 138 Mha (Chaturvedi et al., 2018). The study employed a novel analysis that identified potential canopy densities in restorable areas. It also used information of carbon stocks of naturally regenerating forests by forest type for different carbon pools, derived from extensive national carbon inventory data. However, this study was limited in that it did not consider natural disturbances (e.g. fire) that prevent ancient open ecosystems (i.e. less dense forests, grasslands, savannah-forest mosaics) to reach their maximum potential of forest canopy density. Additionally, the analysis did not exclude croplands with less than 40% forest cover density, raising potential conflicts with food security.

In this study, we assess the potential of forest restoration to mitigate climate change by completing a spatially explicit mapping analysis of the feasible area of opportunity for forest restoration in all 28 Indian states (and six of eight Union Territories), hereby referred to as jurisdictions. We take advantage of a rich variety of India-specific datasets including a 60 m vegetation classification map, with over 100 vegetation classes, forest cover canopy densities and land uses and land covers (LULCs) (see full description of all datasets in Table S1). We expect reduced climate change mitigation opportunities mainly because of the complex regional variations in current LULCs, forest types, forest cover canopy densities and associated carbon stocks that could naturally regenerate, that are unaccounted for in global studies. Consequently, we analyse the climate change mitigation potential of agroforestry, at the national scale, here defined as systems and technologies which include woody perennials, like trees, deliberately in agricultural cropland, in some form of spatial arrangement or on a temporal sequence (Dagar et al., 2014).

3.3 Methods

We define the feasible area of opportunity to be all land area that could sustain natural forests at biophysically appropriate forest canopy densities without compromising non-forest endemic ecosystems and without endangering food security. The resulting cumulative sequestration potential of the naturally regenerating forests is the climate change mitigation potential, hereby referred to as mitigation potential. First, we estimate the bioclimatic envelope of forest cover, and then map it against existing LULCs, excluding those that are unfeasible for forest restoration resulting in the opportunity. Second, we determine the current LULC of the estimated opportunity by using published national datasets, validated by satellite imagery. Third, we estimate the mitigation potential. Lastly, we complete a national assessment of the maximum mitigation potential of agroforestry, focusing on agro-silvicultural systems (Dagar et al., 2014) (See 3.11 Supplementary Information, Table S3.2 for information about data used and Fig S3.4 for workflow outline).

3.3.1 Feasible Area of Opportunity

3.3.1.1 Mapping of bioclimatic envelope of forest

We modelled the bioclimatic envelope of forest cover as a function of 12 edaphic, climatic and topographical variables using the random forest algorithm (See 3.11 Supplementary Information and Table S3.3). We used 11,116 GPS gathered points of presences (unpublished from (Roy et al., 2015) (Fig S3.5) of different forest types in each jurisdiction. This field data was collected based on a stratified random sample design resulting in a 60m resolution map of different vegetation types across India (including different types of forests and non-forest vegetation) (Table S3.2). We extracted 22,574 pseudoabsences (PsAb) or background sites as random points from areas with no current forest cover (Barbet-Massin et al.,2012) (See 3.11 Supplementary Information, Fig S3.6 and S3.7). We used 10 random bootstrap sampled presences and PsAb (equally weighted), optimized with 700 trees and five predictors at each node using the randomForest package (Liaw & Wiener, 2002). We calculated four accuracy metrics for each bootstrap and the ensemble

model, which was used for the final prediction (See 3.11 Supplementary Information, Fig S3.9 and S3.10). Additionally, we completed 10-fold non-spatial and spatial repeated cross validation (100 reps) of the ensemble model estimating the Area Under Curve (AUC) metric, as recent research has emphasized the importance of accounting for spatial autocorrelation to control for type I error rate inflation and ensure reliable validation statistics (Ploton et al., 2020). We estimated the bioclimatic envelope by setting the presence threshold to the mean of the predicted probabilities of 0.423, that allowed us to estimate the bioclimatic envelope of forests (Fig S3.10).

3.3.1.2 Spatial exclusions of land use and covers (LULCs) to estimate of opportunity

We excluded current ice/snow land cover that cannot be restored to forests, and wetlands due to different carbon accounting methodologies. We recognize that wetlands especially, could provide considerable mitigation potential, but have dominant belowground processes which are as or more important than aboveground vegetation, the latter being the focus of this study. We also excluded all current forests to meet the additionality benchmark i.e. mitigation that will occur with no forest restoration, assuming that these areas are not converted to another LULC. Additionally, we excluded all natural grasslands and woodlands, including savannahs, to protect native and endemic ecosystems. We then sequentially excluded national highways, all agricultural lands including irrigated cropland to secure food supply, and statutory towns, census towns and villages (termed as settlements), resulting in our estimation of opportunity. We then estimated the area suitable for agroforestry within the same region as the bioclimatic envelope of forests after excluding ice/snow and wetlands, current forests, natural grasslands and woodlands and national highways, in irrigated and agricultural lands which are classified as “villages” and “uninhabited”. Opportunity classified as current *jhum* (shifting cultivation) was included in opportunity for agroforestry, to protect the livelihoods, food security and cultures of people practising *jhum*. We assumed no net change in food production from adoption of agroforestry in current cropland system. We deducted 25.31 Mha from the maximum opportunity for agroforestry (Fig S3.11) (Dagar et al., 2014), to meet the additionality benchmark (see 3.11

Supplementary Information for further details about reasons for exclusions, Table S3.2 and Fig S3.4 for more details on the datasets used and the workflow outline respectively).

3.3.1.3 Visual assessment of opportunity

We extracted the current LULC using Roy et al., (2015) for 560 random points in 28 jurisdictions (excluded Delhi and Tripura because of no opportunity). Additionally, we described the presence of forest cover and, where possible, the driver of absence of forest cover such as presence of paths and agriculture, within a 60 m square buffer around each point, using Google Earth imagery at a 1:4500 scale. We did not distinguish between natural forests, plantations (e.g. timber), shade-grown coffee and other tree-based land uses, as the imagery did not allow for this.

3.3.2 Assessment of carbon stock

In each biogeographic zone and state, we allocated the dominant forest type and forest canopy density in the opportunity and assigned the associated carbon stocks, for all pools, except for soil organic carbon, estimated from national forest inventory plots of naturally regenerating forests. Where opportunity could not clearly be assigned a dominant forest type or canopy cover density, we used a weighted average of the carbon stocks occurring in the biogeographic zone and state the opportunity was present in. Lastly, we used the mean net carbon sequestration potential of 6.68 $MgCha^{-1}$ (3.01- 8.13 $MgCha^{-1}$) over the simulated period of 30 years from Ajit et al., (2017) to calculate the additional mitigation potential of agro-silvicultural systems at the national scale (see SI for additional information and Table S3.2 for details of datasets used). We reported the additional mitigation potential from forest restoration by aggregating the jurisdictions into six regions (Table S3.5) and reported the national-level mitigation potential of agroforestry separately.

All analyses were completed in R (R Core Team, 2020).

3.4 Results

We estimated the total forest bioclimatic envelope to be 101.0 Mha. Of this area of bioclimatic envelope, we sequentially excluded current ice/snow or wetlands (0.2%), existing forests (42.7%), natural grasslands, woodlands and savannahs (1.3%), national highways (0.2%), irrigated croplands (17.1%), other agricultural lands (24.2%) and finally settlements (12.7%). We estimated 1.58 Mha of opportunity after all exclusions, nationally (1.6% of the bioclimatic envelope). We estimated 39.9 Mha of agroforestry opportunity from the bioclimatic envelope in all agricultural lands, current *jhum* and all croplands in "uninhabited" areas (Fig S3.11), of which 14.7 Mha corresponded to the additional opportunity for agroforestry. The biophysical envelope and opportunity varied widely, by region and state (Fig 3.1 and Table S3.6). Chhattisgarh and Madhya Pradesh in central India had the highest opportunity of 0.26 Mha each, while Goa in western India and Mizoram in north-eastern India had the least opportunity of 0.002 Mha each and there was no opportunity remaining in Delhi and Tripura.

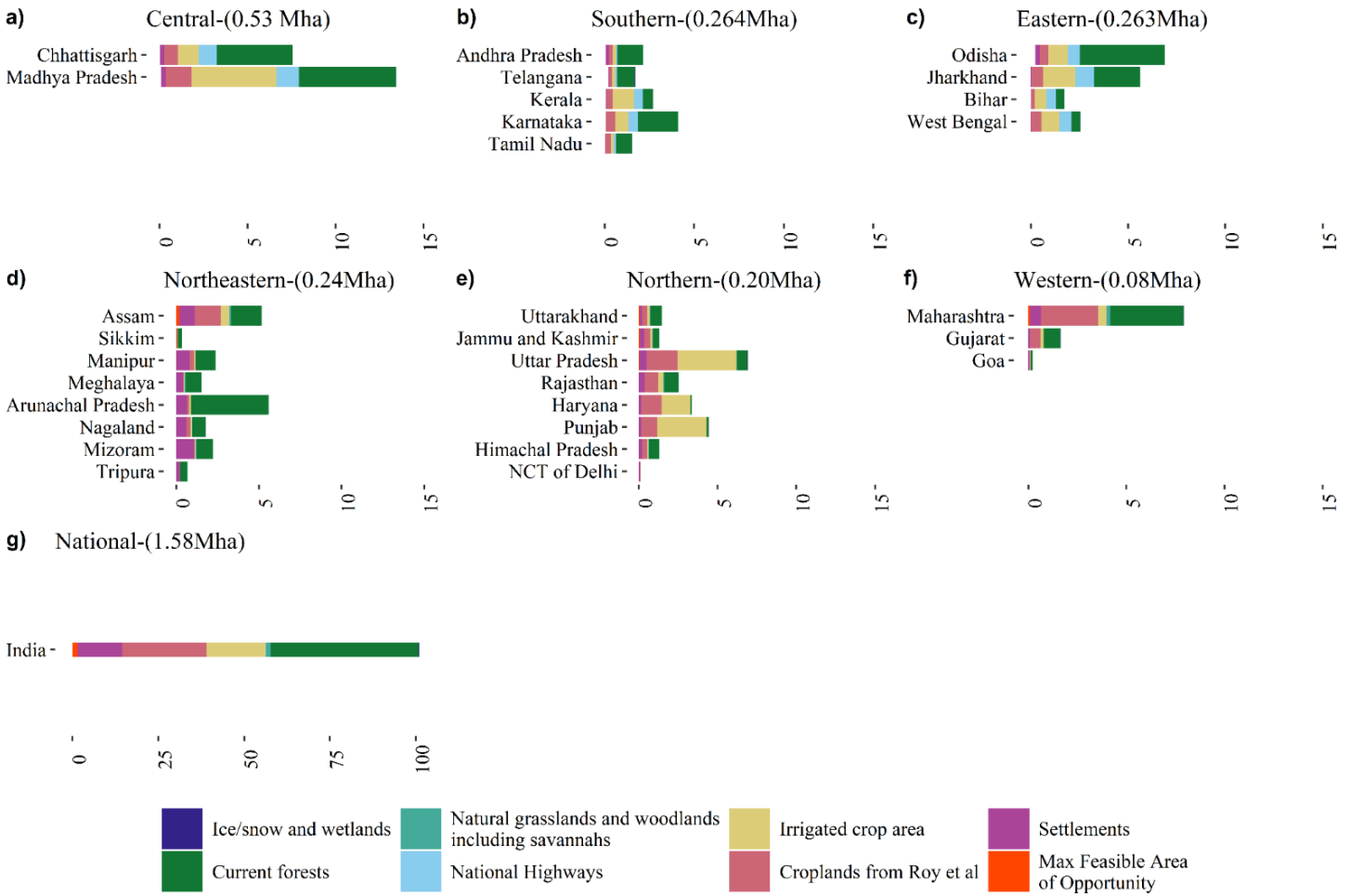


Figure 3.1 Opportunity (Mha) considering all LULCs that cannot be restored, by region (indicated in Fig 3.3 and listed in Table S3.5) arranged in decreasing order of total opportunity included in the title of each plot, left to right a)-f). Central states have the highest total opportunity of 0.53 Mha and western states have the least opportunity of 0.08 Mha. Within each plot, states are arranged in decreasing order of opportunity. Chhattisgarh has the highest opportunity of 0.26 Mha overall and within the central region while Goa has the least opportunity of 0.002 Mha overall and in the western region. Delhi and Tripura have no opportunity remaining after accounting for all unrestorable LULCs. The size of each bar is the bioclimatic envelope of forest cover in that state (Mha) while the remaining colours indicate the area of different LULCs that cannot be restored and the feasible area of opportunity. National estimate of opportunity (Mha) of 1.58 Mha considering all LULCs that cannot be restored is shown in g), follows the same interpretation as the remaining figure with a different scale. See Table S3.6 for detailed estimates of opportunity for all jurisdictions.

The dominant LULC of the opportunity of 1.58 Mha was degraded forests (33.2%) followed by scrub (28.8%). Visual inspection of opportunity showed a range of forest covers including minimal forest cover due to agriculture, forests with open canopy cover and visible bare ground, no forest cover and visible bare ground and scattered trees in small holding agriculture and settlement matrices (Fig 3.2, Fig S3.12).

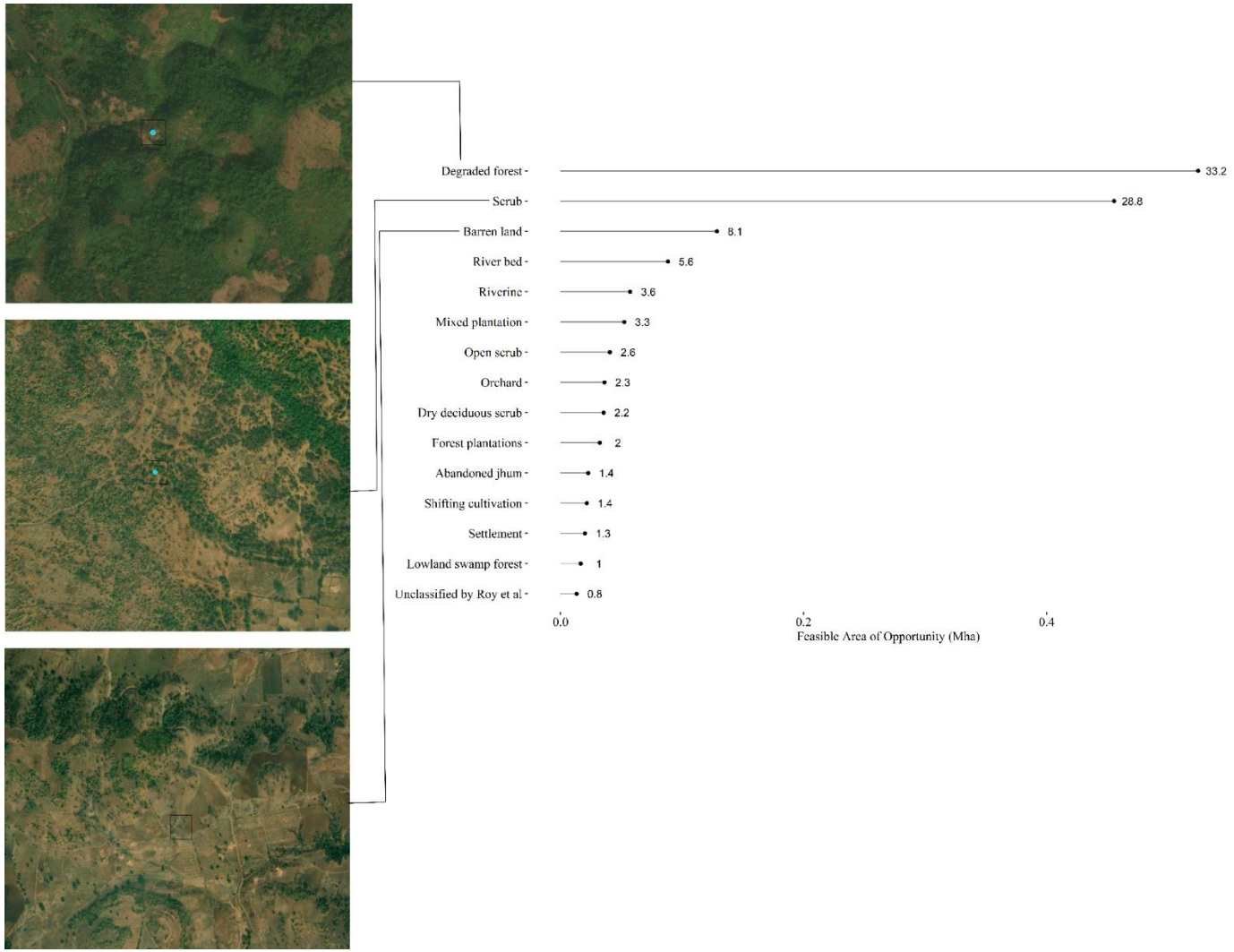


Figure 3.2 Assessment of current LULC of feasible area of opportunity. Proportion of top 15 current LULC classes (Roy et al., 2015) accounting for 97.6% of the estimated 1.58 Mha opportune areas, where the percentage is indicated by numbers at the end of each bar. 33.2% of the opportune area was classified as degraded forests, 28.8% was classified as scrub and 8.1% was classified as barren land. Examples of visual assessment of opportunity classified in the top three LULCs is shown in Meghalaya and Madhya Pradesh (top to bottom), where the teal dot is the centroid of the opportunity pixel and/or indicated by the black square (60m side). See Fig SS3.12 for more examples of visual assessment in remaining LULCs in other jurisdictions.

At the national scale, we calculated 61.3 TgC mitigation potential across 1.58 Mha with variation across states and carbon pools (Fig 3.3 and Table S3.7). The central Indian states of Madhya Pradesh and Chhattisgarh had the highest mitigation potential of 12.6 TgC and 10.9 TgC respectively. Lastly, at the national scale, we estimated the maximum additional mitigation potential from agroforestry to be 98.1 TgC (44.2-119.6 TgC) over 14.67 Mha.

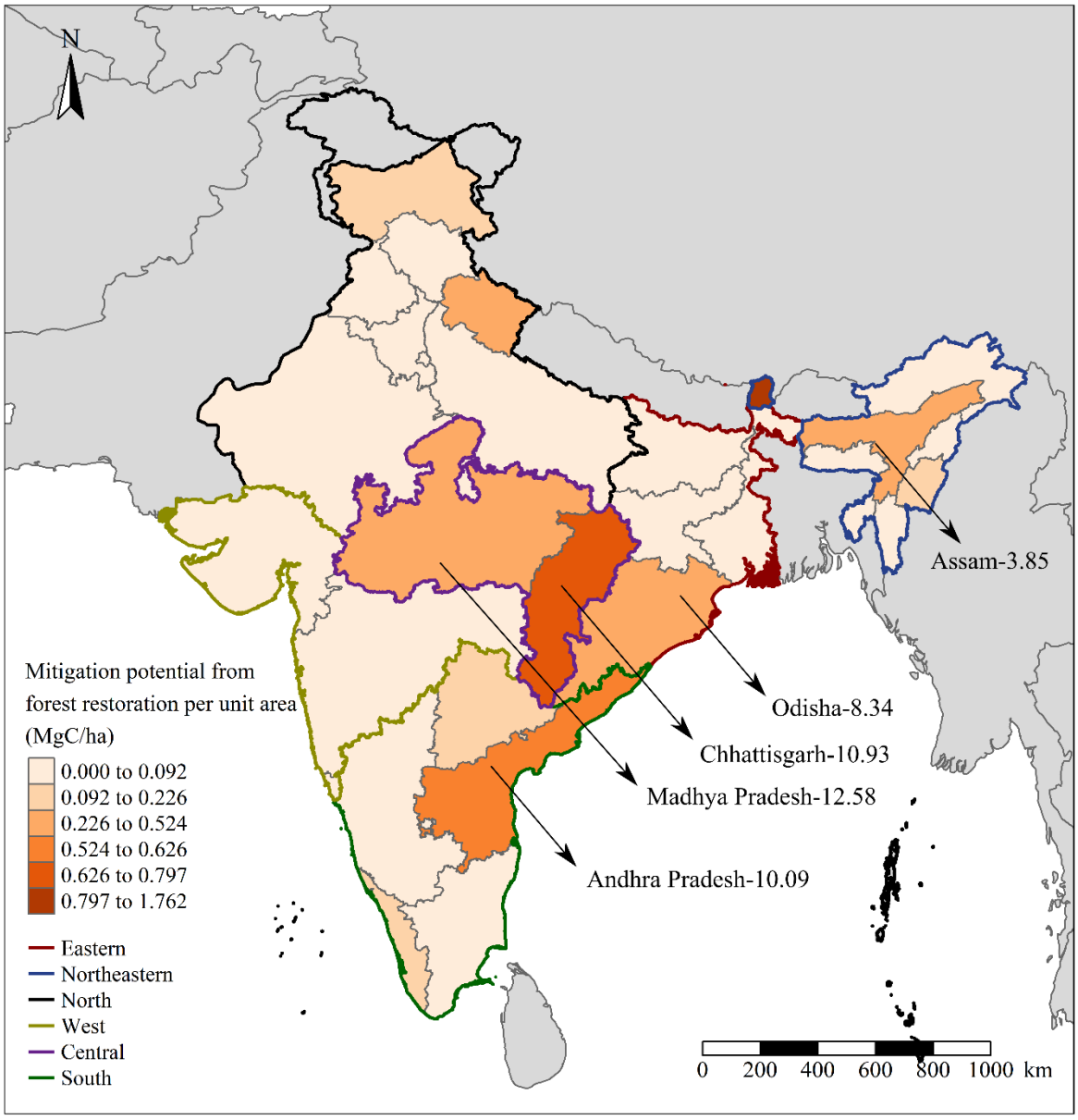


Figure 3.3 Mitigation potential of forest restoration normalized by total area of each state (MgC/ha) (no agroforestry). All areas in grey are not included in the analyses. Top five states with highest mitigation potential are indicated with units TgC. The highest potential is in the central Indian states of Madhya Pradesh and Chhattisgarh, totalling 23.5 TgC cumulative. See Table S3.7 for mitigation potential estimates of all jurisdictions.

3.5 Discussion

3.5.1 Forest Restoration Opportunity

Our estimates of opportunity and potential are substantially lower than those derived from global studies (Table 3.1). We recognize that the criteria we have used to exclude LULCs that cannot be restored are strict. For example, by completely excluding all agricultural lands and irrigated lands, we do not account for opportunity and potential in agricultural lands that are invaded by exotic species. *Lantana*, an invasive species of growing prominence, has invaded the majority of India's pasture lands (13.2 Mha) in addition to forests and fallow lands (Negi et al., 2019). Clearance of these invaded lands to allow natural regeneration could lead to mitigation without compromising food supply. However, restoring forests across the majority of the bioclimatic envelope in India would require taking current cropland out of production, with potential impacts on food supply and livelihoods.

Also, our analyses indicate that different starting points of where forests could be sustained if restored, given bioclimatic conditions, might lead to different results of opportunity. Our resulting area of the bioclimatic envelope is comparable to that of Bastin et al., (2019) showing close congruence of potential areas where natural forests can be restored in the absence of land use constraints. We recommend that future studies, about the area and location for forest restoration, thoroughly investigate the bioclimatic envelope of forests as the starting point.

We highlight the immense regional variation in opportunity and potential that remains unaccounted for in global studies, by primarily using national datasets that account for this variation in different LULCs, forest types and forest cover canopy densities. Additionally, we strictly adhere to the constraints of additionality, food security and protection of endemic and native ecosystems, accounted for to a lesser extent by other studies. The highest potential is achievable in the central Indian states, which implies that restoration could be a priority climate change mitigation strategy in areas that have undergone historical deforestation, with consistent forest conversion for agriculture and mining activities (Reddy et al., 2016). The western Indian states have the least opportunity

compounded by the least potential due to lower carbon stocks of local forest types (dominantly tropical thorn and dry deciduous forests from Reddy et al., 2015). Lastly, our results highlight that the high forest cover in the north-eastern states needs to be conserved via effective protection strategies for continued climate change mitigation and other ecosystem services including habitat for biodiversity. However, our visual assessment suggests that opportunity classified as 'degraded forests' and 'scrub' needs further investigation considering the maximum bioclimatic forest canopy cover and biomass achievable at different successional stages, natural disturbances such as herbivory and fires, and drivers of degradation (Ratnam et al., 2011).

Further fine-scale analyses could verify if forests could be sustained across the apparent bioclimatic envelope. Despite the careful selection of bioclimatic variables to develop the envelope, large uncertainty remains, especially in areas that are currently almost completely forest-free (e.g., the north-west regions of Punjab and the Gangetic plain south of Nepal which have a long history of agriculture). This could include comparisons with a historic baseline such as pre-colonial forest cover in India, since areas where forests were present provide evidence that forests could still be sustained there. Also, we assumed that the newly regenerating forests will have the same composition and characteristics as current forests, in the biogeographic zones of each state. However, future climate change will cause shifts in temperature and precipitation regimes, changing forest species community composition and dynamics (Scheiter et al., 2020), which we do not account for here. Scenario-based analyses for different climate change projections, including global vegetation models will provide more insights into the composition and dynamics of regenerating forests (Kumar & Scheiter, 2019). Lastly, future work could assess how trends in cropland area associated with rural-urban migration may affect future opportunities for forest restoration and agroforestry.

Table 3.1 Comparison of estimates of feasible area of opportunity and mitigation potential estimated in this study against India specific estimates from global studies. Our estimates of mitigation potential are cumulative carbon stocks that would naturally regenerate in the opportunity, while some of the studies included provide a rate of carbon stock accumulation, not allowing for direct comparison.

Study reference	**Estimates for India specifically from respective reference**		**Reasons for discrepancies**
	Area of Opportunity as defined in the respective reference	**Mitigation potential as defined in the respective reference**	
This study	1.58 Mha forest restoration opportunity 14.67 Mha agroforestry opportunity	61.3 TgC forest restoration potential 98.1 TgC (44.2-119.6 TgC) agroforestry potential	
Griscom et al., 2017	33.16 Mha	519 $TgCO_2eyr^{-1}$ (141.67 $TgCyr^{-1}$)	Reliance on ecoregional maps to define biophysical potential of forest systems vs our use of GPS gathered field points of forest cover to develop biophysical envelope as the starting point is one reason for our area estimates being lower. Additionally, use of various global datasets to exclude LULCs such as agricultural lands and current forests vs the use of national datasets in this study that show regional variation could explain the lower area estimates of this study. Additionally, our cumulative estimates of mitigation potential are lower than Griscom et al., 2017 as we use refined and fine resolution carbon stocks data from an extensive Indian national inventory as opposed to from the literature. Our cumulative mitigation potential is not comparable with Cook-Patton et al., 2020 as they calculate annual increase in stocks from natural regeneration. However, we highlight that Cook-Patton et al., 2020 extracted over 10000 data points from the literature, none of which are from India and used over 60 environmental predictors in the same machine learning framework as us, without accounting for spatial autocorrelation between environmental predictors.
Cook- Patton et al., 2020	33.16 Mha	106.9 $TgCyr^{-1}$	
Bastin et al., 2019	9.93 Mha	Mitigation potential estimated at biome level and hence unavailable for India specifically	Though their biophysical envelope of 98.72 Mha is close to our estimates of 101.0 Mha, they do not exclude native and endemic savannahs, grasslands and woodlands to estimate reforestation opportunity making our estimates of potential area lower.
Brancalion et al., 2019 and Strassburg et al., 2020	No estimates of area available and incomparable to our study	No estimates of mitigation potential available and	The primary goal of both studies is spatial prioritization/ optimization analyses when considering a variety of ecosystem services, and not just climate change mitigation potential, hence making the results

		incomparable to our study	incomparable with that of our study. Also, the area estimates of both studies use completely different criteria for exclusion of land uses and land cover. For example, Strassburg et al., 2019 estimates opportune areas as areas that have natural forest cover but have been converted to agricultural lands and proposes restoration of these areas back to natural forests, raising the important point of endangerment of food supply.
Busch et al., 2019	No estimates of area available and incomparable to our study	191 $MtCO_2e$ between 2020 and 2050 at $\$20/tCO_2e$	Estimates from reforestation in marginal agricultural lands, primarily based on economic analyses of opportunity costs, while in our study, we completely exclude all agricultural lands to secure food supply.
Chaturvedi et al., 2018	17.98 Mha 'protection' strategy 33.6 Mha 'wide-restoration' strategy	No estimates of mitigation potential available for comparison.	There are differences in conceptual groupings of area of opportunity. However, methodologically, Chaturvedi et al., 2018 exclude a variety of LULCs from India's total land mass as the starting point resulting in higher estimates relative to our study that uses a bioclimatic envelope as the starting point.
Chapman et al., 2020	No estimates of area available for comparison.	72.73 TgC	Our estimates of agroforestry are higher because of the use of different datasets of aboveground biomass and, crop and pasturelands (we do not distinguish pasturelands separately) and the thresholds in Chapman et al., (2020) that define additional potential gain in crop and pasturelands.
Chaturvedi et al., 2018	87.22 Mha 'mosaic-restoration' strategy	No estimates of mitigation potential available for comparison.	The relatively higher estimates of mosaic restoration strategy are due to inclusion of all croplands with less than 40% forest canopy cover, while we exclude all croplands and irrigated lands for food security.

3.5.2 Agroforestry Opportunity

The higher opportunity and potential of agroforestry relative to forest restoration emphasizes the need for a diverse portfolio of strategies to mitigate climate change (Griscom et al., 2017). Additionally, the various benefits of agroforestry including additional income source at the time of crop failure (Schroeder & Ladd, 1991), the creation of biodiversity corridors (Kremen & Merenlender, 2018), improved human health (Wolff et al., 2018) and national agroforestry policies can accelerate implementation of the agroforestry strategy.

The maximum potential of agroforestry estimated in our study, though coarse, highlights the complex reality, especially because we consider only agri-silvicultural systems. We can obtain more accurate estimates by accounting for other dominant agroforestry systems, such as silvo-pastoralism

(Chavan et al., 2015). Additionally, mitigation potential from agroforestry depends on various factors such as the tree species planted, age of trees, geometry of planting, crop type, geographic location related to climatic conditions, soil health and management practices (Ajit et al., 2017). Further understanding of the fine spatial-scale interplay of these many factors will be needed to provide more accurate estimates of the total mitigation potential of agroforestry. Our mitigation potential is conservative, since some agroforestry may also be feasible outside the bioclimatic envelope of forests. We also acknowledge that the assumption of no change in food production when using land sharing practices of agroforestry, compared to land sparing practices of converting a portion of cropland to forests is challengeable. We recommend further analyses to better characterize food production- climate change mitigation trade-offs from agroforestry. Lastly, we do not account for soil organic carbon pool, mainly due to lack of comprehensive data, which might have resulted in underestimates of potential, especially from agroforestry (Bossio et al., 2020).

3.5.3 Climate policy implications

Our estimates of 61.3 TgC from forest restoration and 98.1 TgC (44.2-119.6 TgC) from agroforestry correspond to only 19.5% to 23.4% of India's LULUCF pledge to the Paris Agreement. India's National Action Plan for Climate Change (2008) includes the Green India Mission (GIM) that aims at protecting and restoring India's forest cover in response to climate change (Ravindranath & Murthy, 2010). However, a recent assessment indicated concerns about the targets and concluded that it is grossly underfunded (MoEFCC, 2019). More importantly, the assessment pointed that afforestation, with non-native tree species such as Eucalyptus, is the main strategy being employed, which is known to adversely affect biodiversity and will lead to overall reduced mitigation (Lewis et al., 2019; MoEFCC, 2019).

Our estimates of the potential from both forest restoration and agroforestry are only 17.5% of India's total GHG emissions in the year 2018 alone (total GHG emissions including LUCF sector is 912.8 TgC; (World Resources Institute, 2021), highlighting the limited additional mitigation potential from forest restoration under current land uses. This finding underscores that forest restoration can only be only

one of many strategies fundamental to meet the goals of the Paris Agreement and that substantial greenhouse gas emission reductions will be needed by other sectors, most importantly energy (Anderson et al., 2019; Griscom et al., 2020).

Our results are consistent with other recent findings that global estimates of forest restoration tend to overestimate climate change mitigation potential in tropical countries with large agricultural holdings. Zeng et al., (2020) showed that although there is 121 Mha of degraded land available for reforestation for climate change mitigation in Southeast Asia, only 0.3-18% of it is feasible when considering on-the-ground financial, land use and operational constraints. Our finding also mirrors the results of Griscom et al., (2020) who estimate that reforestation is only a minor component of the total mitigation potential in countries with large agricultural land use footprints and other dominant non-forest ecosystems like grasslands and savannahs. Like Griscom et al., (2020), we find that integrating agroforestry in agricultural lands is likely to be an effective and alternative strategy to restoration of closed canopy forests. In this respect, our case study of India has parallels to many African countries like Chad, Sudan, Somalia, and Kenya (Griscom et al., 2020).

Moving ahead, we recommend further research to investigate not only the total area available for forest restoration and agroforestry, but also social and cultural dimensions like forest governance and land tenure issues because of historical and current land use legacies, and other factors associated with the political economy of specific forest restoration schemes. This information will be crucial for prioritization of different states and regions for implementation and monitoring activities (Le et al., 2012; Lele & Menon, 2014). This information will also help prioritize policies, enable financial resources and guide on-the-ground implementation activities in the upcoming UN Decade of Restoration.

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3.7 Author's Contributions

Conceptualization - TG; Data Acquisition - PSR, PKJ; Methodology - TG, GL, DB, JAG; Formal Analysis - TG; Investigation – TG, GL; Writing Original Draft - TG; Writing Review & Edition - TG, GL, DB, JAG, PSR, PKJ, YM ; Visualization - TG; Supervision – YM.

3.8 Data Accessibility Statement

Data of presences of different vegetation types was acquired under a Memorandum of Understanding with Dr. P.S. Roy and Dr. P.S. Joshi. Map of forest canopy cover densities was acquired under a Memorandum of Understanding with the Forest Survey of India. Remaining data is freely available and listed in Table S1. Bioclimatic envelope of forests developed in this study is available on Zenodo https://zenodo.org/record/5789318#.YbywFlmnxaQ (DOI 10.5281/zenodo.5789318).

3.9 Conflict of Interest

The authors declare no conflicting interests.

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3.11 Supplementary Information

3.11.1 Supplementary Methods

3.11.1.1 Forest Restoration Area of Opportunity

3.11.1.1.1 Mapping biophysical envelope of forests

We used the random forest algorithm to calculate a biophysical envelope of forest presence based on current forest cover. The random forest algorithm, rooted in Classification & Regression Tree (CART) analyses, is a machine learning algorithm that performs bagging or bootstrap aggregation of the data to build an ensemble of classifiers (Breiman et al., 1984). It selects a random subset of all the data to split at each node thereby reducing the correlation between the classifiers in the ensemble. It is routinely used in classifying LULC, due to its high accuracy (Thanh Noi & Kappas, 2017; Zafari et al., 2019).

Here we used the random forest algorithm to classify presence of forest as a function of various environmental variables. We map the biophysical envelope of forests at the pan-India scale including Andaman & Nicobar and Lakshadweep islands and all union territories. We do not include the disputed areas of Aksai Chin and Azad Kashmir and Gilgit- Baltistan, in the former princely state of Jammu and Kashmir in these analyses.

3.11.1.1.2 Compiling forest cover presence/pseudoabsence data

To obtain forest presence points, we filtered 15565 ground control points (unpublished Roy et al., 2015), retaining only points in all mixed forest formation (n = 9142), all gregarious forest formation (n = 1547, no points for *Abies sp*), sacred groves (locale specific) (n = 4) and degraded formation (n = 629). This gave us a total of 11322 presence points, with no points in Daman & Diu, Lakshadweep, Nagaland and Puducherry (Fig S3.5).

We sampled pseudoabsences (PsAb) randomly from the LULC categories scrub/shrub (n = 15446) , grasslands (n = 5957, excluding manmade grasslands), woodlands (n = 1212), *kans* (n = 12), riverine (n = 310), ravine (n = 38) and sholas (n = 25) which are locale specific from Roy et al., 2015,

using the *dismo* R package (Hijmans et al., 2017) (total = 23000, Fig S3.6 and Fig S3.7). Firstly, we chose this approach of developing training data because ideally, presence-absence data-driven models perform better than presence-only data driven models. Thus, presence only -models have increasingly been replaced by presence-absence data driven models, where the absence, called pseudoabsences or background sites, are artificial absence data (Elith et al., 2006). We chose twice the number of presences as pseudoabsences to allow capturing of all possible environmental information in areas where forests could be sustained as per Barbet-Massin et al., (2012). No PsAb were sampled from *Ephedra* and coffee vegetation classes, though these areas were included and there were no PsAb sampled in Chandigarh, Daman & Diu, Lakshadweep, Manipur, Mizoram, Nagaland and Puducherry.

We excluded all vegetation classes in the 'Other', 'Plantations', 'Managed Ecosystems' and *Phoenix spp*, mangrove forest and scrub, *Avicennia spp.*, *Lumnitzera spp.*, *Rhizophora spp.*, *Xylocarpus spp.*, littoral, freshwater, lowland and *Syzigium spp.* swamps, and manmade grasslands from sampling (both presence and PsAb points), so as to not train the model using the information from areas that do not and will not have/will have limited terrestrial aboveground vegetation due to the native ecological state of the system and/or management.

After extracting all environmental predictor variables for presences (Fig S3.5) and PsAb (Fig S3.7), we removed duplicate presences and PsAb (when considering the environmental predictor information), thereby retaining only one presence or one PsAb point in each 0.0089° pixel.

3.11.1.1.3 Compiling environmental predictor variables

We extracted 12 bioclimatic variables (Table S3.3) using gridded and reanalysis climate products because of (a) improved accuracy and precision of these products over interpolated products using meteorological station data (Burton et al., 2018) and (b) usage of the latest climatological standard normal period (1st January 1981 to 31 December 2010) (at the time of analyses). We used maximum climatological water deficit to approximate the severity of dry seasons,

as this has been shown to strongly determine distribution, ecophysiology, and ecosystem responses to change in climate conditions (Malhi et al., 2015; Schwartz et al., 2020; Zelazowski et al., 2011). Lastly, due to lack of accurate national spatial soil datasets, we used bulk density, coarse fragments, sand, silt and clay percentages (0-30cm depth) from the ISRIC World Soil Grids data (n = 202 data points in India) (Hengl et al., 2017).

For the biophysical envelope modelling, all environmental predictors were in WGS 1984 Coordinate Reference System (CRS) and resampled to 0.0089° using the bilinear interpolation method, using a combination of QGIS (QGIS Team, 2020) and *raster* R package (van Etten, 2012).

3.11.1.1.4 Random forest algorithm, cross validation and verification

For each of the 10 random forest models built, we calculated the mean decrease in accuracy and mean decrease in Gini index (measure of homogeneity of the final classified groups), misclassification rates, sensitivity and the Boyce index accuracy metric (for presence only data models (Hirzel et al., 2006)). Misclassification rates were calculated in the form of error rates in classifying forest presences and PsAb. Sensitivity was tested with an exact one – tailed binomial test to test the probability of a true forest presence (Fig S3.9). These tests and metrics were run and calculated using a combination of *PresenceAbsence* (Freeman & Moisen, 2008) and *ecospa*t (Di Cola et al., 2017) R packages. The average Area Under the Curve (AUC) from the 10-fold repeated spatial cross validation (CV) was 0.788 versus 0.953 for the repeated non-spatial CV (Fig S3.9), indicating a more reliable accuracy metric when accounting for spatial autocorrelation in the training data.

For each of the 10 random forest models and the ensemble model built, we calculated four threshold metrics that could be used to develop the bioclimatic envelop of forest: mean of the predicted probabilities (0.422-0.426), equal prevalence of prediction and observation (0.72-0.79), maximized *Kappa* statistic (0.70-0.76) and maximized sum of sensitivity and specificity (0.68-0.71). Despite the lowest percent correctly classified and Cohen's Kappa accuracy statistics, we used the mean of the predicted probabilities of 0.423 of the ensemble model because it has the highest sensitivity metric (Fig S3.10). This threshold was the lowest, allowing us to identify all possible

potential areas that could sustain forests, in the absence of the true areas that could sustain forests. Additionally, remaining three thresholds are recommended to be used only if the training data consists of both presences and absences, while our study only consists of presence training data. Lastly, mean of the predicted probabilities is one of the best performing threshold metrics for presence-only training data. (Cramer, 2005; Liu et al., 2005).

The classified forest presence/absence product was reprojected to WGS 1985 UTM 43N and resampled to 60 m resolution using nearest neighbour method in QGIS (QGIS Team, 2020). All union territories, except that of Jammu and Kashmir (which was treated as a state), were included as part of the state they are in (Table S3.4). We excluded Andaman & Nicobar and Lakshadweep islands from here onwards, due to lack of remaining spatial datasets.

3.11.1.2 Spatial exclusions of land and covers (LULCs) to estimate opportunity

Additional details of the different datasets used for the spatial exclusions of LULCs that cannot be restored to forests are in Table S3.2. The focus of this study is terrestrial tree related ecosystems and hence we excluded wetlands that have dominant belowground processes. Additionally, wetlands have specific hydrological habitat preferences which we did not model as part of the biophysical envelope of forests, supporting our decision to completely exclude wetlands from further analyses. For agroforestry, we estimated the bioclimatic envelope of forests in irrigated and agricultural lands, in each state followed by deducting 25.31 Mha nationally and not spatially to pass the additionality benchmark resulting in the maximum additional opportunity for agroforestry. We recognize that not all of the maximum additional opportunity will be feasible for agroforestry considering the diverse fine scale condition biophysical conditions and other socio-economic and cultural preferences associated with agroforestry.

We highlight that we excluded 43.12 Mha of current natural forests as opposed to 71 Mha as reported as the current forest area in India's State of Forests Report 2019. The reason for the discrepancy, is that forest cover in the State of Forests Report 2019 does not make distinction between the origin of tree crops i.e. natural or planted or tree species i.e. native or alien irrespective

of the predominant land use (amidst agricultural land use), while our study focuses only on naturally regenerating native forests.

3.11.1.3 Assessment of carbon stocks

To calculate potential carbon storage, we used the carbon stock (MgC/ha) by forest type (n=10) for four carbon pools – aboveground biomass (AGB), belowground biomass (BGB), dead wood and litter – published in the latest India State of Forest Report 2019. The report estimates carbon stocks for three forest cover canopy densities: open forest (10-40%), moderately dense forest (40-70%) and very dense forest (>70%), for each forest type and biogeographic zone, based on resampling of plots under the National Forest Inventory programme of the Forest Survey of India (*India State of Forest Report*, 2019) (details in Table S3.8).

We assigned 103.68 Mg C/ha AGB for all dry evergreen forest type from Mani & Parthasarathy, 2007 and assigned the mean carbon stocks for all pools of subtropical pine forest type and subalpine & dry temperate forest type to all area of opportunity that is of montane temperate forest type (Salunkhe et al., 2018). We assigned the mean carbon stocks across all canopy cover densities for the four carbon pools of montane and moist temperate forests to montane wet temperate forests, due to lack of data in Sikkim and West Bengal. All forest types other than tropical wet evergreen forests and tropical semi evergreen forests in the Eastern Deccan and Western Ghats biogeographic zones were assigned carbon stocks data from the remaining forest types. We assigned the carbon stocks of all pools of the closest biogeographic zone (by distance) in each state for any feasible area of opportunity for which we could not identify the dominant forest type (from Reddy et al. ,2015).

We used the mean net carbon sequestration potential of 6.68 MgC/ha from Ajit et al., 2017, that primarily uses a process-based carbon estimation model called CO2FIX that uses real time observed data under Indian conditions. This model can simulate carbon dynamics for single/multiple tree species simultaneously accounting for age class of trees grown in the agroforestry system under consideration.

We believe that reliable field collected data including tree species, number of trees, diameter at breast height, crops grown with area and yield information and annual growth rates of tree species collected across 12 villages in each district in 10 India states, using a random sample, makes the findings of this study robust and reusable in our study. Also, considering the parameters used in the modelling, we assume that the type of system is agro-silvicultural systems, which is the focus of our study.

We calculated the carbon sequestration potential of 6.68 MgC/ha as the mean of the net carbon sequestered, and the first and third quartiles of 3.01 MgC/ha and 8.12 MgC/ha in agroforestry systems over the simulated period of 30 years across the various districts (n=26), found in Table 6 of Ajit. et al., 2017.

3.11.2 Supplementary Tables

Table S3.2 Brief description of spatial datasets used in developing the biophysical envelope of forests, spatial exclusions of LULCs that cannot be restored to forests, area of opportunity for agroforestry, assignment of carbon stocks and estimation of mitigation potential and verification of feasible area of opportunity

Dataset Reference	**Brief description**	**Analytical step**	**Purpose in this study**
(Roy et al., 2015)	Seamless vegetation map of India with 100 vegetation classes at 60m resolution, mapped using remote sensed imagery and field samples. Primary methodology included on-screen visual interpretation and hierarchical classification scheme considering Champion and Seth 1968. 90% accuracy estimates using over 15000 ground control points for validation.	Biophysical envelope of forests, Spatial exclusions of LULCs that cannot be restored, Current LULC of feasible area of opportunity	15565 ground control points (unpublished and provided by the author) filtered for presence of forest cover used to develop biophysical envelope of forest cover. Mixed forest, gregarious forest formations and sacred groves (locale specific) vegetation classes used to exclude current forests to meet additionality benchmark. Agricultural vegetation class used to exclude agricultural lands to meet food supply security and to calculate area of opportunity for agroforestry by accounting for feasible area of opportunity in current *jhum* area. Grasslands and woodlands vegetation classes excluded to protect endemic and native non-forest ecosystems. Current LULCs of feasible area of opportunity extracted using this dataset.
(Roy et al., 2016)	Decadal land use and land cover classification across India for 1985, 1995 and 2005	Spatial exclusion of LULCs that cannot be restored	Used to exclude ice/snow that cannot be restored to forests. Used to exclude wetlands, restoration of which is not included due to different carbon accounting.
(Nayak et al., 2020)	Study of the importance of linear infrastructure development in forest fragmentation, leading to habitat and biodiversity loss and other ecosystem services.	Spatial exclusion of LULCs that cannot be restored	Used to exclude national highways that cannot be restored to forests (polyline data available at https://indiaunderconstruction.com was downloaded and converted to 60m raster in QGIS, using nearest neighbour method)
(Ambika et al., 2016)	High resolution irrigated area maps across all agroecological zones of India produced using 250m normalized difference vegetation index (NDVI) with 95% accuracy	Spatial exclusion of LULCs that cannot be restored	Used to exclude irrigated cropland for food supply security and to calculate area of opportunity for agroforestry.

(Balk et al., 2020)	Gridded estimates of Indian population (based on 2011 census) at 1km resolution with two spatial renderings- official tabulations of population and settlement types and the other base don remotely sensed measures of built-up derived from the Global Human Settlement layer	Spatial exclusion of LULCs that cannot be restored	Used to exclude statutory towns, census towns and villages as areas not likely to be restored to forests (see definition of classes in Balk et al,. 2020). Used to calculate area of opportunity for agroforestry in all agricultural lands (including irrigated crops) classified as 'uninhabited' or 'villages'.
(Reddy et al., 2015)	Broad scale (5km spatial resolution) map of 29 LULCs including 14 forest types and 7 scrub types, that aligns with forest types defined by the Forest Survey of India.	Forest type of feasible area of opportunity, for assignment of carbon stocks	Used to identify the forest type that would naturally regenerate in the feasible area of opportunity.
(*India State of Forest Report*, 2019)	Biennial reports from the Forest Survey of India, Government of India including carbon stocks data for 5 carbon pools for 3 forest cover canopy densities in each biogeographic zone and state. Based on extensive national forest inventory plot data.	Assignment of carbon stocks	Carbon stock data used to calculate mitigation potential from forest restoration, via natural regeneration in the maximum feasible area of opportunity. Carbon stock (MgC/ha) by forest type (similar to Reddy et al., 2015) available for four carbon pools – aboveground biomass (AGB), belowground biomass (BGB), dead wood and litter for three canopy cover densities- open forest (10-40%), moderately dense forest (40-70%) and very dense forest (>70%).
Forest Canopy Cover Densities classification of different current forest types	This spatial dataset classifies current forestlands into three canopy cover densities, as described above for each forest type. This data is unpublished and was acquired by the first author from the Forest Survey of India.	Assignment of carbon stocks	Used to determine the proportion of feasible area of opportunity in each forest type, biogeographic zone and state to assign carbon stocks. Same proportions were used to assign carbon stocks to remaining feasible area of opportunity that does not have a current forest type (because it is classified as scrub, barren land and other non-forest classes)
(Rodgers, W. A., Panwar, 1988)	Study about planning a wildlife protected area network in India.	Mitigation potential	Biogeographic zones used to calculate mitigation potential.

Table S3.3 Brief description and details (source, reference, spatial and temporal resolution) of environmental predictors used

Environmental variable	Source and Reference	Description of preparation	Spatial and temporal resolution
Annual Precipitation	CHIRPS (Funk et al., 2015)	As described in (O'donnell & Ignizio, n.d.) Data processed in Google Earth Engine(Gorelick et al., 2017)	0.0089° 1981-2019
Precipitation Seasonality			
Annual temperature	ERA5 Land Reanalyses Product (Hersbach et al., 2020)		
Temperature seasonality			
Maximum Climate Water Deficit	TerraClimate (Abatzoglou et al., 2018)	As described in and R code published by (Aragão et al., 2007) using total monthly precipitation and monthly potential evapotranspiration	0.0089° 1981-2019
Elevation	SRTM (Jarvis et al. 2008)	Data extracted and processed in Google Earth Engine(Gorelick et al., 2017) at 90m resolution and resampled to 0.0089° using bilinear method	90m
Slope			
Soil texture- sand %	ISRIC World SoilGrids (0-30cm depth)(Hengl et al., 2017)	Apart from extracting these data to India and resampling to 0.0089° using bilinear method, no processing done	0.0020°
Soil texture- silt%			
Soil texture- clay%			
Bulk density			
Coarse fragments %			

Table S3.4 Details of the state to which Indian union territories were included as part of for the analyses after estimation of maximum biophysical potential of forest restoration; Andaman and Nicobar and Lakshadweep islands have been excluded from the analyses at

Chandigarh	Punjab
Dadra and Nagar Haveli and Daman and Diu	Gujarat
Puducherry	Tamil Nadu

Table S3.5 List of regions and states assigned to each of the regions

Northern India	Delhi, Haryana, Himachal Pradesh, Jammu and Kashmir, Punjab, Rajasthan, Uttarakhand, Uttar Pradesh
Northeastern India	Assam, Arunachal Pradesh, Manipur, Meghalaya, Mizoram, Nagaland,Tripura, Sikkim
Eastern India	Odisha, Bihar, Jharkhand, West Bengal
Central India	Madhya Pradesh, Chhattisgarh
Southern India	Karnataka, Tamil Nadu, Kerala, Andhra Pradesh, Telangana
Western India	Maharashtra, Gujurat, Goa

Table S3.6 State level results of area estimates of the bioclimatic envelope followed by the area remaining after sequential exclusion of LULCs that cannot be restored, resulting in the feasible area of opportunity (Mha). Settlements includes statutory towns, census towns and villages as per Balk et al., 2020., see Supplementary Methods for details about remaining exclusions. States arranged in decreasing order of feasible area of opportunity

State Name	Bioclimatic Area	Ice/snow and wetlands	Current forests	Native grasslands and woodlands including savannas	National Highways	Irrigated crop area	Croplands from Roy et al	Feasible Area of Opportunity after excluding settlements
Chhattisgarh	7.5695	7.565	3.2489	3.235	3.2311	2.2136	1.0279	0.2678
Madhya Pradesh	13.4588	13.456	7.9244	7.8304	7.8174	6.5359	1.7404	0.2623
Odisha	6.88	6.8794	2.5219	2.3027	2.2987	1.6837	0.6755	0.2429
Assam	5.1771	5.1724	3.3279	3.2214	3.2097	2.7074	1.1301	0.2004
Andhra Pradesh	2.1505	2.1503	0.697	0.6532	0.6528	0.5759	0.4055	0.1832
Uttarakhand	1.4789	1.4788	0.7488	0.7015	0.6982	0.5404	0.2126	0.0868
Maharashtra	7.9246	7.9158	4.1904	3.9766	3.9698	3.5536	0.6447	0.0809
Jammu and Kashmir	1.3082	1.3074	0.8834	0.861	0.8572	0.7126	0.3422	0.0681
Telangana	1.6994	1.6985	0.6869	0.4767	0.4762	0.3836	0.2019	0.0488
Uttar Pradesh	6.9412	6.9039	6.2421	6.2066	6.1932	2.4596	0.4773	0.044
Sikkim	0.3371	0.3301	0.0888	0.0888	0.0883	0.0683	0.0464	0.0243
Kerala	2.705	2.6996	2.1358	2.0767	2.0712	1.5727	0.3985	0.0188
Jharkhand	5.604	5.604	3.2515	3.251	3.2431	2.2924	0.6325	0.015
Karnataka	4.1	4.0934	1.8562	1.7979	1.7926	1.2738	0.5447	0.0119
Manipur	2.3891	2.3818	1.1602	1.1601	1.153	1.0858	0.8263	0.0073
Meghalaya	1.5338	1.5316	0.5673	0.4935	0.4918	0.4631	0.4395	0.0029
Bihar	1.7252	1.7141	1.2961	1.283	1.2792	0.7845	0.1819	0.0028
West Bengal	2.5671	2.5619	2.0972	2.0915	2.0859	1.4518	0.5393	0.0026
Arunachal Pradesh	5.6068	5.604	0.9093	0.8876	0.8828	0.7898	0.6618	0.0025
Rajasthan	2.5338	2.521	1.6163	1.5659	1.5617	1.2251	0.3663	0.0021
Tamil Nadu	1.5374	1.5355	0.6357	0.6001	0.5899	0.4723	0.3116	0.0019
Gujarat	1.6509	1.6503	0.793	0.787	0.7714	0.604	0.0944	0.0012
Haryana	3.3642	3.3642	3.2843	3.2806	3.2673	1.4537	0.1637	0.0009
Punjab	4.4479	4.4272	4.3158	4.3152	4.2908	1.1654	0.1427	0.0009
Himachal Pradesh	1.3012	1.3009	0.6502	0.6258	0.6216	0.5209	0.1993	0.0005
Nagaland	1.7947	1.7914	0.9573	0.9573	0.9514	0.8579	0.6294	0.0003
Goa	0.217	0.2161	0.109	0.1089	0.1083	0.0821	0.0603	0.0002
Mizoram	2.2351	2.2151	1.1851	1.1851	1.1787	1.1271	1.0882	0.0002
NCT of Delhi*	0.1343	0.1343	0.1315	0.1315	0.1309	0.1123	0.0688	0
Tripura	0.6765	0.6741	0.2392	0.2392	0.2386	0.2159	0.2009	0

Total	**101.0493**	**100.8781**	**57.7515**	**56.3918**	**56.2028**	**38.9852**	**14.4546**	**1.5815**

*NCT- National Capitol Territory

Table S3.7 State level estimates of mitigation potential (TgC) by carbon pools- aboveground biomass (TotalAGB), belowground biomass (TotalBGB), deadwood matter (TotalDeadwood) and litter (TotalLitter). Delhi and Tripura have no potential because there is no opportunity remaining after all exclusions. States are ordered in decreasing order of mitigation potential

State	TotalAGB	TotalBGB	TotalDeadwood	TotalLitter	Mitigation Potential
Madhya Pradesh	9.452971	2.586823	0.068562	0.478947	12.5873
Chhattisgarh	7.845796	2.360902	0.082143	0.641706	10.93055
Andhra Pradesh	7.153723	2.768419	0.026182	0.146954	10.09528
Odisha	5.616916	1.196571	0.072953	1.45766	8.344099
Assam	2.639901	0.898081	0.051638	0.261612	3.851231
Maharashtra	1.93862	0.636703	0.022105	0.229274	2.826701
Uttarakhand	1.954285	0.475559	0.043811	0.19223	2.665885
Jammu and Kashmir	1.813064	0.46306	0.018924	0.090782	2.385831
Telangana	1.806154	0.456644	0.013934	0.103706	2.380437
Sikkim	0.859672	0.225768	0.007733	0.035801	1.302721
Uttar Pradesh	0.892765	0.263095	0.014955	0.097311	1.268126
Kerala	0.523495	0.161162	0.0058	0.061199	0.751655
Karnataka	0.374482	0.13791	0.002412	0.018784	0.533587
Jharkhand	0.312045	0.064231	0.004413	0.077333	0.458022
Manipur	0.222716	0.066933	0.00116	0.006526	0.297335
Meghalaya	0.0717	0.014758	0.000918	0.019054	0.10643
Bihar	0.071143	0.017274	0.001292	0.006065	0.095774
Tamil Nadu	0.065381	0.024809	0.000386	0.001815	0.092391
Rajasthan	0.060409	0.023717	0.000296	0.001141	0.085563
West Bengal	0.057225	0.019511	8.76E-05	0.00139	0.085563
Arunachal Pradesh	0.045673	0.009934	0.001023	0.005394	0.062024
Gujarat	0.039057	0.015194	0.000171	0.000655	0.055077
Haryana	0.021457	0.008424	0.000129	0.000499	0.030509
Punjab	0.01456	0.003033	0.000474	0.002026	0.020093
Himachal Pradesh	0.012363	0.003041	0.000174	0.000704	0.016282
Nagaland	0.009322	0.002505	8.02E-05	0.00069	0.012597
Goa	0.003684	0.000758	7.36E-05	0.001123	0.005638
Mizoram	0.00278	0.001092	2.26E-05	0.000102	0.003996
Total	**43.88136**	**12.90591**	**0.441851**	**3.940482**	**61.35046**

Table S3.8 Carbon stocks for aboveground biomass (AGB), belowground biomass (BGB), deadwood and litter for three canopy densities of Very Dense Forest (VDF) (>70%), Moderately Dense Forest (MDF)(40-70%) and Open Forests(OF)(10-40%) for different forest types and biogeographic zones, from Table 4.6 Chapter 4 India's State of Forests Report 2019. We excluded carbon stock information for 'Plantation/TOF' and 'Alpine Scrub' forest types from our analyses and have hence not included this information in this table.

Forest Type Stratum	Density	AGB	BGB	Dead wood	Litter
Tropical Wet Evergreen Forests- North East	VDF	49.29	17.05	1.2	2.71
Tropical Wet Evergreen Forests- North East	MDF	27.44	8.17	0.37	3.18
Tropical Wet Evergreen Forests- North East	OF	18.21	7.25	0.2	2.86
Tropical Wet Evergreen Forests- Western Ghats	VDF	70.67	24.45	4.1	7.18
Tropical Wet Evergreen Forests- Western Ghats	MDF	46.62	16.13	0.35	3.51
Tropical Wet Evergreen Forests- Western Ghats	OF	11.92	4.12	0.27	2.27
Tropical Semi Evergreen Forests	VDF	58.74	12.08	1.36	2.72
Tropical Semi Evergreen Forests	MDF	30.07	6.19	0.37	2.43
Tropical Semi Evergreen Forests	OF	9.28	1.91	0.2	1.79
Tropical Semi Evergreen Forests- Eastern Deccan	VDF	42.79	8.8	4.1	42.85
Tropical Semi Evergreen Forests- Eastern Deccan	MDF	40.59	8.35	0.35	17.24
Tropical Semi Evergreen Forests- Eastern Deccan	OF	25.35	5.21	0.27	14.27
Tropical Semi Evergreen Forests- Western Ghats	VDF	51.88	10.67	4.1	8.18
Tropical Semi Evergreen Forests- Western Ghats	MDF	34.55	7.11	0.35	7.29
Tropical Semi Evergreen Forests- Western Ghats	OF	12.09	2.49	0.27	6.84
Tropical Moist Deciduous Forests	VDF	37.16	7.64	1.17	2.74
Tropical Moist Deciduous Forests	MDF	25.46	5.24	0.82	3.3
Tropical Moist Deciduous Forests	OF	11.81	2.43	0.4	1.83
Littoral & Swamp Forests	VDF	75.62	26.16	0.02	1.27
Littoral & Swamp Forests	MDF	42.95	14.86	0.02	0.68
Littoral & Swamp Forests	OF	13.97	4.83	0.02	0.39
Tropical Dry Deciduous Forests	VDF	61.93	24.32	0.46	5.87
Tropical Dry Deciduous Forests	MDF	59.16	23.23	0.15	0.6
Tropical Dry Deciduous Forests	OF	12.82	5.03	0.13	0.41
Tropical Thorn Forests	VDF	13.87	5.44	0.37	2.19
Tropical Thorn Forests	MDF	13.21	5.19	0.25	1.44
Tropical Thorn Forests	OF	4.98	1.96	0.13	0.76
Tropical, Sub Tropical Dry Evergreen And Broadleaved Hill Forests	VDF	35.17	13.81	0.91	1.57
Tropical, Sub Tropical Dry Evergreen And Broadleaved Hill Forests	MDF	25.25	9.92	0.37	2.4
Tropical, Sub Tropical Dry Evergreen And Broadleaved Hill Forests	OF	16.33	6.41	0.2	1.79
Subtropical Pine Forests	VDF	50.34	12.71	1.19	1.47
Subtropical Pine Forests	MDF	31.72	8.01	0.37	1.29
Subtropical Pine Forests	OF	19.68	4.97	0.2	0.96
Montane & Moist Temperate Forests	VDF	64.1	16.18	1.36	3.21
Montane & Moist Temperate Forests	MDF	50.58	12.77	0.37	2.44

Montane & Moist Temperate Forests	OF	24.8	6.26	0.2	1.94
Sub Alpine & Dry Temperate Forests	VDF	79.08	21.44	1.2	2.06
Sub Alpine & Dry Temperate Forests	MDF	45.86	12.43	0.37	1.11
Sub Alpine & Dry Temperate Forests	OF	32.9	8.92	0.2	0.72

3.11.3 Supplementary Figures

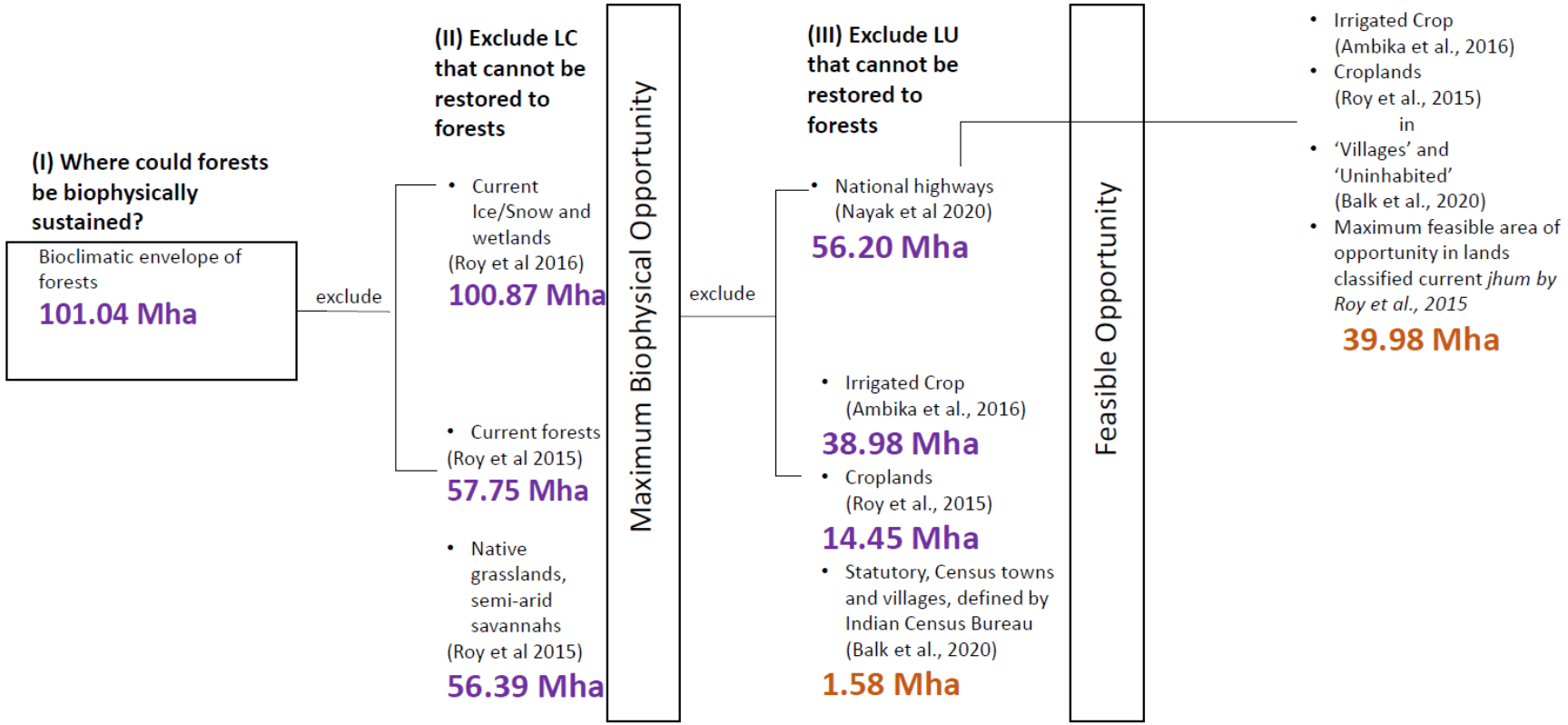


Figure S3.4 Workflow methodology to calculate feasible area of opportunity and area of opportunity for agroforestry. The methodology includes estimation of the maximum bioclimatic area followed by sequential exclusions of LULCs that are unlikely to be restored to forests. Area remaining after each exclusion is shown in purple and bold and the results are shown in burnt orange and bold. At the national scale. 39.98 Mha of maximum opportunity for agroforestry is obtained by estimating the area of the bioclimatic envelope of forests in irrigated crop and croplands mentioned after excluding current ice/snow and wetlands, current forests, native grasslands, semi-arid savannahs and national highways from the bioclimatic envelope of forests.

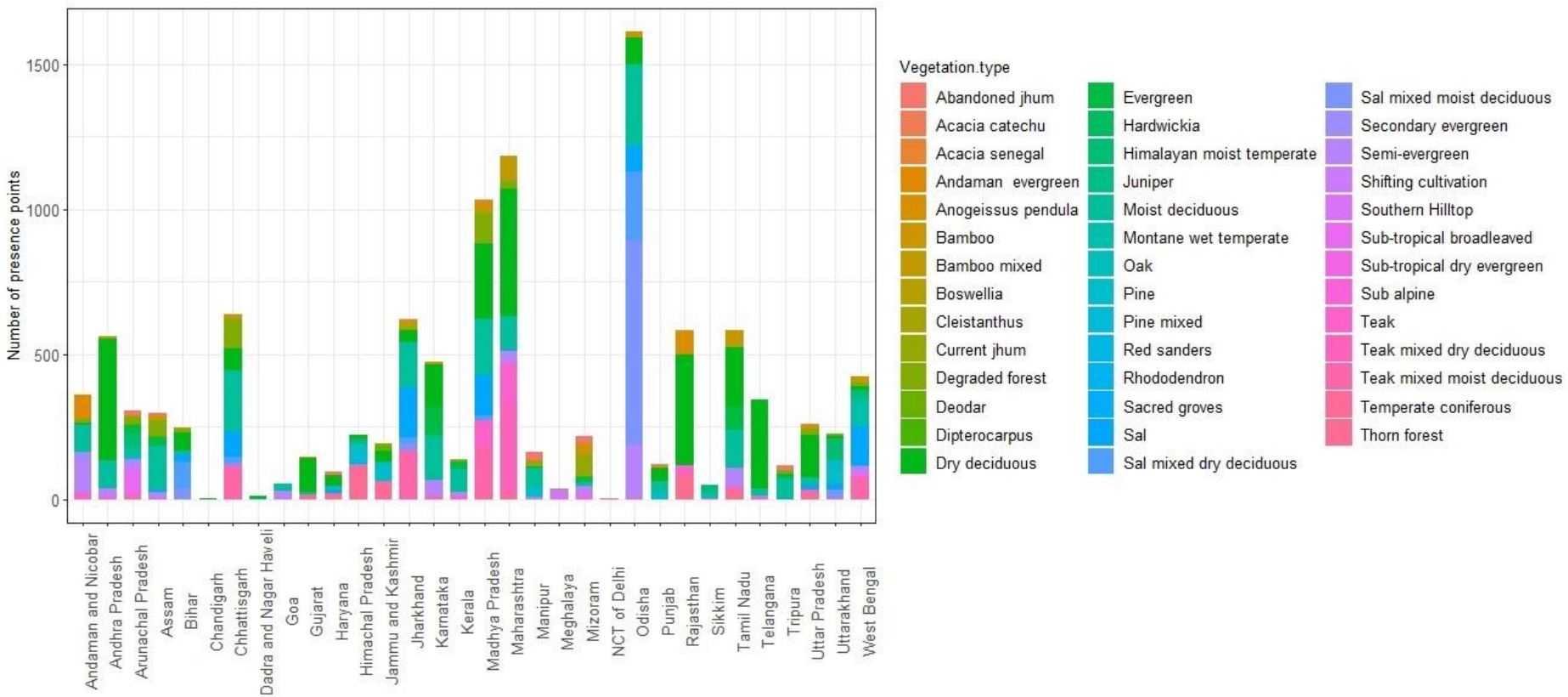


Figure S3.5 Distribution of presence points across different vegetation classes in Indian states. Total of 11116 GPS- gathered points of presences of different forest types in each Indian state including all union territories. There were a maximum of 1610 presence points in Odisha and 1 presence point in Chandigarh and a maximum of 2850 presence points in dry deciduous forests and 1 presence point in *Acacia Senegal* forests.

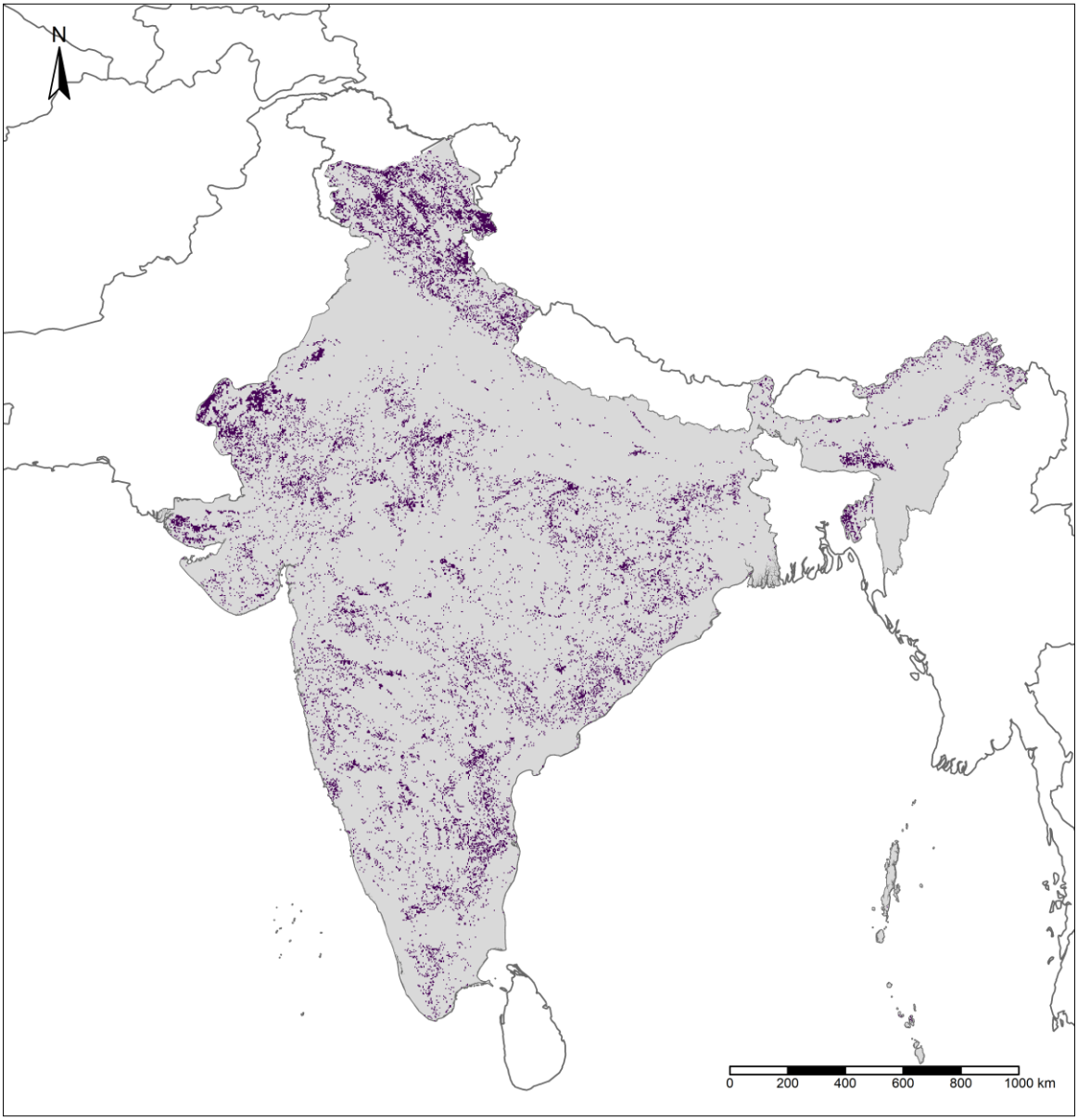


Figure S3.6 Sampling area for PsAb. 23000 PA points were sampled from areas in purple. Sampling area included scrub/shrub, grasslands (excluded manmade grasslands), woodlands, *kans*, riverine, ravine and shola forests (locale specific). All areas in white were not included in the entire analyses

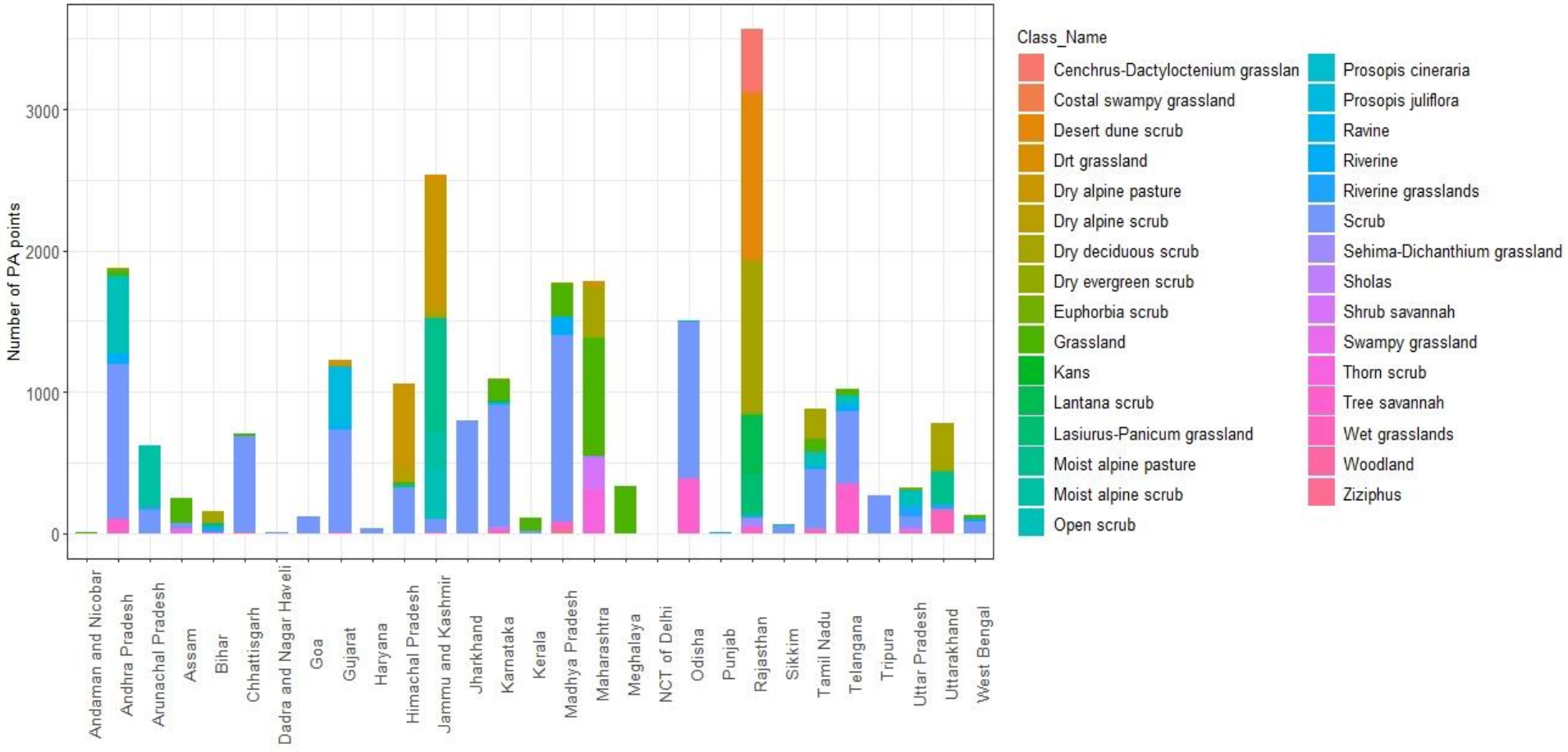


Figure S3.7 Distribution of PsAb across different vegetation classes in Indian states. Total of 22574 PsAb were randomly sampled in different forest types in each Indian state including all union territories, with a maximum of 3566 points in Rajasthan and minimum of 1 point in Delhi with a maximum of 8140 points in shrub/scrub and minimum of 1 point in *Prosopis cineria* forest type

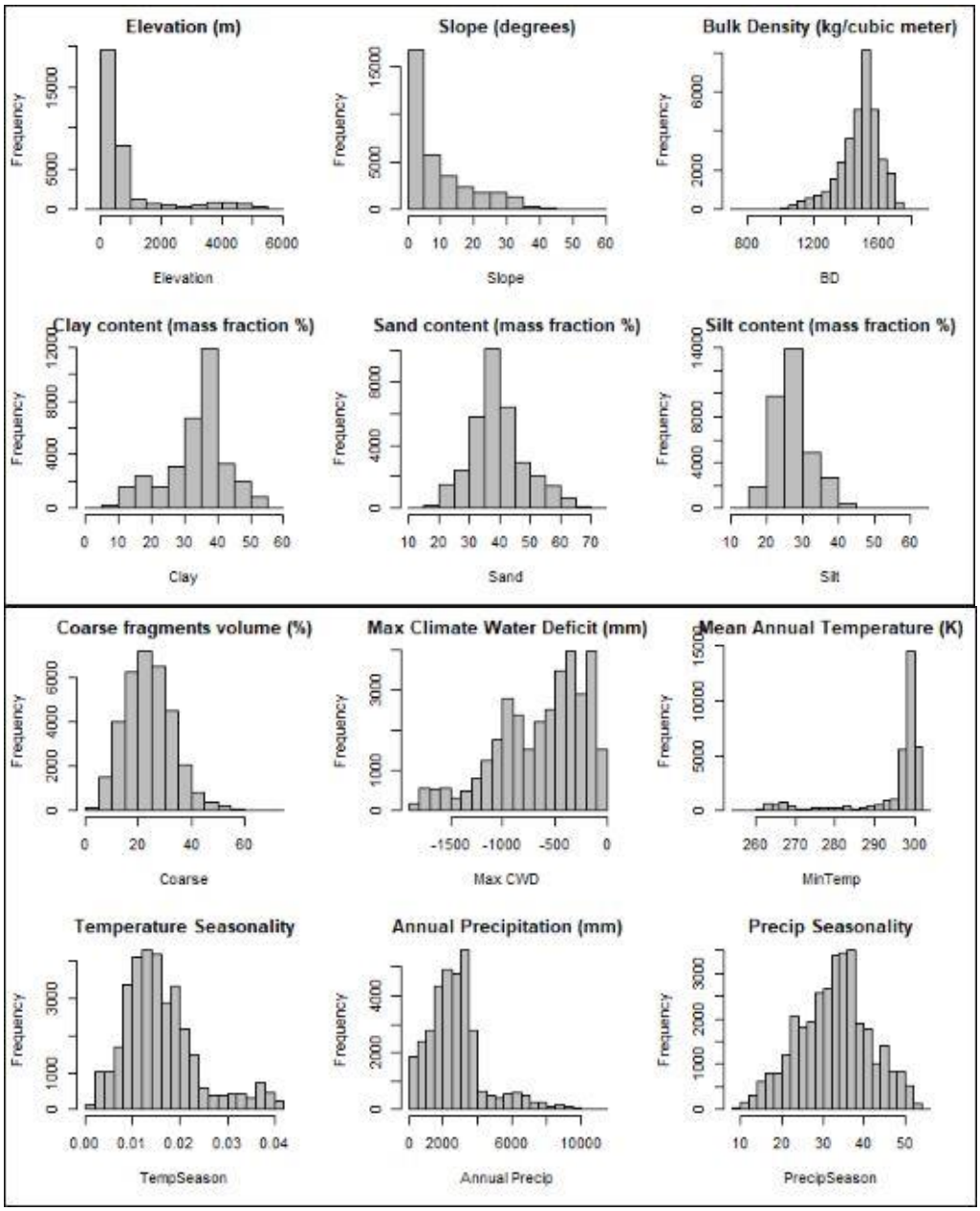


Figure S3.8 Distribution of environmental predictors across all presences and PsAb.The values of the different environmental predictors (see Table 1) were extracted for all 33690 points (presences and PsAb). Visual assessment of normality was completed, and we concluded that many variables are skewed- elevation, slope, mean annual temperature, while majority of the variables followed a normal distribution

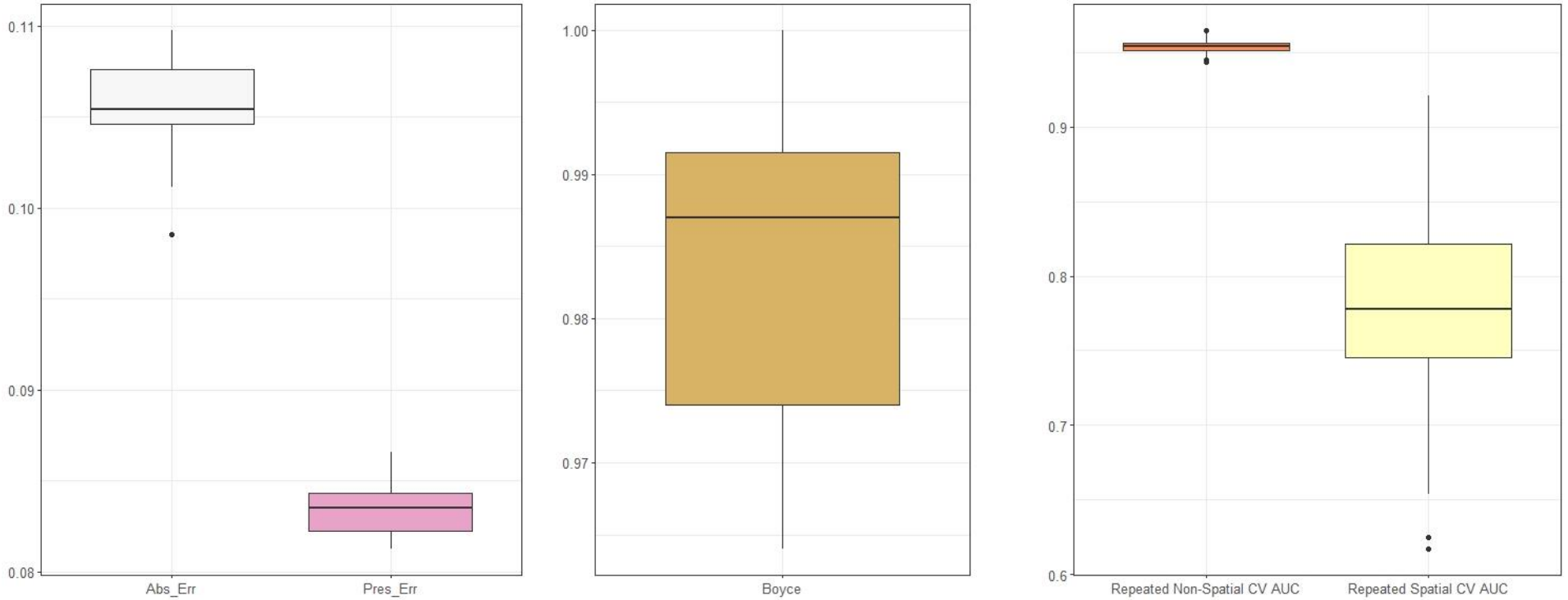


Figure S3.9 Sensitivity metrics for the 10 random forest models and ensemble model. (a) Misclassification rates for presences and absences were 0.081-0.086 and 0.098- 0.109 (maximum and minimum) (b) Boyce index had a range of 0.964-1 (c) Average AUC from the 10-fold repeated spatial CV was 0.788 vs 0.953 for the repeated non-spatial CV

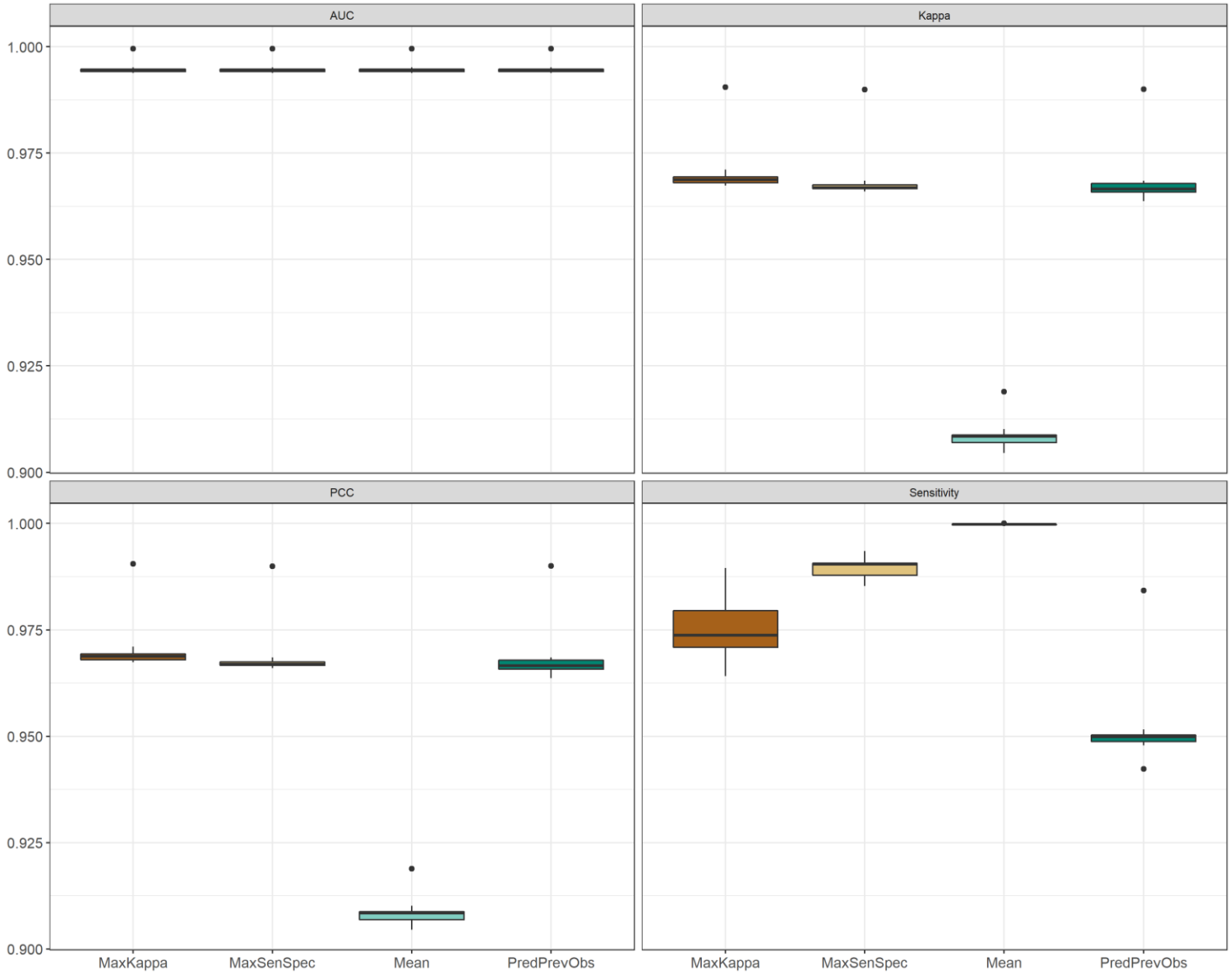


Figure S3.10 Accuracy metrics for 10 random forests and ensemble models – Area Under the Curve (AUC), percent correctly classified (PCC), Cohen's *Kappa* statistic and sensitivity for each of the four threshold metrics testes- maximized *Kappa* statistic (MaxKappa) (0.70-0.76 across 10 models, 0.7 for ensemble), maximized sum of sensitivity and specificity (MaxSenSpec) (0.68-0.71 across 10 models, 0.68 of ensemble), mean of all predicted probabilities (Mean)(0.422-0.425 across 10 models, 0.423 of ensemble) and equal prevalence of prediction and observation (PredPrevObs)(0.72-0.79 across 10 models, 0.72 of ensemble). We chose the mean threshold of predicted probabilities of 0.423 to threshold the bioclimatic envelope of forests because of its high sensitivity accuracy metric.

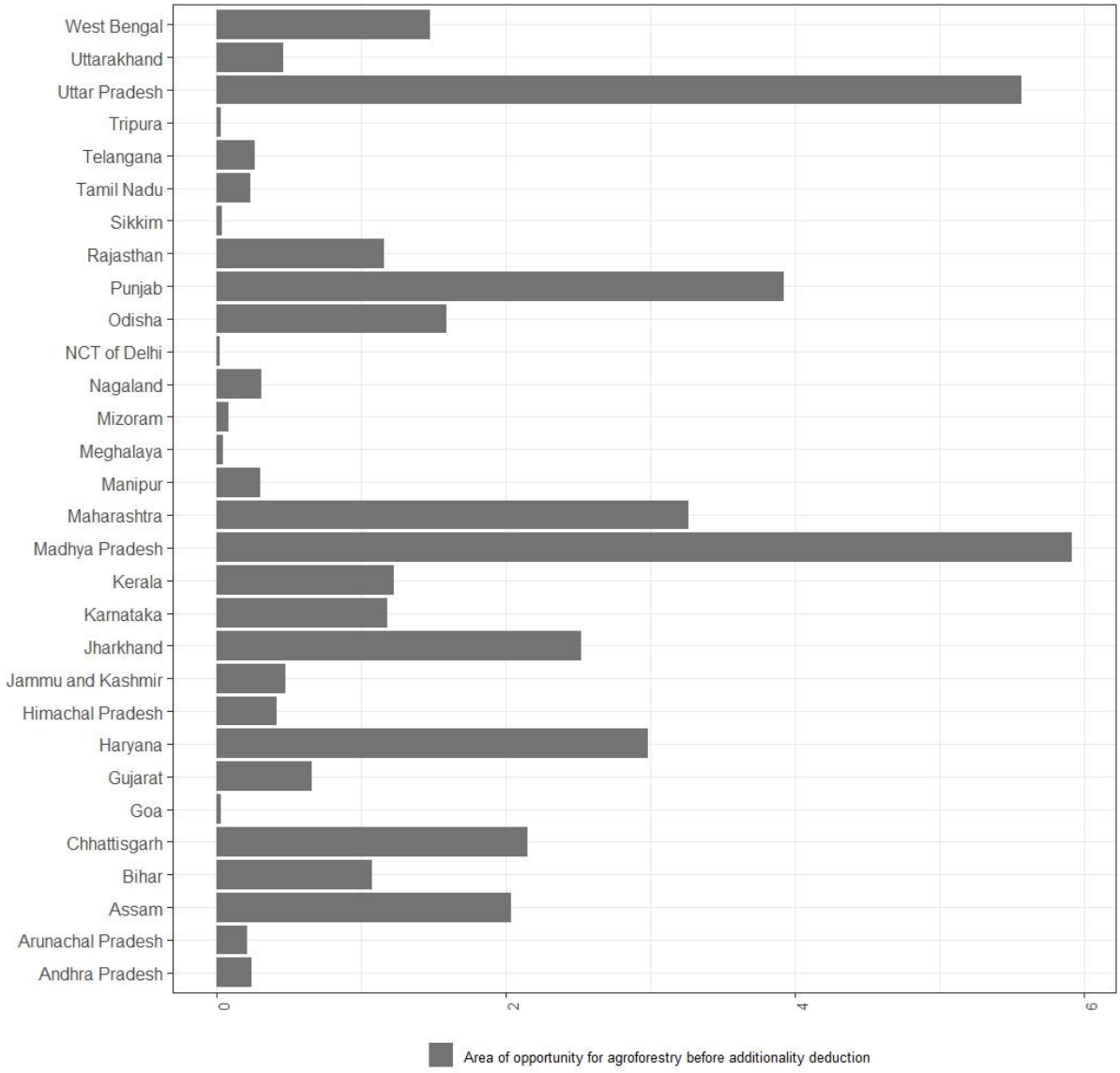


Figure S3.11 Bioclimatic potential of agroforestry in each state including 0.001 Mha of current jhum in Mizoram, Manipur and Assam and 1.41 Mha of croplands classified as uninhabited, totalling 39.98 Mha. From this estimate, 25.31 Mha was deducted (non-spatially i.e. subtracted) resulting in the national estimate of maximum available opportunity for agroforestry of 14.67 Mha. We acknowledge that not all of the maximum available opportunity will be feasible for agroforestry practises considering safeguarding food supply.

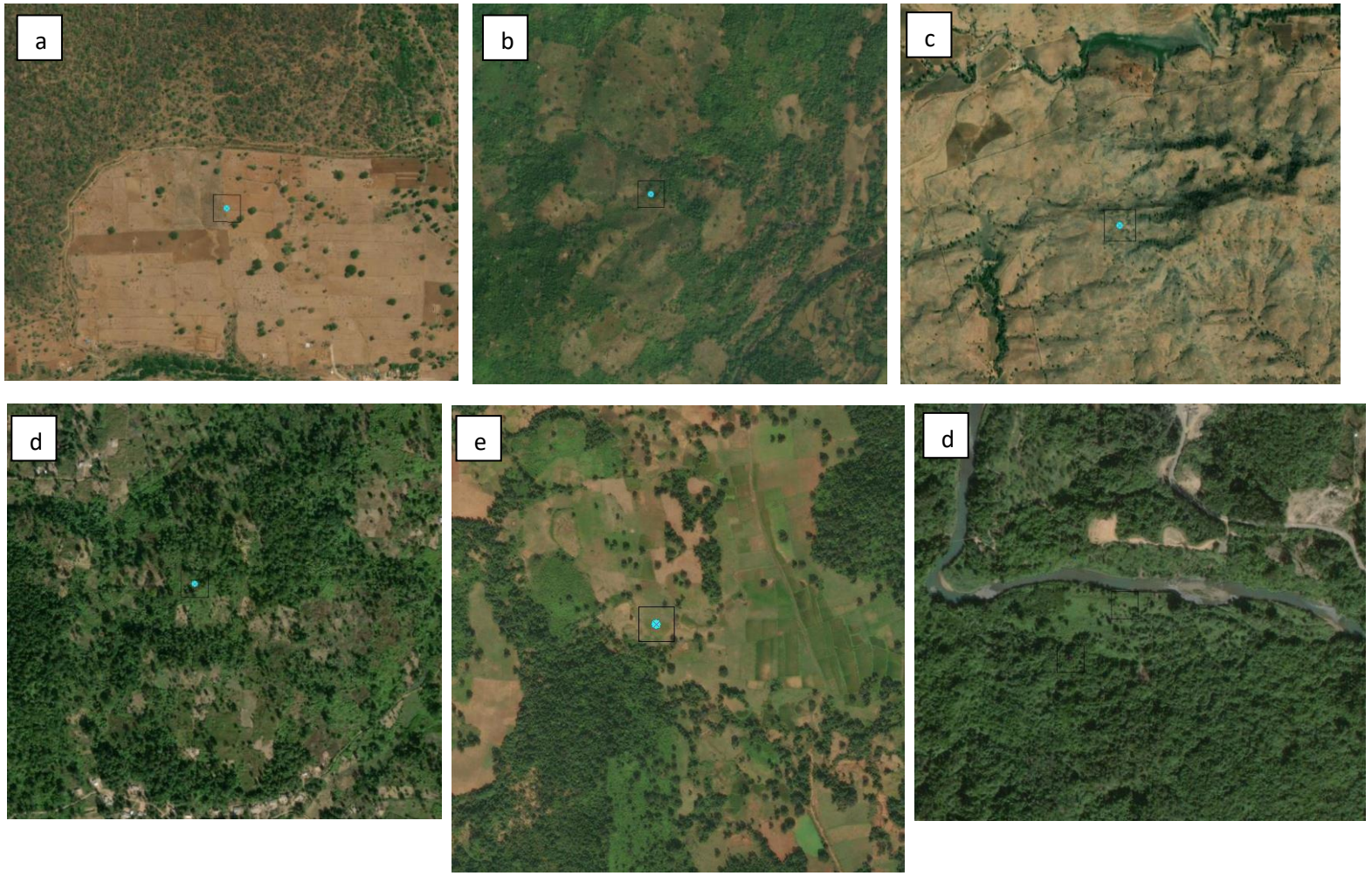


Figure S3.12 Examples of feasible area of opportunity inspected qualitatively using Google Earth imagery. Current LULCs in estimated opportunity shown by teal dot and surrounded by black square in a) Karnataka where opportunity seems to be in land cleared for agricultural purposes b) Odisha where opportunity is land with mosaic vegetation including open ecosystems with minimal tree cover c) Madhya Pradesh where opportunity seems to be in barren rock lands d) Assam with mixed land uses including sparse tree cover, open tree cover and agricultural lands e) Jharkhand in agricultural lands abutting forests f) Nagaland where forests seem to be cleared on river banks

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Chapter 4 The geography and drivers of tree cover across India's forest and savanna biomes

Linking Statement: In *Chapter 3*, I determined that one third of the opportunity area is classified as 'degraded forests', followed by scrub and barren land. However, recent scholarship has indicated that majority of India's open ecosystems including savannas, grasslands and woodlands have been misclassified and mislabelled as 'degraded forests' due to persistence of colonial legacies of land management. Also, to meet India's ambitious climate goals, these mislabelled open ecosystems are being targeted for afforestation schemes and expansion of grid scale solar energy farms. Hence, in this chapter, I evaluate tree cover across India's forests and savannas and its determinants. I primarily used remote sensed imagery products of tree cover, empirical evidence of endemic savanna plants and climate to delineate four climatic zones with different combinations of tree cover. One of the zones is the core savanna zone which I concluded should not be afforested. Using generalized additive models, I determined that physical factors such as topography and soil sand fraction, and anthropogenic disturbances and high herbivory pressure are factors that should be accounted, when designing forest restoration strategies.

I am currently working on revisions of the manuscript titled "*The geography and drivers of tree cover in India's forest and savanna biomes'* for the peer-reviewed journal *Global Ecology and Biogeography.*

Contribution Statement: I completed the conceptualization, methodology development and formal analyses of this research. I investigated and visualized the results and wrote the original draft manuscript. I am currently editing the manuscript based on the reviewer's comments I have received. Dr. Sami W. Rifai, Dr. Jayashree Ratnam, Dr. Nicola Stevens and Dr. Imma Oliveras- Menor supported the methodology development and investigation. Prof Yadvinder Malhi provided overall supervision and was involved in all steps of analyses. All co-authors helped in edition of the manuscript drafts.

4.1 Structured Abstract

Aim

For effective and appropriate ecosystem restoration strategies, we need information about the natural tree cover across biomes, and its determinants. Environmental factors of climate, soil, fire and herbivory have been widely studied in the forest and savanna biomes of Africa, South America and Australia. However, there is little to no information from the lesser known forest and savanna biomes in Southern Asia. Here, we examine forest and savanna biome distribution in India through the lens of evaluating the drivers of tree cover, focusing on two research questions. First, what is the distribution of tree cover across forest and savanna biomes in India? Second, what drivers maintain the distribution of tree cover and hence these biomes?

Location

The study encompasses the entire of India

Methods

We used remote sensing derived data of tree cover, resource drivers of climate and soil and disturbance drivers of fire and herbivory pressure and empirical information about the location of savanna understorey plants to delineate four zones with distinct determinants of tree cover. Furthermore, we used generalized additive models to estimate the significant resource and disturbance drivers of tree cover.

Results

We identified four zones with distinct determinants of tree cover- a low and predominantly high tree cover zone where climate is the main driver, a core savanna zone consisting of savanna plants and where climate limits the maximum tree cover and a mixed forest - savanna zone with savanna plants and where tree cover is not limited by climate. We determined that topography is a key regulator of tree cover in India in addition to precipitation seasonality and soil sand fraction. Also, we found tree cover is limited by anthropogenic activity and high herbivory pressure. Contrary to global paradigms, we did not find clear evidence of fire reducing tree cover from its maximum potential, suggestive of high fire suppression in this highly populated and agricultural country.

Main Conclusions

Considering the increased momentum of tree planting strategies globally and various scientific studies about the potential opportune area available for forest restoration, we highlight the need to understand consequences on non- forest ecosystems. Our results highlight the need to better delineate 'no- go' areas of savannas where afforestation should not be done. Our results also confirm the need for nuanced strategies accounting for topography, anthropogenic disturbance, grazing management and reintroduction of fire regimes instead of simplistic tree planting strategies.

4.2 Introduction

There is increased momentum of strategies for ecosystem restoration and expansion of tree cover to address climate change mitigation and adaptation. To do so effectively, we require information about the natural tree cover and its drivers. This information can help design appropriate restoration techniques that are tailored to the natural states of diverse landscapes (Buisson et al., 2019, 2020). However, a key challenge is to distinguish between land areas that naturally host forests and those that do not, such as savannas.

Tree cover is commonly used to differentiate between forests and savannas. Tropical mesic savannas are predominantly characterised by a mix of continuous layers of C_4 grasses and varying densities of fire tolerant and shade intolerant tree species, while forests largely lack C_4 grasses and consist of fire intolerant and shade tolerant tree species (Ratnam et al., 2011). The distinct dichotomy of low tree cover in savannas and high tree cover in forests has been found in Africa, South America and Australia (Aleman et al., 2017; Dantas et al., 2016; Hirota et al., 2011; Staver et al., 2011a). A similar pattern has also been confirmed in southeast Asia as being scale dependent i.e. distinct at the landscape scale compared to the regional scale (Pletcher et al., 2022). Hence, this characteristic reinforces the use of tree cover as a proxy for both biomes, especially using remote sensing products.

South and Southeast Asian savannas are widely underrecognized and are frequently mislabelled as degraded forests (Pletcher et al., 2022; Ratnam et al., 2016). In the case of India, many savannas are mesic and share physiognomies that are very similar to closed canopy forests, contrasting the grassy open landscapes that characterise African and South American savannas (Ratnam et al., 2016). Colonial practices of managing land for forestry (Roy & Fleischman, 2022) have trickled down to vegetation classification maps that classify Indian open ecosystems to be degraded lands (Madhusudan & Vanak, 2022). Additionally, with the target of restoring 26 million hectares, by 2030, India's pledges to the Bonn Challenge are among the most ambitious among the southern Asian countries (Burnwal, Kundan, Bharat, 2020). Consequently, many Indian savannas ("degraded

forests") have become easy targets for afforestation (Vanak et al., 2017). These mounting pressures on Indian savannas are further amplified by the limited knowledge of the drivers of savanna and forest biome distribution, thereby hindering appropriate ecosystem restoration strategies (Dudley et al., 2020).

Broadly, resource based drivers, such as climate and soil and disturbance based drivers including herbivory pressure and fire, provide insight into tree-grass competition and in turn distribution of forests and savannas. From the macroecological and biogeographic perspectives, climate, specifically rainfall and its seasonal distribution, is a key determinant of tree cover (Staver et al., 2011a; Staver et al., 2011b). Evidence from global studies and from African savannas, suggests that by regulating tree growth and mortality, climatic drivers constrain the maximum potential tree cover (Bucini & Hanan, 2007; Sankaran et al., 2005; Zeng et al., 2014). Indeed, relative to forests, savannas tend to be found in areas with lesser precipitation (Hirota et al., 2011; Staver et al., 2011b), higher seasonality (Staal et al., 2016) and higher interannual variability (Holmgren et al., 2013), all implying water use related physiological processes that control tree cover. Indeed, the availability of water determines soil moisture, another key factor that evokes different responses of tree and grass water use in savannas (d'Onofrio et al., 2015; Holdo, 2013). However, there is limited insight into the relationship between severity of water stress and savanna and forest distribution (Malhi et al., 2009). The classic root niche separation mechanism elucidated in the 'Walter hypothesis', invokes differential root zones for trees versus grasses with trees accessing deep soil layers for water versus grasses accessing shallow layers (Walter & Burnett, 1971). Yet, there is disputed evidence of overlapping root niches between grasses and trees, primarily in African savannas and no inferences globally (Hipondoka et al., 2003; Verweij et al., 2011).

Natural disturbances such as fire and herbivory are key regulators of tree cover, maintaining savannas, by preventing complete canopy closure that would result in forests (Bond, 2005; Bond et al., 2005; Lehmann et al., 2011). Typically, fires are extensive in the tropical savanna biome due to the abundance of highly flammable C_4 grasses (Ratnam et al., 2011). Fire regulates tree cover at

various stages of tree growth with frequent fires limiting saplings from escaping the 'fire trap' at juvenile stages, thereby reducing tree cover (Oliveras & Malhi, 2016). Conversely, forests (with 45-50% canopy cover according to Whittaker & Levin, 1977), sustain shady and humid microclimates that limit the extent and connectivity of C_4 grasses, giving trees the competitive edge over grasses and hence increasing tree cover (Oliveras & Malhi, 2016). With majority of evidence from African and South American savannas (Bond et al.,2003; Bond, 2008; Lehmann et al., 2009; Sankaran et al., 2005; Staver et al., 2009; Zeng et al., 2014), there are few insights in areas where there is a long history of fire suppression such as the case of South Asia (Wanthongchai et al., 2011). Similarly, herbivory affects tree cover, with experimental evidence, primarily from Africa, showing that wild grazing increases tree cover by suppressing grasses and wild browsing and wild mixed feeding reduce tree cover (Sankaran et al., 2008; Staver et al., 2021; Staver & Bond, 2014). We suspect that this is also the case with domestic livestock, the dominant herbivores in most tropical open ecosystems (Hempson et al., 2015). However, evaluation of herbivory pressure has been limited to field-based studies, due to the lack of availability of accurate large-scale spatial information of herbivore distribution, making it an important research gap yet to be filled in remote sensed tree cover based studies (Staver et al., 2011b). This tension between resource- based and disturbance- based drivers has been heavily debated (Staal & Flores, 2015; Veenendaal et al., 2015) with an occasional middle ground being proposed (Langan et al., 2017). However, there are no such insights from South Asian savanna and forest biomes.

Here, we examine forest and savanna biome distribution in India through the lens of evaluating the drivers of tree cover, focusing on two research questions. First, what is the distribution of tree cover across India's savanna and forest biomes? Based on previous global studies (Americas-Africa-Australia), we expected a bimodal distribution of tree cover with low percent tree cover across the savanna biome and high tree cover across forests (Staver et al., 2011a). Second, what drivers maintain the distribution of tree cover and hence India's savanna and forest biomes? We hypothesized that climatic drivers, specifically precipitation seasonality, controls the maximum potential tree cover in a non-linear pattern, with soil texture, via soil moisture availability, playing an

additional role (Case & Staver, 2018). We expected that fire would be the primary driver that limits tree cover from reaching its maximum potential, followed by herbivory pressure as is the case in mesic systems (Oliveras & Malhi, 2016).

4.3 Methods

4.3.1 Study area delineation and sampling strategy

We considered the entire terrestrial area of India, from which we excluded land uses and covers of built-up area, croplands (including abandoned and current *jhum* - a shifting agriculture practise in India - and irrigated croplands), aquaculture, mangroves, salt pans, permanent wetlands and snow and ice. Additionally, we excluded all areas with elevation greater than 1200m because temperature gradients limit tree growth, which is beyond the scope of this study (Shi et al., 2020), resulting in our final study area (Fig S4.5). We stratified the study area into 150mm bins of mean annual precipitation (MAP) (n=31) and sampled 300 random points in each bin (total n= 9600), for an unbiased representation of tree cover across the precipitation gradient. We excluded 10.8% of the sampled points due to lack of comprehensive data across all environmental drivers (n=8554).

4.3.2 Selection of environmental drivers to predict percentage tree cover

Using remote sensing-derived products, we evaluated the relationship between tree cover and environmental drivers at the sampled points. We used the Mod44BB.006 MODIS Terra Vegetation Continuous Fields product for mean annual percentage tree cover estimates. We used the Terraclimate products (Abatzoglou et al., 2018) for the climatic drivers, of which mean annual precipitation (MAP) and maximum climate water deficit (MCWD) were least correlated against other climatic drivers. MCWD was calculated as the most negative value of the cumulative difference between annual precipitation and potential evapotranspiration (Aragão et al., 2007; Malhi et al., 2009). We used SoilGrids250m v2.0 (Poggio et al., 2021) estimates of sand fraction at 0-30 cm soil depth. For fire, we used both fire intensity, proxied by fire radiative power from the VIIRS 375m active fire product (Schroeder & Giglio, 2018) and the MCD64A1.006 MODIS burned area monthly global 500m product for fire frequency i.e. number of times a sampled point burned in 2000-2021

time period. The reason is the differing effects of fire on tree cover in forests and savannas, as savannas persist through more frequent and more intense fires compared to forests (Dantas et al., 2016; Pausas & Bond, 2020). We calculated herbivory pressure as the dry matter intake of buffalo, goat, sheep, cattle and horses using livestock census from the Gridded Livestock of the World product (Gilbert et al., 2018) and the metabolic demand, as per allometric equations in Wolf et al., (2013). Based on principal component analyses, we retained the dry matter intake of buffalo, sheep and goats to account for browsing and grazing effects on tree cover (Fig S4.6; Table S4.3) (Staver et al., 2021). We used human population density as an imperfect, but quantitatively data driven predictor to estimate the effect of anthropogenic disturbance on tree cover. Lastly, we included heat load index and topographic position index, to account for the effect of topography on tree cover (see full description of datasets and methodologies to process all environmental drivers in Table S4.2).

4.3.3 Analyses of distribution of tree cover and drivers that limit tree cover from reaching its climatically determined maximum potential

We evaluated the distribution of percentage tree cover against MCWD in combination with the data of the percentage tree cover and MCWD at the location of endemic savanna understorey plants, derived from species distribution data from national, regional and local taxonomic and floristic accounts from Nerlekar et al., (2022). Collectively, we delineated four zones of tree cover- predominant low tree cover zone, predominant high tree cover zone, core savanna zone and mixed forest- savanna zone (see Results section).

We followed a two- step analysis to determine drivers of tree cover in the core savanna and mixed forest-savanna zones (final n= 3118, see Supplementary Methods). First, we estimated the Potential Tree Cover Shortfall, henceforth shortfall (see below). Second, we used generalized additive models to evaluate the relationships between environmental drivers and shortfall, as implemented in the *mgcv* R package (Wood, 2011).

Shortfall was calculated as the difference between 1 and the ratio of realized tree cover and the climatically determined maximum potential tree cover, such that values close to 1 indicate

maximum divergence (i.e. zero tree cover) of realized tree cover from the climatically determined maximum potential tree cover and values close to 0 indicate realization of maximum potential tree cover. We calculated the climatically determined maximum potential tree cover using the 95th percentile smooth additive quantile regression model of percentage tree cover and MCWD and MAP, as implemented in the *qgam* R package (Fasiolo et al., 2021) (Fig S4.7).

We used two models to determine the relationship between shortfall and environmental drivers- (1) considering soil and topographical drivers of shortfall and (2) considering all drivers, *i.e.* soil, topography, fire, herbivory pressure and anthropogenic disturbance drivers. In both models, we applied penalized cubic regression smoothing functions for each driver, fitted with the Restricted Maximum Likelihood criterion to reduce overfitting (Marra & Wood, 2011). In both models, we partitioned the data into 80% training and 20% testing, used the beta family distribution with a logit link and interaction term of fire intensity and fire frequency. Lastly, diagnostic plots of residuals were evaluated, and the models were validated against testing data by comparable estimates of the root mean square error and deviance explained.

4.4 Results

Tree cover across a gradient of MCWD did not show distinct clusters of high and low tree cover for sampled points (black dots, n=8554) (Fig 4.1). Using endemic savanna plants data from Nerlekar et al., 2022 (orange diamonds), we delineated four zones of tree cover: (1) a low tree cover zone (MCWD > 1300 mm) in which maximum percent tree cover is very low (uncoloured); (2) a core savanna zone (MCWD 930-1300mm) in which characteristic savanna plants are frequently found and maximum percent tree cover ranges up to ~40%, a clear ceiling determined by MCWD (light mustard) (3) a mixed forest - savanna zone (MCWD 580-930mm) in which savanna plants sometimes occur and maximum percent tree cover ranges up to ~80% i.e. MCWD does not constrain maximum percent tree cover (lavender); (4) a predominant forest zone (MCWD < 580 mm) where MCWD has little influence on maximum percent tree cover, which is around ~85% (light green), and in which savanna plants are not found. Visual assessment of the mixed forest – savanna zone revealed a variety of

information about the visible vegetation and landscape including distinct topographical features of ridges and valleys (suggesting natural topographic features cause variation in tree cover), signs of anthropogenic disturbances indicated by the presence of cleared land, roads and paths and lastly, bare ground (Fig 4.1).

In terms of geography, the low tree cover zone stretched across north - western India including the desert areas of the states of Rajasthan and Gujarat (MAP range: 112.8 – 1095 mm). The predominant forest zone occurred in the north-eastern region of India and the Malabar coast in the south - western state of Kerala (Fig S4.8 a; MAP range: 1100 - 4893 mm). The core savanna zone stretched across the Deccan plateau, the Central Highlands and the western semi-arid zones of Gujarat, Rajasthan and north-western Madhya Pradesh (Fig S4.8 b; MAP range: 152.6 - 3008 mm). The mixed forest - savanna zone mainly separated into two montane regions:- inland from the east coast (northern Coromandel coast) in the states of Odisha, Jharkhand and Chhattisgarh and along the western coast, parallel to the central Western Ghats (Fig S4.8 c; MAP range: 566 - 3771 mm).

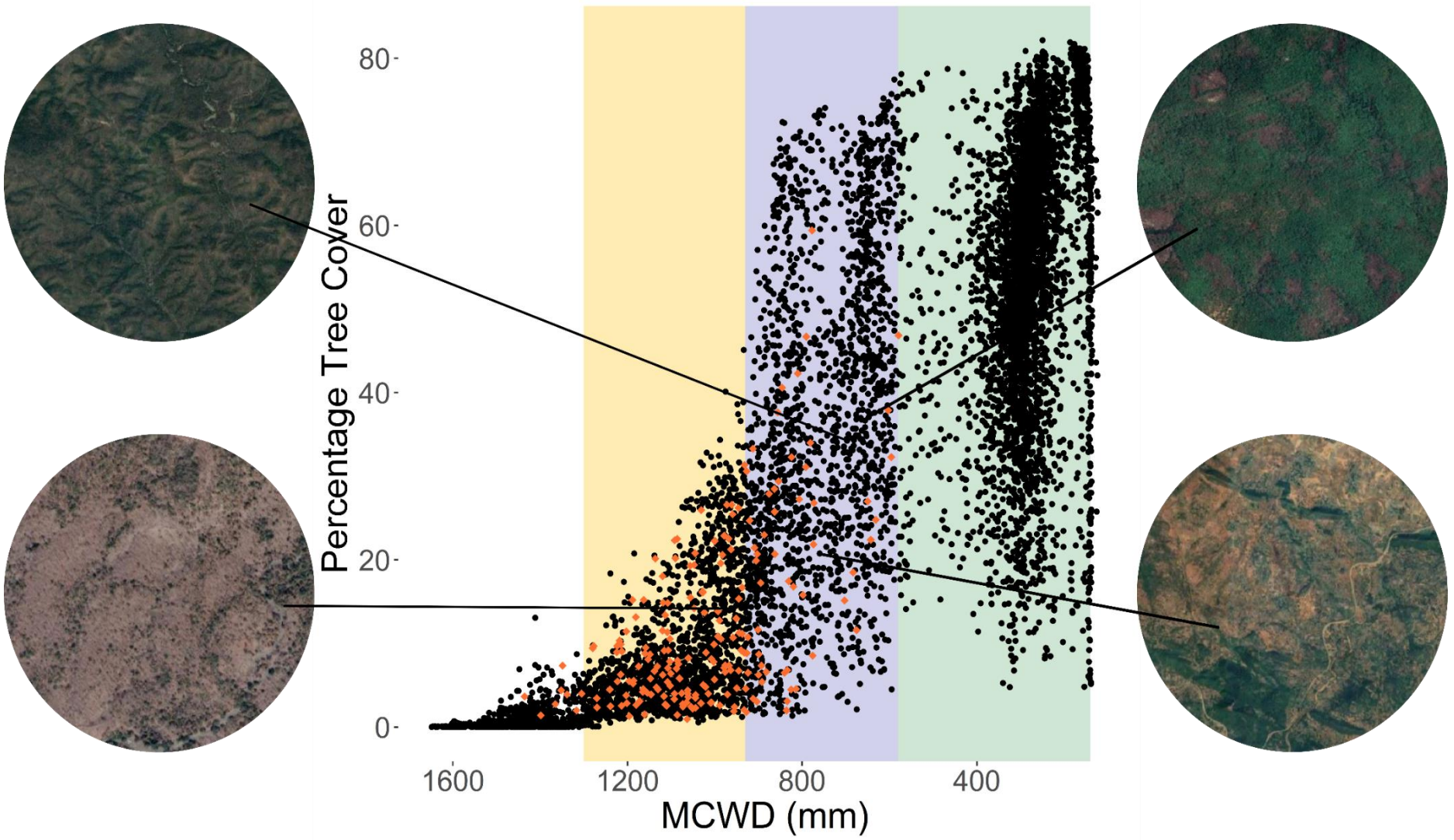


Figure 4.1 Percentage tree cover across a gradient of maximum climate water deficit (MCWD) (black dots, n=8554). Points with occurrence of endemic savanna plants from Nerleker et al., 2022 are indicated as bright orange diamonds. We delineate four vegetation zones (1) a low maximum tree cover zone beyond 1300 mm deficit (uncoloured), a core savanna zone 930-1300 mm deficit (light mustard); a mixed forest-savanna zone 580-930 mm deficit (lavender) and a predominant forest zone 0-400 mm deficit (light green). Inset images, clockwise starting top left, are examples of the landscape in the core savanna and mixed savanna forest zones- MCWD 912 mm and one observed fire, MCWD 680 mm and no fire, MCWD 887 and no fire and MCWD 1059 mm and 7 observed fires. See Fig S4.8 for geographic locations of the coloured zones and Fig S4.9 for distribution of environmental drivers across the points in the coloured zones

Climatic maximum potential percent tree cover increased linearly up to 3000 mm MAP, after which it plateaued, and between 1300 and 580 mm MCWD (deviance explained= 92%) (Fig S4.7). Using this relationship, we mapped maximum potential tree cover, which was highest in the north-eastern regions, the central and southern sections of the Western Ghats, and along the foothills of the Himalayas in the north. It was least in the desert and semi- arid zones of western India and increased slightly in the Central Indian Highlands region (Fig 4.2 a). Tree cover shortfall was, however, generally greatest in central regions including the Deccan plateau, Central Highlands and northern section of the Western Ghat. Shortfall was the least in the north-eastern regions and southern and central sections of the Western Ghats (Fig 4.2 b). Note that shortfall was the highest in the desert areas of north- western India due to zero or negligible realized tree cover relative to the small climatic maximum potential tree cover. Hence, we excluded these areas from the shortfall map, as these areas are probably unsuitable for restoration through tree planting (Fig 4.2 b)

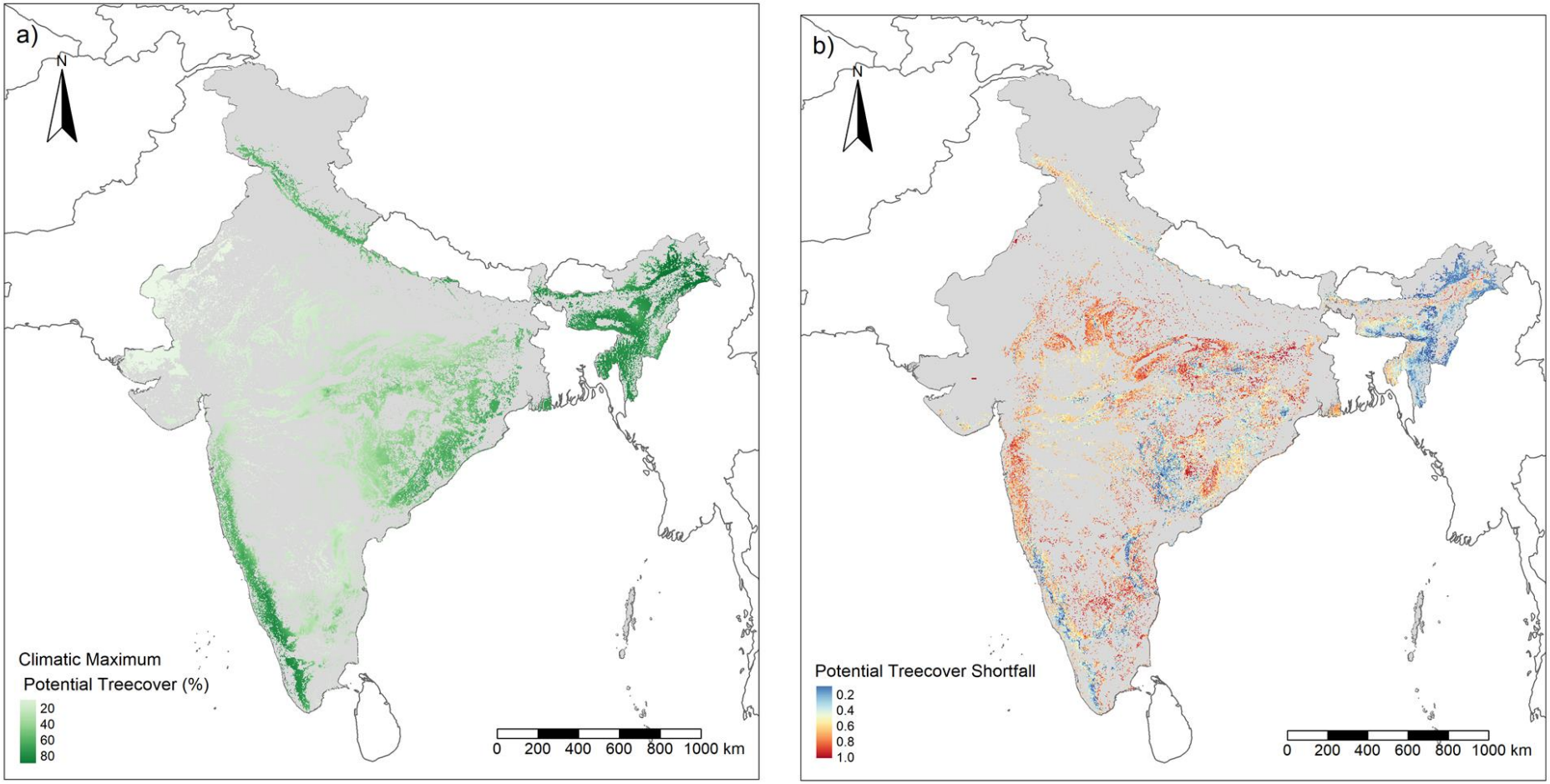


Figure 4.2 Climatic maximum potential tree cover (%) is the maximum tree cover based on the mean annual precipitation (MAP) and maximum climate water deficit (MCWD) regimes, fitted with a 95th percentile smooth additive quantile regression model. The climatic maximum potential tree cover is highest in north - eastern India and the stretch of the Western Ghats along with western coast of peninsular India (a). Potential tree cover shortfall (PTCS) is a measure of the convergence/divergence of the realized tree cover from the climatic maximum potential tree cover with range 0-1, where values close to 1 indicate divergence of realized tree cover from the climatic maximum potential tree cover or there is zero realized tree cover (shades of red), and values close to 0 indicate convergence (shades of blue). Note that all areas less than 1300mm MCWD has been excluded, predominantly north - western India, as these areas have zero tree cover and are areas of caution for tree planting activities (b). Study area (coloured) was delineated by excluding built-up land, water bodies, aquaculture, mangroves, salt pans, permanent wetlands, snow and ice and all forms of agriculture (croplands, shifting agriculture, irrigated croplands) and by excluding all land area greater than 1200m in elevation from terrestrial land area of India (grey) (Fig S4.5)

We next analysed how much of the tree cover shortfall in the core savanna and mixed forest savanna zones can be explained by physical factors and disturbance factors. Significant physical factors were sand fraction, topography and significant disturbance factors were burn frequency, sheep herbivory pressure and human population density (the latter a proxy for general intensity of human activity) (deviance explained = 48.6%). Shortfall decreased with increasing soil sand fraction (increased certainty in the 10- 50% sand fraction interval). Tree cover shortfall increased significantly up to Heat Load Index = 0.87, beyond which it decreased i.e. shortfall was least in cool north easterly facing regions (Heat Load Index ~0), increased linearly with increased incident solar radiation, but decreased beyond a threshold towards warm south westerly facing regions (Heat Load Index ~1). We estimated a similar significant relationship between shortfall and Topographic Position Index (TPI): shortfall was the least in the bottom of valleys but increased in lower slopes and flat areas (up to TPI=0) and then significantly decreased in middle slopes, upper slopes and ridges (Fig 4.3; Table S4.4).

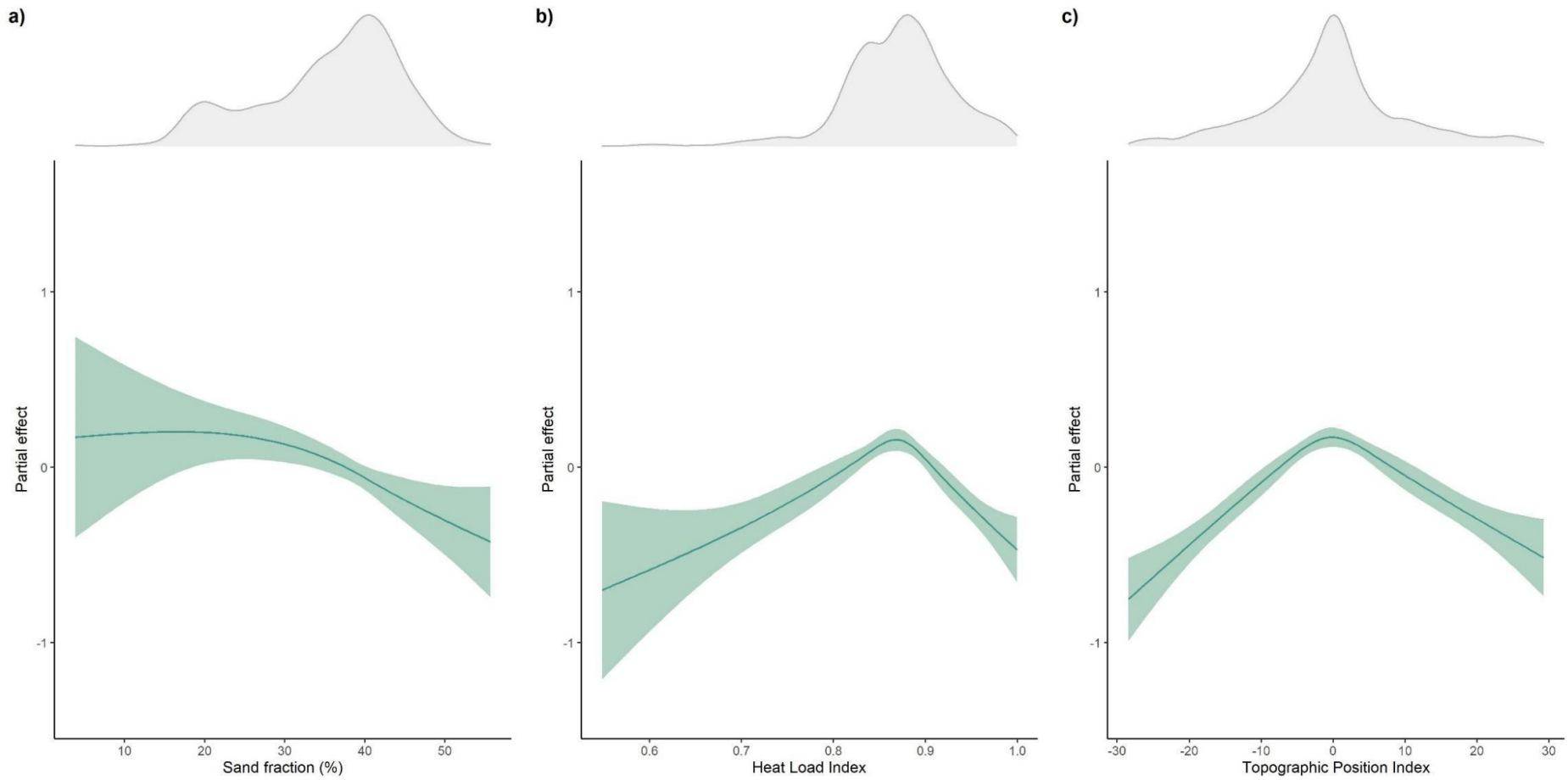


Figure 4.3 Partial effect plots of physical drivers of potential tree cover shortfall (PTCS) (Fig 4.2 b)) across sampled points in the core savanna and mixed forest savanna zones (n= 3118). Each plot shows the additive contribution of the respective driver on the linear component, which is exponentiated to obtain PTCS. Within each plot, the density plot (grey) shows the distribution of the respective driver in the data considered. There was a decreasing trend of shortfall with increase in sand fraction (%) (a). There was a steady increase in shortfall in cool north easterly areas (up to Heat Load Index = 0.87) after which shortfall decreased towards warm south westerly areas (b). Shortfall was the least in valleys but increased towards flat areas (up to Topographic Position Index = 0) and decreased towards ridges (c). Note that only significant relationships are shown, and the shaded area is the 95% confidence intervals

There were strong linear effects of human population density on shortfall, indicating that realized tree cover does not meet the climatic maximum potential in areas with high anthropogenic disturbances. Interestingly, we found a threshold- based relationship between herbivory pressure of sheep and shortfall. For low levels of herbivory pressure, there was a decreased shortfall with increasing herbivory. However, beyond 1 tonnes km^{-2} yr^{-1}, the shortfall significantly increased. Lastly, we found a significant relationship between shortfall and burn frequency. However, considering the highly skewed and limited burn frequency across the two zones (0-13 fires in the 21 years), we concluded the trend of decreasing shortfall with increase in burn frequency to be unreliable (Fig 4.4; Table S4.5).

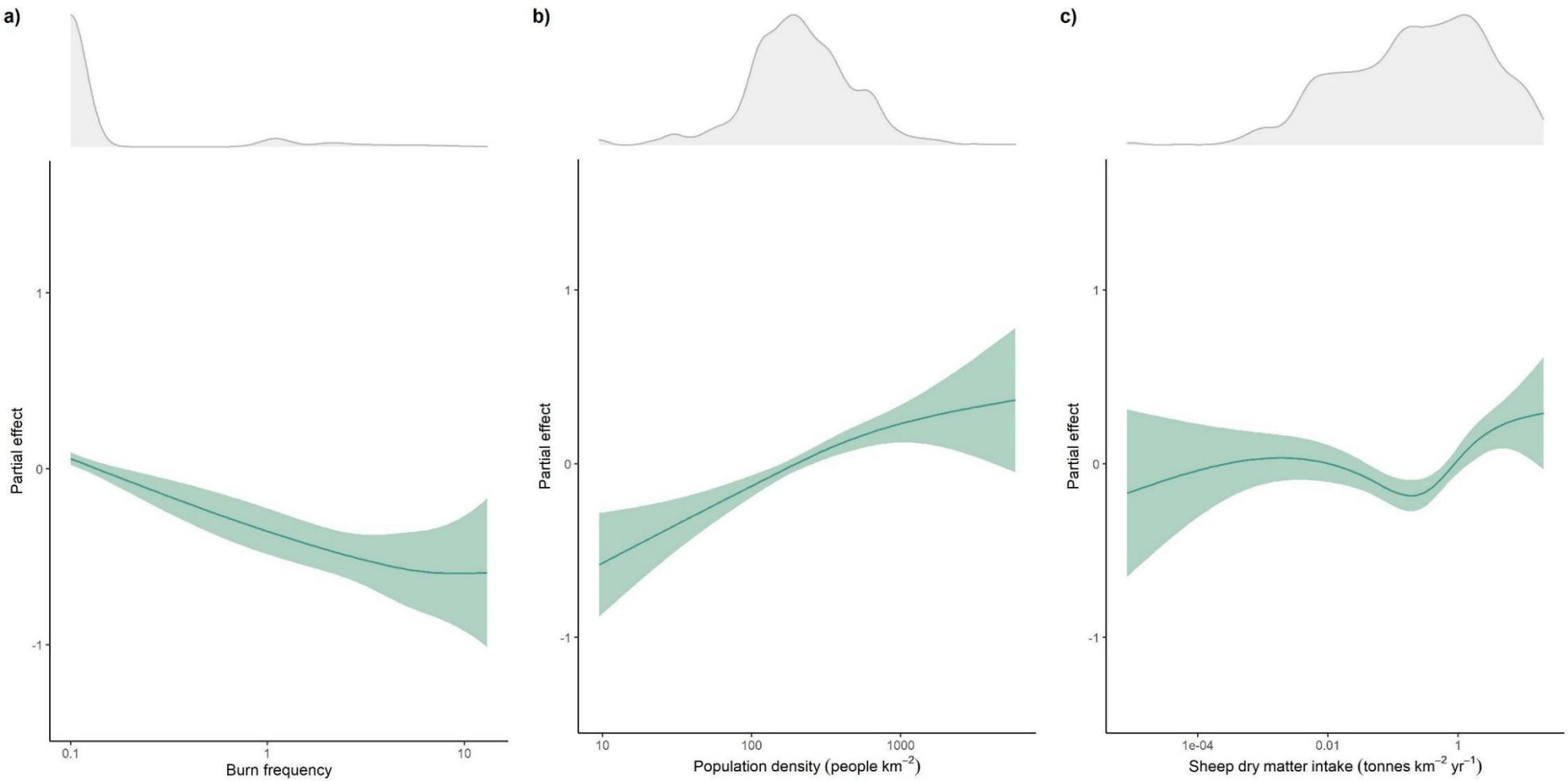


Figure 4.4 Partial effect plots of disturbance drivers of potential tree cover shortfall (PTCS) (Fig 4.2 b)) across sampled points in the core savanna and mixed forest savanna zones (n= 3118). Each plot shows the additive contribution of the respective driver on the linear component, which is exponentiated to obtain PTCS. Within each plot, the density plot (grey) shows the distribution of the respective driver after log transformation. There was a steady decrease in shortfall as burn frequency increased, considering the highly skewed burn frequency across the data (a). Shortfall increased with increasing human population density (b). There was no significant trend between shortfall and sheep herbivory up to 1 tonne km^{-2} yr^{-1}. However, beyond this threshold there was a strong linear increase in shortfall with sheep herbivory pressure (c). Note that only significant relationships are shown, and the shaded area is the 95% confidence intervals

4.5 Discussion

Our study examines key drivers of tree cover across the Indian subcontinent , filling an important research gap in our understanding of the distribution and drivers of South Asian savanna and forest biomes. Our analyses suggest that in the monsoon-driven climate of the subcontinent, seasonal water limitation, as measured by maximum climate water deficit (MCWD), as well as mean annual precipitation (MAP) limit maximum potential tree cover. Combining tree cover with empirical information on the occurrence of endemic savanna understorey plants, we delineated (1) a core savanna zone (930 – 1300 mm MCWD) where there is a clear ceiling of maximum tree cover ~40% and there is presence of majority savanna plants and (2) a mixed savanna forest zone (580 – 930 mm MCWD) where there is no limit on maximum tree cover and savanna plants exist. We found that local microenvironmental features (low sand fraction and topography) and anthropogenic disturbances significantly reduced tree cover from reaching its climatic maximum potential. Further, although low levels of herbivory did not affect tree cover, beyond a threshold, there were significant declines in tree cover with increasing herbivory.

4.5.1 Seasonality and soil texture drive savanna and forest biome distribution

We found a significant sigmoidal response of realized tree cover to maximum climate water deficit (MCWD). This corroborates the general hypothesis that precipitation seasonality is an important driver of biome distributions, with realized tree cover being negligible in dry, drought-prone regions and high in wet regions with infrequent droughts (Good & Caylor, 2011; Holmgren et al., 2013; Lehmann et al., 2011). Indeed, there is evidence that expansion of India's savannas in the Holocene was reinforced by the reduced monsoonal moisture supply, despite constant fire activity (Riedel et al., 2021). An intuitive explanation is that seasonal water stress drives differences in survival and growth rates of forest and savanna trees and savanna grasses (Sankaran et al., 2004). These insights suggest that predicted changes in seasonal water stress due to climate change (Konapala et al., 2020) via their effects on tree cover are likely to drive future changes in the distributions of savanna and forest in South Asia (Kumar et al., 2020).

We found that soil texture, primarily sand fraction, can limit tree cover below its climatic potential, similar to findings in Africa (Bucini & Hanan, 2007; Case & Staver, 2018; Kulmatiski & Beard, 2013; Sankaran et al., 2005). Increased soil sand content explained the increase in tree cover. By increasing drainage, high sand content can drain moisture in shallow soil layers but can lead to an accumulation of water in deeper layers, such that deep-rooted trees can access water at greater soil depths (Holdo et al., 2018; Sankaran et al., 2004; Schenk & Jackson, 2002). In contrast to our findings, a recent study of continental Southeast Asian savannas found no significant effects of soil sand fraction on tree cover (Pletcher et al., 2022), suggesting that our results are not generalizable across all Asian savannas. While monsoonal rains characterise all of continental Asia, dry seasons in Southeast Asia are shorter (3-5 months; (Bunyavejchewin et al., 2011)) than in South Asia (6-8 months, this study), while island south-east Asia is highly seasonal. We suggest that studies on the interactive effects of soil texture and seasonality, along with the functional rooting characteristics of dominant savanna and forest tree species, across the seasonality gradient will yield interesting insights into the factors structuring vegetation in savanna and forest biomes.

4.5.2 Novel insights of topography and disturbances on tree cover shortfall variation

At the landscape scale of our analyses, we found significant relationships between tree cover shortfall and topography. We suggest that the threshold responses of tree cover in valleys, flat areas, slopes and ridges are mediated through variation in soil moisture and ground water dynamics across the topographic gradient (Kim & Eltahir, 2004; Rossatto et al., 2012). Tree cover was greatest on both ridge tops and valley bottoms, and least in flat areas. This suggests diverse water uptake strategies from deep soil depths as trees have deep roots and hence deep root niches (Rossatto et al., 2012). Contrary to our findings, valleys in the highlands of Central Brazil, tend to accumulate water at shallower depths, thereby supporting grasses (Rossatto et al., 2012). However, in drier climates, water logging in wet, shaded valleys can support tree cover over grasses (Villalobos-Vega et al., 2014). Clearly, in addition to topography related soil moisture variations, there is a seasonal dimensionality that regulates tree and grass cover existence at different elevations (Kim & Eltahir, 2004; Rossatto et al., 2012; Villalobos-Vega et al., 2014). It also might be the case that temperature

gradients related to topography, creates heterogeneity in energy distribution, thereby driving responses of tree cover (He et al., 2017). Warming can correspond to increased woody cover (He et al., 2017), as evident in our results of decreasing shortfall beyond a threshold towards warm south westerly areas.

Topography is also likely to influence anthropogenic interactions, with flat areas more prone to small-scale clearing than slopes or ridge-tops (Sandel & Svenning, 2013). We found clear patterns of decreasing tree cover with increase in anthropogenic disturbances. After accounting for land use and cover conversion, as we have done in the study area delineation, there are various activities such as fuel wood collection, small- scale farming and harvest of non-timber forest products that affect tree cover from reaching its climatic maximum potential. Similar evidence of the impact of human disturbances are evident in savanna and forest biome distribution in Africa (Aleman et al., 2017; Bucini & Hanan, 2007) and South America (Rull et al., 2015).

Herbivory pressure has direct effects on tree cover shortfall and promoting savanna biome distribution (Jia et al., 2018; Oliveras & Malhi, 2016; Staver et al., 2011b). At moderate densities, grazers such as sheep can increase tree growth rates by consuming grasses (Oliveras & Malhi, 2016; Ratnam et al., 2011; Sankaran et al., 2005). Hence at low levels of grazing, there can be an increase in woody biomass and tree cover as shown in our study (Sankaran et al., 2004; Staver & Bond, 2014). However, the clear threshold after which there is an increase in tree cover shortfall, indicates that at intense levels of grazing there are additional factors at play. Like wild herbivores, high densities of livestock with diverse seasonal feeding strategies (Staver et al., 2021) can damage trees and consume saplings (LaMalfa et al., 2021), ultimately leading to increased shortfall. Complimentary to livestock, it would be valuable to understand the impacts of wild herbivores on savanna biome maintenance considering the relatively distinct and last remnant populations in south and southeast Asia (Sankaran & Ahrestani, 2016) and the possible different pressures between wild herbivores and domestic livestock (Hempson et al., 2017).

Although we found a significant and decreasing trend for tree cover shortfall with increasing fire frequency, these results are difficult to interpret for multiple reasons. First, we emphasize the limited range and the high skew in fire frequencies in these data (mean fire frequency is 0.01 (+/- 0.05) with a range of 0-0.6 i.e. 0-13 fires in the 21 year time period). The fire return interval in South Asia is significantly shorter and the fires are of small spatial extent and of reduced intensity, compared to vegetation fires in Africa and possibly South America (Bowman et al., 2020; Giglio et al., 2018). For example, in 2001-2017, 16% of African savanna area burned as opposed to 1.6% in south and southeast Asia (Ratnam et al., 2019) and small fires accounted for 90- 150% of the burned area in south and southeast Asia versus 30% in Africa (Randerson et al., 2012). Hence, the small and less intense fires might continue to maintain or even increase tree cover. Additionally, we suspect that fires across India are difficult to detect accurately using satellite remote sensed products which have been confirmed globally (Laris, 2005; Ramo et al., 2021; Roy & Boschetti, 2009; Vadrevu et al., 2019). Reduced fire activity has been reported in savannas and grasslands mainly because of agricultural expansion and intensification (Andela et al., 2017), which is evident considering the large extent of India's agricultural lands (Moulds et al., 2018; Roy et al., 2015). With the strong evidence of the role of fire on savanna biome distribution in south-eastern Asia (Pletcher et al., 2022) and globally (Bond, 2005; Bond et al., 2005; Lehmann et al., 2011; Staver et al., 2011a) , we conclude that though significant, our findings of decreased tree cover shortfall at high fire frequency requires additional exploration.

4.5.3 Implications for ecosystem restoration and tree planting for climate change mitigation

Tree planting, especially for climate change mitigation, is gaining momentum globally and in India (Busch & Mukherjee, 2018; Roy & Fleischman, 2022). With various estimates of area of opportunity and climate change mitigation potential by tree planting being analysed globally and nationally (Basuki et al., 2022; Gopalakrishna et al., 2022; Zeng et al., 2020), there is a need for understanding the consequences on non-forest ecosystems (Temperton et al., 2019; Veldman et al.,

2019). We recommend improved delineation of ‘no-go’ areas of savannas when planning tree planting activities. For instance, estimating the trajectory of tree cover across a limiting factor of water deficit, can reveal a core savanna zone where afforestation activities are not appropriate. The presence of a mixed forest savanna zone reveals that specific strategies accounting for topography and impacts of human disturbances are to be considered. Factors such as grazing management and reintroduction of fires that control tree cover are to be examined (Buisson et al., 2019, 2020), requiring nuanced restoration strategies that go beyond simple mass tree-planting. Lastly, our study shows that there are landscapes traditionally dependent on fire that are becoming increasingly decoupled from respective fire regimes. Such landscapes that might differ in function and form from recent or historical states, require novel restoration strategies (Hobbs et al., 2009; Kéfi et al., 2016; Suding et al., 2004).

4.6 Data Availability Statement

All data used in this study are freely available and are listed, described and referenced in Table S4.2. The empirical data about the savanna understorey plants from Nerlekar et al., (2022) is published with the respective manuscript. No new and/or additional data was generated.

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4.8 Supplementary Information

4.8.1 Supplementary Methods

4.8.1.1 Study area delineation and sampling strategy

All union territories, except that of Jammu and Kashmir (which was treated as a state), were included as part of the state they are in (Table S4.1). We excluded Andaman & Nicobar and Lakshadweep islands from here onwards, due to lack of remaining spatial datasets. We do not include the disputed areas of Aksai Chin and Azad Kashmir and Gilgit- Baltistan, in the former princely state of Jammu and Kashmir in these analyses. These analyses were completed at the native resolutions of 100m and 60m of the two main datasets (Roy et al., 2016) and (Roy et al., 2015), WGS 1984 UTM 43N and then resampled to 250m resolution using the nearest neighbour method and WGS 1984 coordinate system.

Of the 9600 sampled points across the mean annual precipitation (MAP) strata in the study area, we excluded 1046 points (10.8% of total n=9600) due to lack of data of herbivory for buffalo, goat and sheep (n=926), sand fraction (n=212), heat load index (HLI) (n=30) and topographical position index and landform classes (n=136).

4.8.1.2 Selection of environmental drivers to predict percentage tree cover

We processed mean annual percentage tree cover and 15 climatic, edaphic, topographic, fire and herbivory pressure drivers (Table S4.2). For the climatic variables, considering the significant correlations between DSL and mean annual aridity ($r > 0.7$, $p<0.05$ (Dormann et al., 2013)) with the remaining climate variables, we finally used MAP and MCWD derived from potential evapotranspiration in the statistical analyses. We excluded VPD because it was correlated with MAP and MCWD ($r > 0.7$, $p<0.05$ (Dormann et al., 2013)). We would like to highlight that MCWD is a nuanced measure of absolute rainfall seasonality indicating severity of drought, and along with MAP, it captures the water balance that drives vegetation distribution in biomes stress (Malhi et al., 2009; Schwartz et al., 2020).

We completed a correlation matrix based principal coordinate analysis to reduce redundancy of herbivory pressure of different domestic livestock (Fig S4.6). Three principal coordinate axes accounted for 77.5% of the cumulative explained variance, where PC1 explained 30.1%, PC2 explained an additional 26.6% and PC3 further explained an additional 20.8%. Horse and buffalo herbivory pressure were associated with PC2, and goat and cattle herbivory pressure were associated with PC1 (Table S4.3).

We randomly sampled 160 points to qualitatively assess the tree cover, using Google Earth imagery at scales ranging from 1:7000 to 1:25000. We assessed the presence or absence of tree cover, recorded a qualitative description of vegetation such as tree cover, grass cover, and shrub/ scrub cover and any evidence of anthropogenic activities such as paths or evidence of agriculture, within a 250m square buffer surrounding each point. We found wide ranging tree cover including bare ground with minimal tree cover or vegetation including a topographical profile, mixture of grass and thick tree cover across valleys, slopes and ridges and mixture of scrub, shrub and grass with bare ground and anthropogenic signs of paths and agricultural clearings. Based on this qualitative assessment of tree cover, we decided to include topographical variables of heat load index (HLI) and topographical position index (TPI) delineating six landforms – valley, lower slop, flat area, mid-slope, upper slope, ridge, as drivers in the statistical analyses. We found no significant differences in the sand fraction across the six landform types ($F_{(5,8548)}$= 0.758, $p>0.05$). However, we found significant differences in tree cover across the six landform types ($F_{(5,8548)}$ = 52.69, $p<0.05$), with significant differences in tree cover all pairs of landforms except for valleys and ridges and lower and upper slopes.

All variables were resampled to 250m resolution and WGS 1984 coordinate systems using bilinear interpolation method, unless mentioned otherwise. We completed all analyses in R (R Core Team, 2020), unless mentioned otherwise.

4.8.1.3 Distribution of tree cover and environmental drivers considered

We extracted the tree cover found in the location of endemic savanna plants from (Nerlekar et al., 2022) coupled with the sampled tree cover data to inform our analyses of drivers of tree cover and drivers that limit tree cover from reaching its maximum climatic potential. Nerlekar et al., (2022) consists of 206 locational points of endemic savanna plants (47 families, 34 woody species with non-woody species being dominant- 135 forbs and 37 graminoids) assembled from a systematic review. Of the 206 points from Nerlekar et al., 2022, 98 points (47.5%) are within our study area. The remainder of the empirical data, which is outside our study area, had a range of current LULCs. Current cropland (46.3%), built-up area (13%) and shrublands (11.1%) were the dominant LULCs of the endemic savanna points that fell outside the delineated study area. Please note that this empirical data is not an exhaustive list of endemic savanna plant species in India (refer to Nerlekar et al., (2022) for additional details). Also, please note that this analysis was limited to peninsular India which means that if endemic savanna plants are found in peninsular India and extra-peninsular India, this data was not included. Across the 206 points, the range of percentage tree cover is 0.95-59.4, MAP is 376.5- 1921.7mm, MCWD is 579-1435mm, sand fraction is 12.17 -52.86 %, FRP is 0 – 33.38 MW, burn frequency is 0-7, buffalo dry matter intake is 0 – 117.45 tonnes^{-1}km^{2}yr^{-1}, goat dry matter intake is 0.28-13.29 tonnes^{-1}km^{2}yr^{-1} and sheep dry matter is 0.00-19.61 tonnes^{-1}km^{2}yr^{-1}, human population density is 9.45- 29636.4 people/km^2. Of the 8554, 3492 points were in the core savanna and mixed forest savanna zones (Fig S4.8 and Fig S4.9). We found no significant difference in tree cover against fire frequency across the core savanna and mixed forest savanna zones (χ^2 = 11.0, p=0.61).

4.8.1.4 Drivers that limit tree cover from reaching its climatically determined maximum potential

From the 3492 sampled points in the core savanna and mixed forest savanna zones, we excluded 9.5% because these points have shortfall > due to artefactual effects (n= 3336). We further excluded 5 points, as areas with human population density >10,000 people km^{-2}, to exclude outliers. Finally, we excluded 213 sampled points to include a gaussian estimate of TPI, resulting in 3118 points being

used in the final analyses. We excluded these 213 points by removing all points beyond 2 SD of TPI. To account for the skewed distribution and kurtosis of some of the environmental drivers (Fig S4.9), we log transformed herbivory pressure drivers and fire intensity and fire frequency drivers. Since buffalo herbivory pressure, burn frequency and fire intensity have 0 values in the final sample of points, we added a constant of 1/10th of the least non zero values in the respective driver, to allow for convergence of models.

We used generalized additive models (GAMs) because its flexibility to accommodate non-Gaussian data, to fit non-linear relationships between tree cover and the drivers and to account for spatial autocorrelation structure in the sampled data. We reduced overfitting of the models in three ways (1) penalized the cubic regression smoothing function for each driver (2) by using a double penalty approach implemented using the *select()* function in the *mgcv* R package (Wood, 2011) and (3) using the Restricted Maximum Likelihood criterion for convergence. We specified an approximation of 5 or fewer knots in the basis function for each driver. We used the beta family distribution with a logit link in the analyses. None of the drivers had a linear relationship with average percentage tree cover. To calculate the climatically determined maximum potential of tree cover, we used the 95th percentile smooth additive quantile regression model with 5 knots for the basis functions of MCWD and MAP (Fig S4.7).

We constructed two models to evaluate the relationships between environmental drivers and mean annual percentage tree cover. In the first model, we considered soil and topography drivers only (Equation 1). In the second model, we included all drivers. We modelled the interactive effects of fire intensity and fire frequency with 5 knots in the basis functions and 12 knots in the basis functions of the spatial structure x, y (Equation 2).

$$\log\frac{PTCS}{1-\ PTCS} = \alpha + s_1(sand\ fraction) + \ s_2(HLI) + s_3(TPI) + \ s_4(x)(y)$$

(*Equation 1)*

$$\log\frac{PTCS}{1-\ PTCS} = \alpha + s_1(FRP) + s_2(fire\ frequency) + \ s_3(FRP)(fire\ frequency) + \ s_4(sand\ fraction) + s_5(buffalo\ dry\ matter\ intake) + \ s_6(goat\ dry\ matter\ intake) + \ s_7(sheep\ dry\ matter\ intake) + s_8(human\ population\ density) + \ s_9(HLI) + s_{10}(TPI) + \ s_{11}(x)(y)$$

(*Equation 2)*

where the link function is logit link that links the shortfall to the drivers listed, α is the intercept and $s_i(driver_i)$ denotes the smooth non-parametric functions.

For the first model i.e. including only physical drivers, we found that the deviance explained from the model 39.5% was close to the deviance explained when using the test data 34. 6%. The validity was additionally reinforced by the close root mean square error of the model 0.376 and that when using test data 0.377. We had similar findings with the second model considering all drivers i.e. similar deviance explained when using the testing and training data, 43.4% and 36.5% respectively and similar root mean square errors when using both data (0.385 when using training data and 0.384 when using testing data).

4.8.2 Supplementary Tables

Table S4.1 Details of the state to which Indian union territories were included as part of for the analyses after estimation of maximum biophysical potential of forest restoration; Andaman and Nicobar and Lakshadweep islands have been excluded from the analyses at this point.

Chandigarh	Punjab
Dadra and Nagar Haveli and Daman and Diu	Gujarat
Puducherry	Tamil Nadu

Table S4.2 Details of datasets used with information about processing

Group	Dataset and reference	Processing information	Temporal and spatial resolution information
percentage tree cover	percentage tree cover MOD44B.006 Terra Vegetation Continuous Fields (yearly)	We calculated the mean annual percentage tree cover from annual tree cover information, using Google Earth Engine (Gorelick et al., 2017).	2000-2020, 250m, WGS 1984 Geographic Coordinate Systems (GCS)
climate	mean annual estimates of precipitation ($mmyr^{-1}$) (MAP), dry season length (DSL) (months), aridity index (precipitation/potential evapotranspiration), vapor pressure deficit (VPD) (kPa) and maximum climate water deficit (MCWD) (mm)	We calculated the mean annual estimates of the climatic variables using TerraClimate monthly climate and climatic water balance product for global terrestrial surfaces (Abatzoglou et al., 2018). We extracted yearly estimates of VPD, precipitation and potential evapotranspiration using Google Earth Engine (Gorelick et al., 2017) and we estimated MAP, DSL and aridity following Schwartz et al., 2020. We calculated MCWD by resetting the climate water deficit to the wettest month of the year following Aragão et al., 2007 and Malhi et al., 2015. To calculate MCWD, we used potential evapotranspiration, as opposed to actual evapotranspiration, because in relatively dry areas with minimal annual precipitation, MCWD derived from actual evapotranspiration breaks down to show reverse trends of water deficit, which is ecologically nonsensical for our study.	1981-2021, 4638.m
fire	mean annual fire radiative power (FRP) (megawatts MW) as a proxy for fire intensity and fire frequency	We estimated mean annual fire radiative power (FRP) (megawatts MW) as a proxy for fire intensity, using VIIRS 375m active fire product (Schroeder & Giglio, 2018) because it appropriately captures fire trends across south and southeast Asia (Vadrevu et al., 2019). We converted the point locations of the active fires to pixels of 375m resolution, considering only those points classified to have 'high' confidence (Schroeder & Giglio, 2018). To account for the limited temporal resolution of the VIIRS 375m active fire product	FRP (2012-2020), 375m and fire frequency (2000-2021) and 500m

		i.e. start date is 2012, we estimated the fire frequency as the number of times an area burned in 2000-2021, using MCD64A1.006 MODIS burned area monthly global 500m product via Google Earth Engine (Gorelick et al., 2017).	
soil	sand fraction (g/100g or percentage)	We used SoilGrids250m version 2.0 to estimate the sand fraction (Poggio et al., 2021). We calculated the weighted mean of sand fraction, considering bulk density (kg/dm^3) across 0 - 5 cm, 5 - 15 cm and 15 - 30 cm as the sand fraction in the 0 - 30cm depth.	snapshot i.e. no temporal resolution at 250m
herbivory pressure	buffalo, goat, sheep, cattle and horse dry matter intake ($tonnes^{-1}km^2yr^{-1}$)	We focused on herbivory pressure from domestic livestock of buffalos, cattle, sheep, goat and horses, the prominent livestock maintained in India (Department of Animal Husbandry, Dairying and Fisheries, Ministry of Agriculture & Farmers Welfare, 2019). We calculated herbivory pressure as the dry matter intake ($tonnes^{-1}km^2yr^{-1}$) of each of the five livestock types. First, we used population census of each livestock type from the Gridded Livestock of the World product, which uses the latest livestock census data from the Department of Animal Husbandry, Dairying and Fisheries, Ministry of Agriculture & Farmers Welfare, Government of India (Gilbert et al., 2018). We calculated the population density as number of livestock heads per unit area (km^2), where area was estimated by excluding permanent water, areas of human population density > 5,000, > 7500 and > 10,000 and core urban areas, and protected areas (Gilbert et al., 2018). Second, we estimated the dry matter per day of each livestock type as the product of population density of each livestock type and metabolic demand (kg dry matter/day). We calculated metabolic demand using the equation $0.021*M^{0.716}$, where M is the body weight (Wolf et al., 2013). We used the mean adult body weight of both male and female types for each livestock type from Singhal et al., 2005. We used this approach, as opposed to IPCC based methods, because it provides a uniform method for all types of herbivores, with limited data requirements.	snapshot i.e. no temporal resolution at 10km
topography	heat load index (HLI) and landform classification based on topographic position index (TPI)	Based on the qualitative assessment using visual imagery, we calculated two topographical indices – (1) heat load index accounting for surface (in terms of steepness of slope), moisture availability and incident solar radiation, where values	snapshot i.e. no temporal resolution at 30m using

		close to 0 indicate north easterly cool regions and values close to 1 indicate south westerly warm regions. We calculated HLI as per (McCune & Keon, 2002) and (2) topographical position index calculated as per (De Reu et al., 2013), lower values of which represent more sheltered parts of the landscape and higher values indicate exposed areas.	
anthropogenic activities	human population density (people/km^2)	We extracted the 2020 human population density from the Gridded Population of the World (v4) (Doxsey-Whitfield et al., 2015) as a proxy of anthropogenic impacts on the landscape, using Google Earth Engine (Gorelick et al., 2017).	For year 2020 at 927.67m

Table S4.3 Loadings of the different herbivory pressure types against five principal coordinate axes

Herbivory pressure type	***PC1***	***PC2***	***PC3***	***PC4***	***PC5***
Buffalo	-0.1543	-0.6908	0.0173	0.6843	-0.1737
Cattle	0.6919	-0.0927	-0.2429	-0.1004	-0.6659
Goat	0.6976	-0.1359	0.1449	0.1847	0.6630
Horse	-0.0808	-0.7008	-0.1036	-0.6838	0.1545
Sheep	0.0642	-0.0665	0.9533	-0.1405	-0.2505

Table S4.4 Physical determinants of shortfall in the core savanna and mixed forest savanna zones (deviance explained = 45.1%, REML = -591.27)

Factor	**Statistics**		
	effective degrees of freedom	***χ2***	***p value***
sand fraction	2.224	16.85	2.51e-05
HLI	3.632	92.52	<2e-16
TPI	3.674	129.06	<2e-16
x,y	20.45	869.32	<2e-16

Table S4.5 Determinants of shortfall, considering all drivers, in the core savanna and mixed savanna forest zones (deviance explained = 48.6%, REML= -659.63)

Factor	**Statistics**		
	Effective Degrees of Freedom	***χ2***	***p value***
FRP	0.601	1.144	0.153
burn frequency	1.948	75.918	<2e-16
FRP, burn frequency	0.287	0.342	0.266
sand fraction	1.970	14.69	5.63e-05
buffalo pressure	1.011	2.783	0.045
goat pressure	0.000	0.000	0.534
sheep pressure	3.584	26.36	1.12e-06
human population density	1.769	35.907	<2e-16
HLI	3.582	78/408	<2e-16
TPI	3.610	126.769	<2e-16
x,y	61.269	570.826	<2e-16

4.8.3 Supplementary Figures

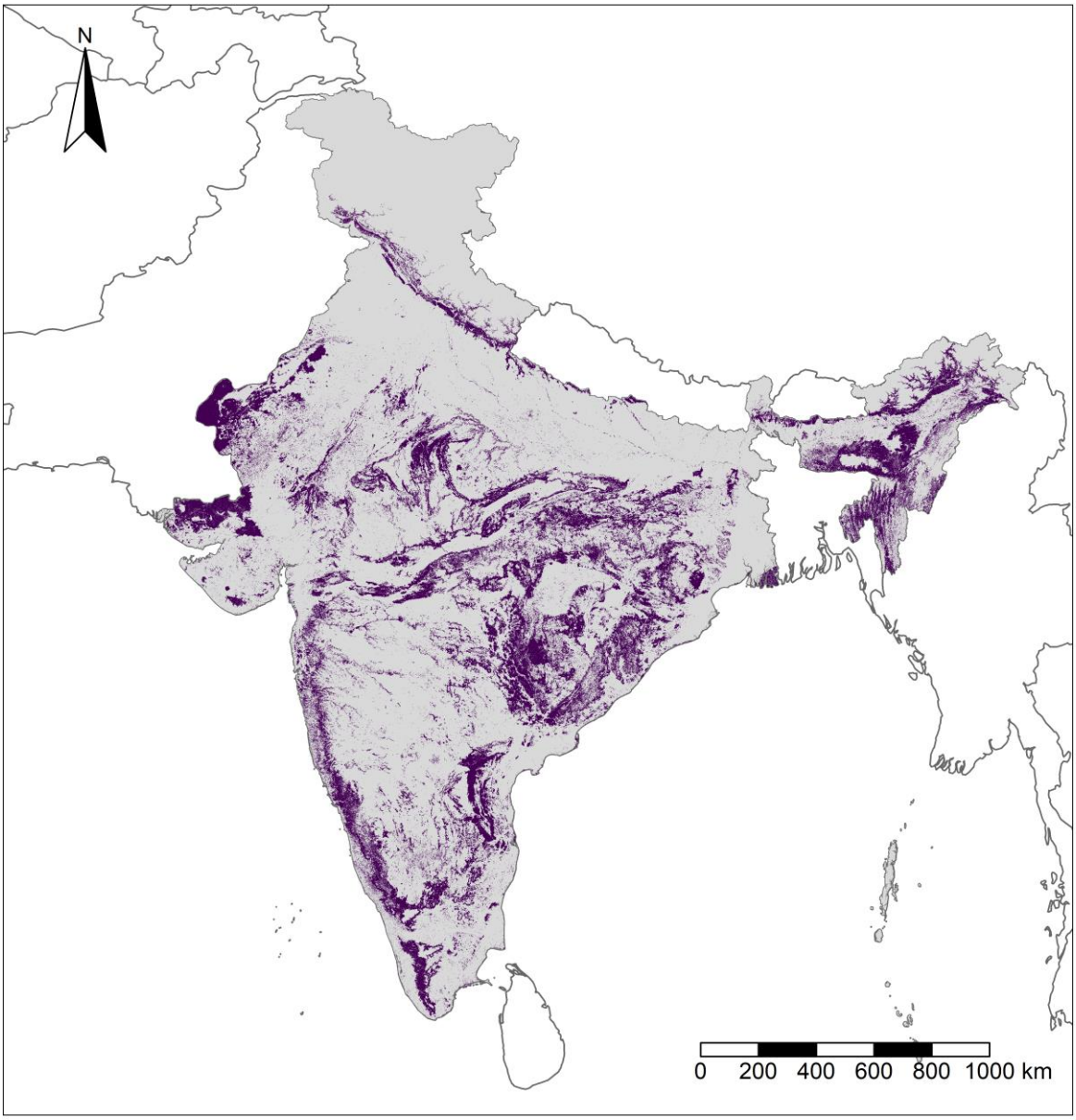


Figure S4.5 Study area for the analyses, shown in purple, after excluding built-up land, croplands, water bodies, aquaculture, mangroves, salt pans, permanent wetlands and snow and ice using Roy et al., 2016 and agriculture, shifting agriculture, abandoned and current jhum from Roy et al., 2015 and all lands classified as irrigated croplands from Ambika et al., 2016, to thoroughly exclude all croplands. Land area with elevations greater than 1200m was also excluded

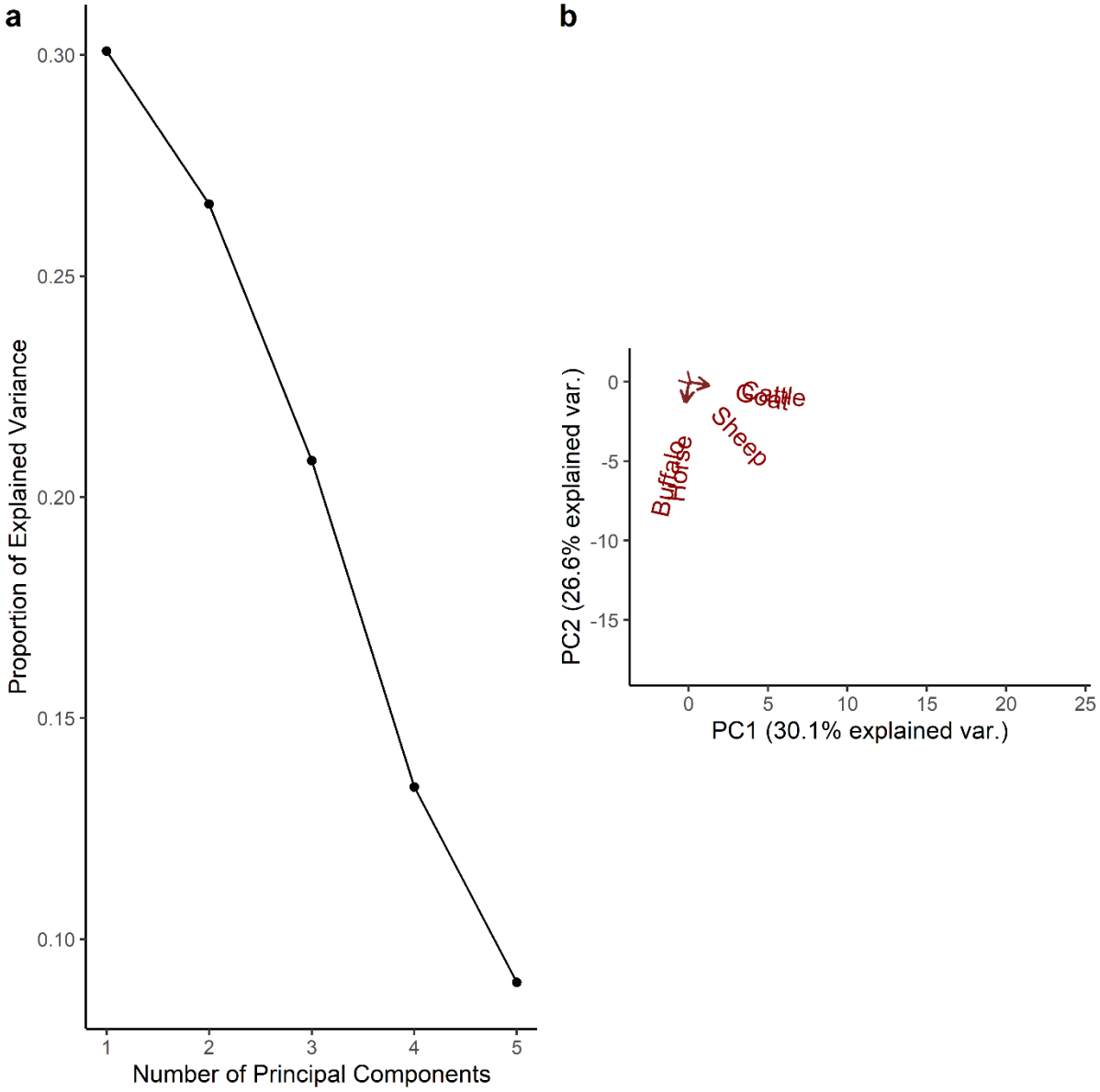


Figure S4.6 (a) Three axes cumulatively explained 77.5% of the variance (PC1 = 30.1%, PC2 = 26.6% and PC3 = 20.8% and (b) horse and buffalo herbivory pressure loaded onto PC2, while goat and cattle loaded onto PC1 and sheep herbivory pressure loaded onto PC3 (refer to Table S3 for loading information)

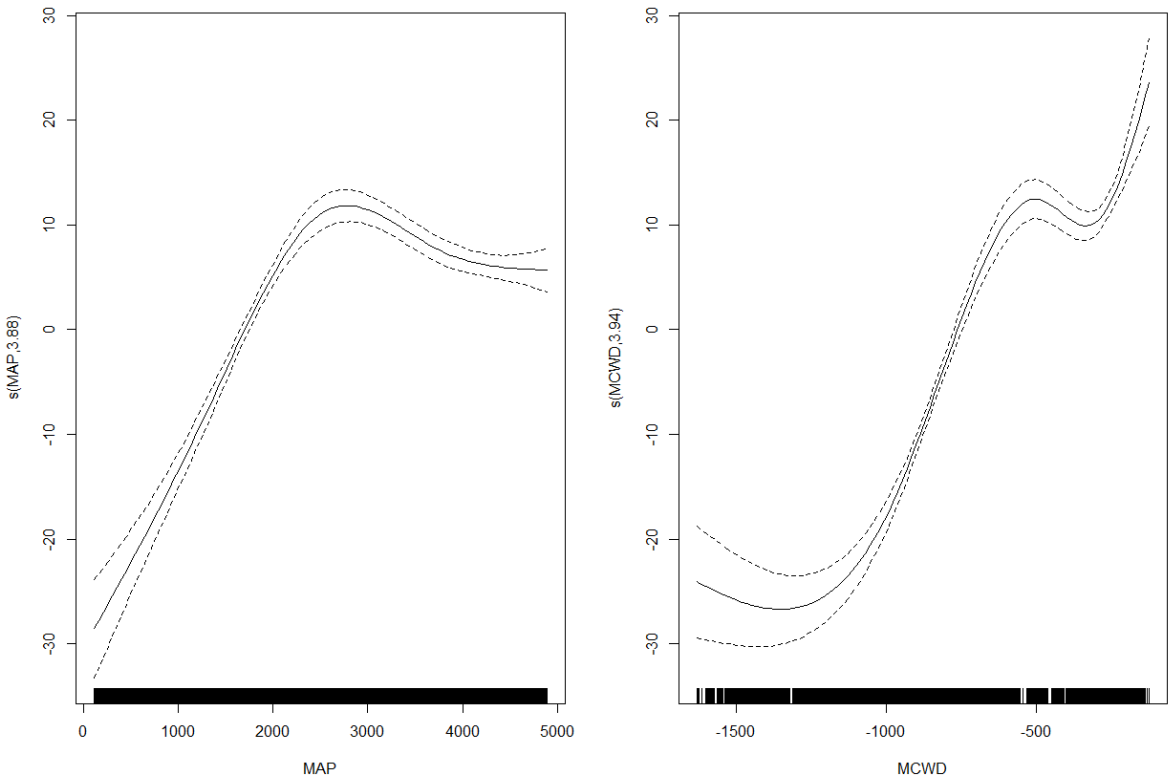


Figure S4.7 Climatically determined tree cover used to define the Potential Tree Cover Deficit was calculated using smooth additive quantile regression models in which 95th percentile smooth additive quantile of tree cover as a function of MAP and MCWD (PET) (deviance explained 92%). s() indicates the smoothed variables and the numbers in the () is the effective degrees of freedom

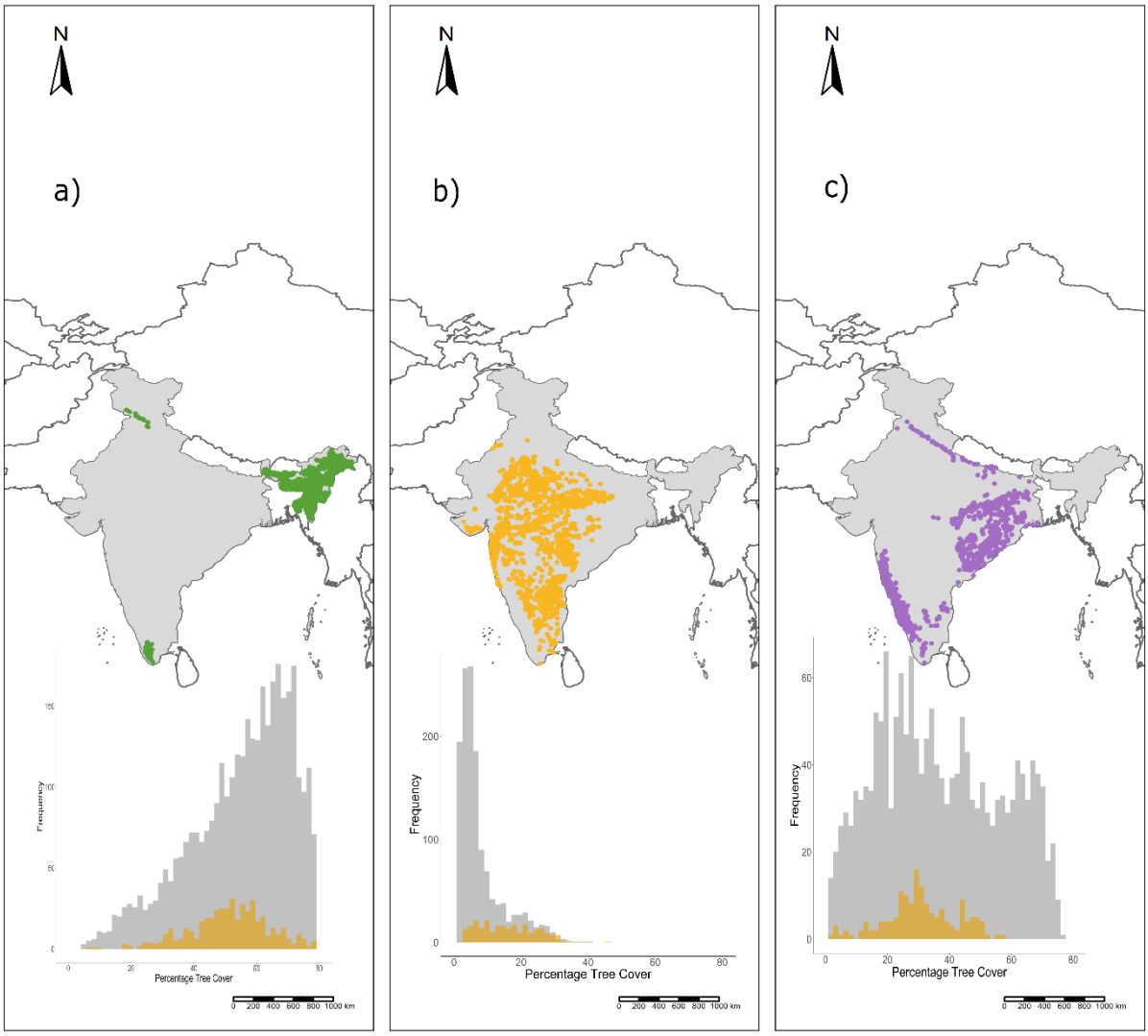


Figure S4.8 Sampled points in the (a) predominantly high tree cover zone in the south western (1300- 1600 mm MCWD) and north- eastern regions of India (0 – 600mm MCWD) (b) core savanna zone (930-1300 mm MCWD) across peninsular India (c) mixed savannah forest zone (580-930 mm MCWD) dominantly present in the Western Ghats and the Eastern Central Highlands. Each respective subplot is the distribution of tree cover in burned (yellow) and unburned (grey) points in each zone. Note that this plot was generated before exclusion of outlier human population density points, considering all points irrespective of being outside 2 standard deviations of the data and artefactual effects resulting in Potential Tree Cover Shortfall >1. Note that for the statistical analyses of drivers and shortfall, points from both zones in (b) and (c) were used

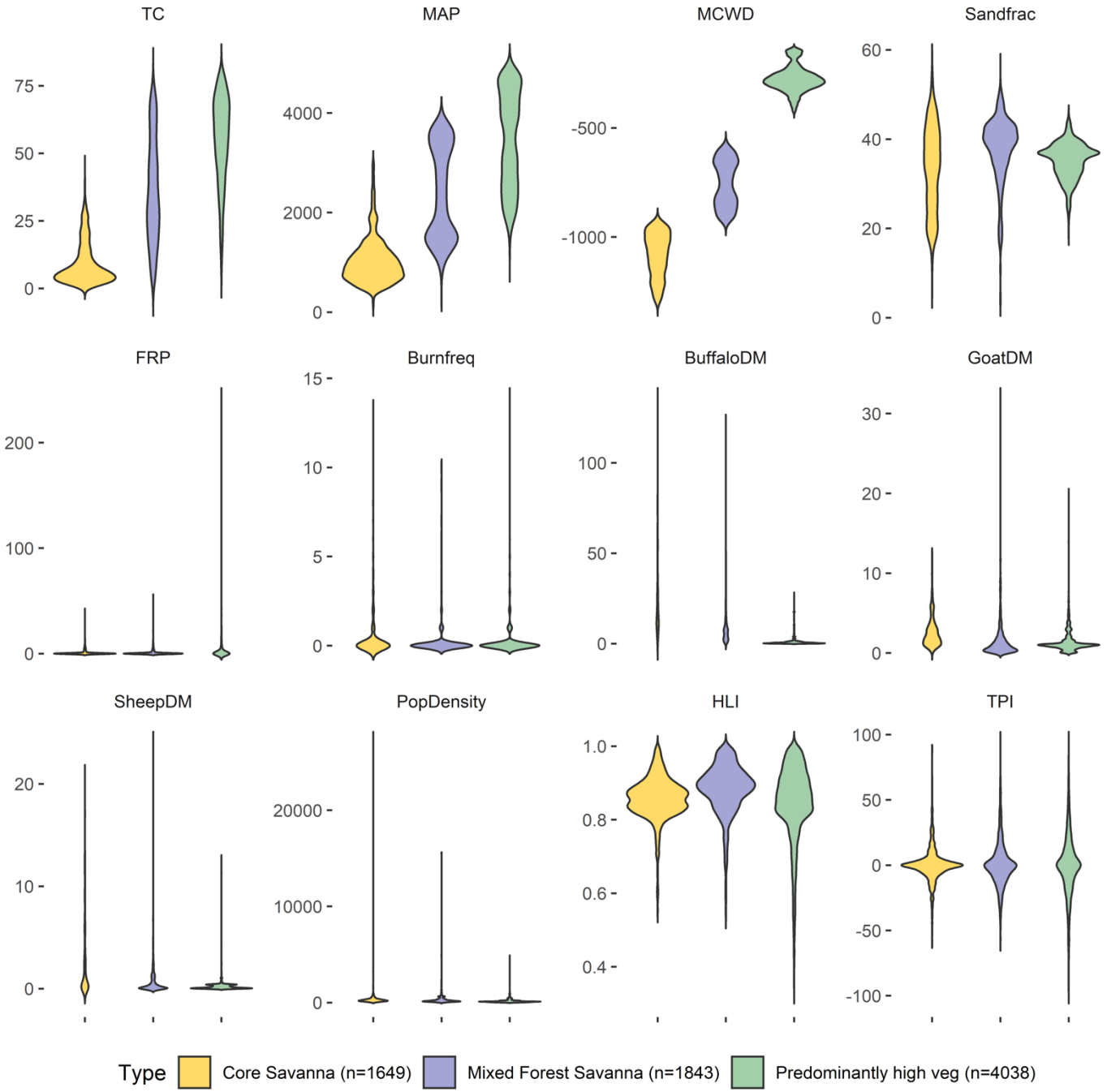


Figure S4.9 Summary statistics of all variables in the predominantly high vegetation zone, points in core savanna zone and points only in mixed forest savanna zone. Note that this plot was generated before exclusion of outlier human population density points, considering all points irrespective of being outside 2 standard deviation of the data and artefactual effects resulting in Potential Tree Cover Shortfall >1. Units of each variable are mentioned in Table S1

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Chapter 5 Trade-offs in nature's contributions to people from multi and single objective forest restoration strategies in India

Linking Statement: After having delineated the opportunity area for forest restoration in *Chapter 3* and having evaluated additional ecological factors for forest restoration in India's savanna and forest biomes in *Chapter 4*, the intuitive next step is to understand how to prioritize India's limited opportunity area for forest restoration, such that multiple environmental and societal benefits are delivered. Hence, in this chapter, I determine the trade-offs between environmental and societal outcomes when designing forest restoration strategies with multiple objectives versus single objectives. I found that multi-objective strategies have the least trade-offs in environmental and societal outcomes considered. There are no spatial patterns in the delivery of these outcomes thereby providing many options for site selection for implementation activities. Lastly, multi-objective strategies are more distributionally equitable than forest restoration strategies with single environmental outcomes.

Contribution Statement: I am currently finalising the manuscript tentatively titled *"Trade-offs in nature's contributions to people from forest restoration strategies in India"*, for submission to peer review. I completed the conceptualization, methodology development and formal analyses of this research. I investigated and visualized the results and am currently revising the manuscript for submission.

This research was based on a preliminary study I completed remotely as part of the Young Scientist Summer Program 2021, International Institute of Applied Systems Analyses (IIASA). I had the good fortune to further develop the ideas and complete this study, in a follow up in-person research summer at IIASA in 2022.

Dr. Piero Visconti and Dr Giacomo Fedele provided data about the biodiversity and societal needs used in the study. Dr. Piero Visconti and Dr. Esther Boere were involved in the methodology

development and investigation phases. Prof Yadvinder Malhi contributed towards investigation of the findings. Ping Yowargana provided overall supervision of the study and was involved in all steps of the analyses. All co-authors are currently helping in edition of the manuscript drafts.

5.1 Abstract

Environmental restoration is inherently a complex activity, with inevitable trade-offs in environmental and societal outcomes. These trade-offs can potentially be large when policies and practices are focused on siloed aspects of nature's contributions to people (NCP). Few global studies have enumerated the trade-offs in NCP and the distributional equity of NCP from restoration strategies. Here, we examine the trade-offs and synergies in the context of forest restoration across India. We apply a systematic conservation planning framework and estimate the trade-offs in climate change mitigation potential, biodiversity conservation (forest habitat created for forest-dependent mammals) and societal reliance for human basic needs. We conclude that multi-objective forest restoration strategies result in the least trade-offs in NCP, delivering 0.6-100% of total climate change mitigation potential, 20.4- 100% of biodiversity requirements and 23.4 - 100% of societal reliance. Multi-objective forest restoration strategies exhibit no strong spatial patterns in delivery of NCP, implying multiple options for on-the-ground implementation. Lastly, multi-objective forest restoration strategies are distributionally equitable, with 38- 41% of total people whose basic needs are met belonging to socioeconomically backwards groups of Indian society. Moving ahead, integrated actions incorporating protection and restoration aimed at multiple outcomes, while considering livelihoods, will help us comprehensively tackle environmental and societal challenges.

5.2 Introduction

While forest restoration has been touted to be a silver bullet for climate change mitigation (Bastin et al., 2019; Griscom et al., 2017), it is in practice a complex endeavour (Brancalion & Holl, 2020; Holl & Brancalion, 2020). There are inherent trade-offs in the benefits accrued from restoring forests (Chhatre & Agrawal, 2009; Ellison et al., 2017; Lamb, 2018). Strategies related to forest management and restoration, such as global pledges like the Bonn Challenge (*Bonn Challenge*, 2011) and policies including financial mechanisms aimed at increasing area restored to forests (Busch & Mukherjee, 2018), provide a carbon-centric approach to decision making, with potential increased trade-offs with other desired outcomes and livelihoods (Locatelli et al., 2015; Temperton et al., 2019). In contrast, strategies addressing multiple objectives, such as Payments for Ecosystem Services (Salzman et al., 2018) and certain national-level policies such as China's Ecological Redline Policy (Bai et al., 2018) can provide a much needed holistic approach for forest restoration by meeting multiple goals (Chazdon & Brancalion, 2019; Donatti et al., 2022).

Systematic conservation planning frameworks are increasingly being used to generate evidence of spatial priorities for conservation activities and trade-offs between multiple ecosystem services globally and regionally (Villarreal-Rosas et al., 2020). Traditionally used for targeting desired biodiversity outcomes from protection strategies (Margules & Pressey, 2000), there are only a few studies, mostly global, that focus on forest restoration. For example, integrated spatial planning, i.e. including both protection and restoration strategies, shows that dual outcomes of global food production and biodiversity can be met from restoring 8-11 % of the land surface, as opposed to strategies designed to optimize only food production or only biodiversity (Fastré et al., 2021). Similarly, by using a spatial optimization methodology, Strassburg et al. (2020) concluded that restoring converted forest lands can result in abatement of 60% of expected biodiversity extinctions and mitigation of 30% of total global emissions, prioritizing Southeast Asia, West African coastal areas, and the Caribbean. Such global studies provide a significant advancement in using simulation generated evidence for better policy and decision making. However, these studies tend to overstate

climate change mitigation potential because of oversimplified assumptions (Doelman & Stehfest, 2022). Also, such studies provide limited insights about the consequences on the people living in the priority areas, especially those marginalized (Fleischman et al., 2022).

The conceptual framework of Nature's contribution to people (NCP) is a tool to understand the relationship between humans and nature in a transdisciplinary, inclusive and action-oriented way (Hill et al., 2021). It includes the concept of ecosystem services, categorized as material, non-material and regulating NCP, with culture and values underpinning all relationships (Díaz et al., 2018; Hill et al., 2021). Hence, it is a conceptual framework that goes beyond economic valuation of conservation and restoration strategies, with emphasis on tangible outcomes to humans (Díaz et al., 2018). NCP in combination with spatial prioritization methodologies is nascent with preliminary findings that priority conservation areas for different NCP rarely coincide (O'Connor et al., 2021). Additionally, NCP provides the opportunity to weave social equity and fairness into the design of conservation actions (Ellis et al., 2019; Pascual et al., 2014). Distributional equity, which is the equitable sharing of costs, benefits, rights and responsibilities is one of four equity aspects that is widely studied in conservation (Friedman et al., 2018; Pascual et al., 2014, however see Brauman et al., 2020). Additionally, there is evidence of the linkages between distributional equity and other equity aspects when doing ecosystem restoration (Wells et al., 2021). However, there are no studies, to our knowledge, that combine NCP trade-offs, spatial prioritization, and distributional equity aspects when designing multi-objective and sole objective forest restoration strategies for environmental and societal outcomes (Villarreal-Rosas et al., 2020).

The issues of trade-offs between NCP and its consequences on distributional equity are among many concerns of forest restoration strategies, especially in tropical countries, including India (Fleischman et al., 2022; Schultz et al., 2022). It provides an exemplary case for two main reasons (1) India has ambitious targets for forest restoration and climate change mitigation (Borah et al., 2018), while having limited suitable land area (Gopalakrishna et al., 2022) (2) India has pledged to align its environmental and socio-economic development through programs such as the Aspirational Districts

Programme (Government of India, 2018) and the National Mission on Biodiversity and Human Well-Being (Bawa et al., 2021). Hence, to best inform this crucial window of opportunity, here we evaluate the trade-offs in NCP from multi and single objective forest restoration strategies across India. We focus on regulating NCP of climate change mitigation potential and forest habitat restored for Indian mammals and material NCP of provision of three human basic needs- energy, housing construction material and livelihoods, from naturally regenerating native forests. We answer three questions – (i) what are the trends in NCP generated from multi- and single-objective strategies? (ii) what are the spatial patterns in the delivery of NCP between the different strategies? and (iii) what is the distributional equity of material NCP from different strategies for prioritizing forest restoration area?

5.3 Methods

5.3.1 Area suitable for naturally regenerating native forests

We estimated the area suitable for naturally regenerating native forests, henceforth opportunity area by (1) modelling the biophysical envelope of native forests at the pan-India scale and (2) sequentially excluding all land uses and covers that cannot be restored to forests, following Gopalakrishna et al., (2022). We modelled the biophysical envelope of native forests as a function of 11 climatic, edaphic, and topographic variables (Fig S5.4) and >10000 GPS gathered points of the presences of different natural forest types, using the random forest algorithm. After exclusions of unsuitable land uses and covers, we estimated the opportunity area that can be restored to native forests to be 3.88 Mha across India (Fig S5.7).

5.3.2 NCP from natural regeneration of native forests in opportune area

5.3.2.1 Regulating NCP- climate change mitigation potential and habitat created for forest dependent mammals

We calculated the climate change mitigation potential as the total above and belowground carbon stocks that would naturally regenerate in the opportunity area, for 30 years, using carbon sequestration rates from Cook-Patton et al., (2020). We estimated the cumulative total carbon stocks accumulated to be 414 MtC (Fig S5.8).

As a proxy for biodiversity protection, we considered 291 forest-dependent mammals with species ranges within the administrative boundary of India, for which data about species ranges and preferences of habitat and elevation were available. Using Jung et al., (2020), we determined the potential forest type that would naturally regenerate in the opportunity area to be that of the nearest forest type, assuming high probability of natural regeneration from nearby seed sources (Crouzeilles et al., 2020). As per Brooks et al., (2019), we estimated the potential area of habitat (AOH) for each species by extracting the area with preferred potential forest type and elevation within its range. For the optimization analysis, we used the opportunity area that intersects with this potential AOH. Lastly, we defined the area of current habitat for each mammal as the potential AOH that is *not* within the opportunity area. The current and potential areas of habitat were then used to estimate the target area to be restored for biodiversity benefits.

We followed a two-step process to estimate the target AOH that is to be restored for each mammal. First, we adapted the area-based target protocol from Jung et al., (2021) and determined a preliminary overall target, considering the current and potential areas of habitat (Table S5.1). Second, from the preliminary target, we deducted the current area of habitat to estimate the final target forest habitat area to be restored for each species. Of the 291 mammal species considered, 80.7% have a current area of habitat that already exceeds the target area needed. Hence, we considered the remaining 56 species for which forest restoration is needed to meet the habitat area requirements. Of these species, 16%, 7% and 1.7% are classified as endangered, near threatened and critically endangered, respectively, 10.7% are listed as vulnerable and data deficient and the remainder are classified as least concern by the Red List Assessment (IUCN, 2020) (Table S5.2).

5.3.2.2 Material NCP- societal reliance for energy, housing construction material and livelihoods

In the opportune area, we calculated the material NCP of each of the three human basic needs as the product of the percentage societal reliance from Fedele et al., (2021) and population density (CIESIN 2018). The product was then weighted by the time taken to reach the closest urban

city centre (Weiss et al., 2018), as the data about societal dependence on nature is only available at state level currently. We estimated 0.48 million, 15.8 million and 15.4 million people are reliant on nature to meet their housing construction material, energy and livelihood needs respectively (Fig S5.9). We included each need separately in the prioritization analyses and present material NCP as the average number of people reliant on naturally regenerating native forests for the three human basic needs.

5.3.3 Systematic conservation prioritization analyses considering different strategies

In 1% increments of the opportune area of 3.88 Mha, we determined the optimum solutions of NCP delivered for four forest restoration strategies, considering specific targets of NCP to be reached in each solution. The four forest restoration strategies were (i) carbon-centric strategy, (ii) biodiversity-centric strategy, (iii) people-centric strategy and (iv) multi-objective strategy. For the first three strategies, we weighted each NCP that the strategy is focused on solely, with no weighting for the remaining NCP. For the multi-objective strategy, we weighted all NCP equally. We considered 100% as the target to be met for the climate change mitigation and material NCP outcomes. The targets for the final set of 56 forest dependent mammals considered had a range 2.1% *(Miniopterus pusillus)* - 100% (for 29 mammals) of the potential area of habitat in the opportune area (Table S5.2).

As there are virtually infinite possibilities of area selection for each of the strategies, we used the integer linear programming approach because it identifies priority opportune areas closest to optimality (Beyer et al., 2016; Naidoo et al., 2008). Such an approach allows us to discuss the implications of the optimal implementation of different strategies, which is useful for informing decision-makers. We solved 400 optimization problems (4 strategies*100 runs for each 1% increment of total opportune area), using the minimum shortfall objective as implemented in *prioritizeR* R package (Hanson et al., 2021). This objective solves for the priority opportune area, by minimizing the overall shortfall for as many targets as possible ,without surpassing the total opportunity area considered in the problem.

5.3.4 Distributional equity of the material NCP delivered

We used the SHRUG database (Asher et al., 2021) to extract the proportion of total population in each of the 5949 subdistricts, that belong to Scheduled Castes and Tribes, the official designation of people who belong to socioeconomically disadvantaged societal groups in India (Revankar, 1971). We assumed the same proportion of socioeconomically disadvantaged people to whom material NCP is delivered to, when considering the total people who will receive material NCP in the priority opportunity area in the subdistrict.

All analyses were completed in R (R Core Team, 2020), unless mentioned otherwise.

5.4 Results

We calculated the NCP from multi and sole objective forest restoration strategies. For climate change mitigation potential, we determined a linear increase in accumulation of carbon stocks with increase in opportunity area restored to native forests. As would be expected, the carbon-centric strategy delivered the highest climate change mitigation potential (6.4 TgC – 414.1 TgC). Between 5%- 21% of the opportunity area, the biodiversity-centric strategy delivered the next best solution with mean 15.6 MtC lower than the carbon-centric strategy (11.3- 32.6 MtC). However, beyond 21%, the multi-objective strategy delivered the second best solution with mean 26.5 MtC lower than the carbon centric strategy (0- 41.8 MtC). The people-centric strategy delivered the least mitigation potential (3.7 TgC – 413.4 TgC) (Fig 5.1 a).

The biodiversity-centric strategy reached the highest number of potential AOH targets for the 56 mammals considered. In this strategy, all targets of potential AOH were met within 17% of the opportunity area with no additional targets met until 46%. Beyond 46% of the total opportune area, all area was prioritized reaching 100% of the targets. This pattern of delivery of NCP from biodiversity centric strategies is reflected across all outcomes (green line in Fig 5.1 a, b and c). The remaining strategies followed a steadily increasing trend of potential AOH targets met. At 17% of

opportune area restored, 78.5%, 14.3% and 12.5% of potential AOH targets were met by the multi-objective, people and carbon centric strategies (Fig 5.1 b).

For material NCP, the people centric and multi-objective strategies followed similar downwards concave increasing trends, with the multi-objective strategy meeting the key needs of a mean of ~56000 people (0- 1.4 million) less than the people-centric strategy. The carbon centric strategy followed a concave upwards increasing trend meeting a mean of 0.6 million people's needs (80,000- 8.4 million). The biodiversity-centric strategy met the least material NCP (21,330 – 3.4 million) (Fig 5.1 c).

Overall, we determined that the outcome of climate change mitigation potential is delivered irrespective of the NCP the forest restoration strategy is focused on. Additionally, majority targets for biodiversity and societal reliance for human basic needs are met within 25% of the opportunity area.

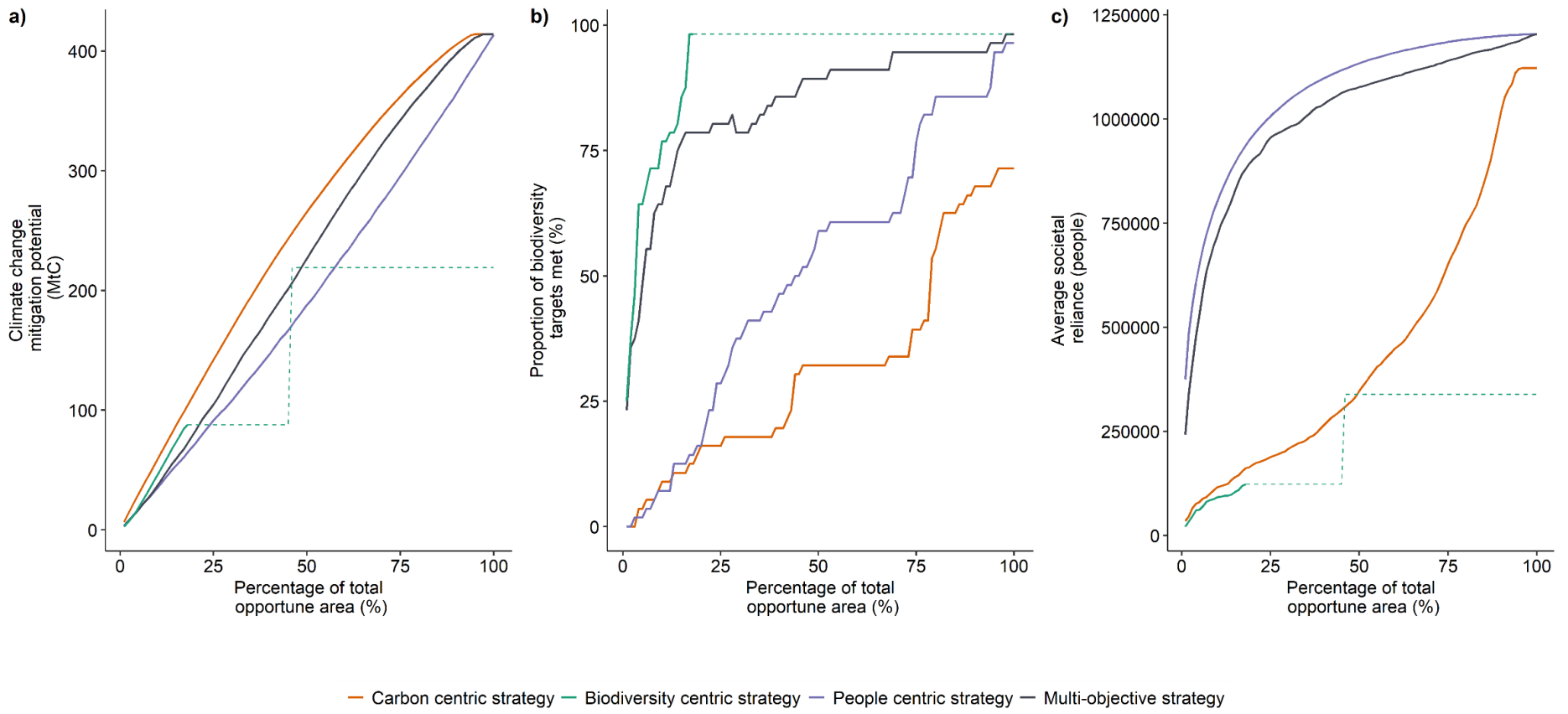


Figure 5.1 Nature's Contribution to People (NCP) delivered across the opportunity area: (a) climate change mitigation, (b) percentage of biodiversity targets met for forest dependent mammals considered and (c) material NCP of average societal reliance for key needs of energy, housing construction material and livelihoods. Strategies aimed at maximizing a sole NCP, provides the highest respective NCP, while the multi-objective strategy provides the next best solution, implying the least trade-off across all strategies ((a), (b), (c)). There is a linear increase in climate change mitigation potential as more opportune areas are restored (a). All biodiversity targets for potential area of habitat were met within 17% of opportune area with no additional biodiversity benefits accrued from restoration of remainder opportunity area. Within 25% of the opportune area, a multi-objective strategy resulted in ~80% targets being met, a people centric strategy resulted in ~28% targets being met and a carbon centric strategy delivered the least proportion of biodiversity targets ~16% (b). The societal reliance benefits follow a concave down increasing trend with a people centric and a multi-objective strategy, and a concave up increasing trend with a carbon centric strategy (c). There is an artefactual effect caused by the optimization method beyond 46% of the opportunity area, indicated by the dashed line in the biodiversity centric strategy response.

We found clear spatial patterns in the delivery of all NCP from the different strategies. The Western Ghats region along the western coast of India was prioritized in the biodiversity and carbon-centric strategies, while north eastern India was only prioritized in the carbon-centric strategy. Both strategies showed contrasting spatial trends across east- west, with the carbon centric strategy prioritizing the Central Highlands and Eastern Ghats and the biodiversity-centric strategy prioritizing sparse opportunity in north west India (Fig 5.2 a and 5.2 b). There were no strong spatial patterns in the opportunity area prioritized in the people centric and multi-objective strategies. However, opportunity areas in the southern Western Ghats, north eastern India, and different regions of central India were repeatedly prioritized in the multi-objective strategy (Fig 5.2 c and 5.2 d).

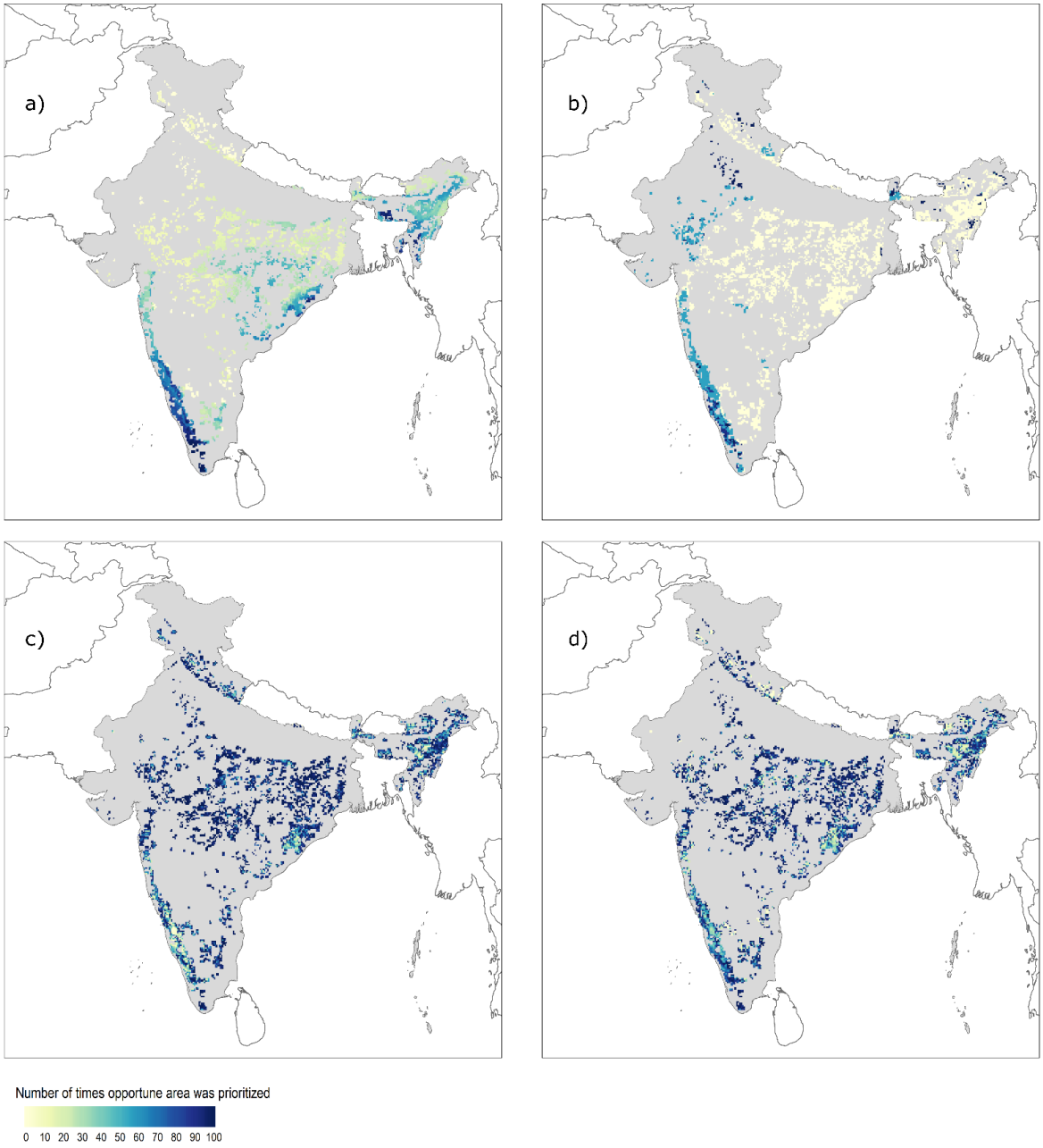


Figure 5.2 Spatial patterns of trade-offs between NCP, considering all optimization scenarios for each strategy . There is strong bias in spatial patterns particularly in the Western Ghats along the western coast of India and the north-eastern region of India (indicated by the shades of blue), when choosing the carbon centric and biodiversity centric strategies (a) and (b). There is no strong spatial pattern in delivery of NCP from a people-centric strategy due to the wide distribution of societal reliance for key needs (c). Similar evidence of no spatial pattern in delivery of NCP is seen when implementing a multi-objective strategy (d). Note all areas in grey were considered when delineating the study area.

Lastly, we analysed the distributional equity of the material NCP of the number of people whose key needs are met (Fig 5.1c) across the total opportunity area. As would be expected, people-centric strategies delivered material NCP to the most people (0.37 – 12 million) and to those who belong to disadvantaged socio-economic groups (38.3- 41.1% of the total number of people to whom material NCP is delivered in this strategy), for different priority areas. Furthermore, there was

negligible difference in the number of socioeconomically disadvantaged people whose material needs would be met by people-centric strategies, with a mean of 40.8% of the total people benefited by this strategy. As with people-centric strategies, for multi-objective strategies we found negligible variation in the disadvantaged fraction of the total people to whom material NCP would be delivered, with a mean of 40.1% (37.3 – 40.9% of the total number of people to whom material NCP is delivered in this strategy). This contrasts with that of a carbon-centric strategy, where the number of socioeconomically disadvantaged people to whom material NCP will be delivered to steadily increased from 21.5% to 41.8% of the total people's reliance in this strategy. At 20% of the total opportunity area prioritized, 26.2% of the total people to whom material NCP would be delivered by biodiversity centric strategies belonged to socioeconomically disadvantaged societal groups (Fig 5.3).

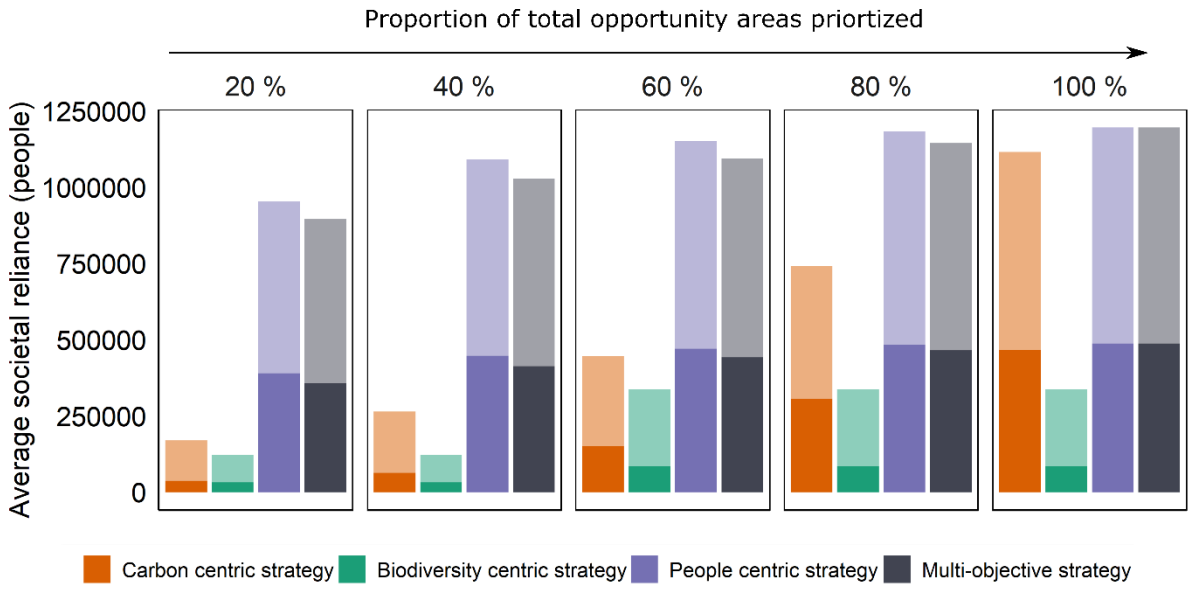


Figure 5.3 Distributional equity of the NCP considered across 20% increments of total opportunity area. Each bar represents the average material NCP of societal reliance for key needs (people). The length of the bar is the total population to whom material NCP would be delivered and the darker shaded portion of each bar is the socioeconomically disadvantaged fraction of this population. Across each increment of total opportunity area, the people-centric strategy delivers material NCP to the highest number of socioeconomically disadvantaged people with negligible differences (shades of purple). A similar pattern is found in the multi-objective strategy (shades of grey), which benefits the next highest fraction of socioeconomically disadvantaged people. In the carbon-centric strategy: there is a steady increase in the total population and socioeconomically disadvantaged population to whom material NCP will be delivered as the priority area is increased (shades of orange). The biodiversity centric strategy delivered material NCP to the smallest total population and socioeconomically disadvantaged population (shades of green). The material NCP delivered using the biodiversity centric strategy between 20 & 100% of the priority area remained constant due to the artefactual effects of the same area being prioritized in the 17- 46% range of total opportunity area.

5.5 Discussion

We determined the potential of multi-objective forest restoration strategies to deliver material and regulating nature's contributions to people (NCP), compared to sole objective strategies that focus on a particular NCP, at the pan- India spatial scale. To the best of our knowledge, this is the first national-scale assessment of the potential of forest restoration strategies aimed at multiple and single NCP. Overall, we estimated that multi-objective forest restoration strategies delivered 2.7 - 414 MtC (0.6- 100% of total), met 23.4 - 100% of potential AOH targets for mammals considered and met the key needs of 0.2 – 1.2 million people (20.4 - 100% of total). These multi-objective strategies have the least trade-offs in NCP and have no significant spatial patterns in the delivery of NCP (Fig 5.1; Fig 5.2), implying a variety of options on the ground for implementation. Consequently, multi-objective forest restoration strategies deliver material NCP to the greatest number of disadvantaged socio-economic groups of people, compared to strategies aimed at a single regulating NCP of climate change mitigation and habitat for biodiversity (Fig 5.3).

5.5.1 The case for multi-objective forest restoration strategies to deliver NCP

Multi-objective strategies deliver a variety of NCP widely distributed across the opportune area considered in India (Fig 5.1, Fig 5.2). By accounting for the widely distributed material NCP, multi-objective strategies spatially prioritize wide and disaggregated spans of opportunity area. With no spatial patterns in the priority opportunity area, multi-objective forest restoration strategies provide a variety of options for on-the-ground implementation of forest restoration schemes. We highlight that this feature of multi-objective strategies enables flexibility in decision-making and increased opportunities for knowledge transfer and co-production across different landscapes, resulting in greater likelihood of successful delivery of NCP (Favretto et al., 2022). However, these spatial options need to be further contextualized. For example, multi-objective forest restoration strategies in priority opportunity areas of central India in this study aligns with evidence from Srivathsa et al., (2023). However, it can be further contextualized with information about the varied potential to alleviate poverty in this region as highlighted by Choksi et al., (2023). Furthermore,

information including potential participation of local and indigenous communities in restoration programs (Erbaugh et al., 2020), governance and land tenure regimes (Choksi et al., 2023; McLain et al., 2021), locally available sustainable seed sources and supply chains (Fremout et al., 2022), and existing and expected potential of financial mechanisms, incentives and economic analyses including opportunity and implementation costs (Busch et al., 2019; Busch & Mukherjee, 2018), should be considered for decision-making processes.

The evidence that multi-objective forest restoration strategies have greater distributional equity of material NCP, compared to sole-objective strategies focusing on climate change mitigation and habitat for biodiversity, supports one of the core visions of the UN Decade on Ecosystem Restoration (Fischer et al., 2021; Wells et al., 2021). This finding is crucial because caste (denoting India's socio-economic societal groups) has a fundamental role in preferential policies in India, including for mobilization of savings (Goedecke et al., 2018), farm landowners' choice for management (Patil et al., 2020) and climate change adaptation strategies (Ravera et al., 2016). By accounting for socioeconomically disadvantaged groups, more inclusive designs of forest restoration schemes can be implemented resulting in higher probability of success. Our findings confirm an advancement in understanding how NCP from forest restoration is distributed across different societal groups (Fleischman et al., 2022; Schultz et al., 2022). However, we recommend that future studies focus on assessing recognitional, procedural and contextual equity aspects using an intersectional lens of gender, age, race and power dynamics (Pascual et al., 2014; Wells et al., 2021).

5.5.2 NCP trade-offs from single objective forest restoration strategies

We found an overall trade-off in biodiversity and climate change mitigation potential from carbon-centric and biodiversity-centric forest restoration strategies. This is because we included forest dependent mammals with potential AOH in areas where there is limited climate change mitigation potential, such as semi-arid regions of north western India and vice versa, such as north eastern and central eastern regions of India including the Central Highlands and northern Eastern Ghats. This is because we only considered forest-dependent mammals in need of additional forest

habitat i.e. mammals that would have maximum gains from forest habitat restoration. Hence, we recommend that future analyses should consider comprehensive forest-dependent taxa to represent biodiversity (Jung et al., 2021), including additional measures of biodiversity such as functional and phylogenetic diversity (Girardello et al., 2019). Also, we recognize that a variety of different biodiversity outcomes and targets, such as reduced extinction risks, can be optimized (Jung et al., 2021; Leadley et al., 2022; Strassburg et al., 2020), resulting in different trade-offs and synergies with climate change mitigation benefits (Girardello et al., 2019).

We found that there is a synergy in climate change mitigation and biodiversity outcomes from biodiversity-centric and carbon-centric forest restoration strategies in 5- 21% of the opportune area. Our reasoning is that there are limited biodiversity strongholds, such as the Western Ghats, that synergistically provide biodiversity and climate change benefits, which is prioritized. Hence, these irreplaceable forest ecosystems should be continued to be protected, while engaging in targeted forest restoration, especially along species movement corridors in fragmented landscapes such as the Western Ghats (Hariharan & Raman, 2021).

We found evidence of trade-offs between material and both regulating NCP from people-centric forest restoration strategies. As with evidence of cultural NCP in Europe (O'Connor et al., 2021), material NCP estimated in our study is delivered across the spectrum of opportunity areas where there are trade-offs and synergies between all the NCP. We posit that the widely distributed material NCP that the people-centric forest restoration strategy focuses on, reflects a rural effect of the high Indian population with high dependence on nature for human basic needs. 65% of India's total population still live in rural areas (The World Bank, 2021), with potential high reliance on nature for key needs. For example, India accounts for 35% of the world's population with no access to electricity (Bhattacharyya, 2006), implying reliance on alternative sources including fuelwood. It would be useful to validate our results by considering the spatial distribution of the supply and demand of materials for energy, housing construction and livelihoods (Burkhard et al., 2012). Furthermore, higher resolution and disaggregated information about livelihoods from forest

restoration and diversified employment in agricultural activities (Brancalion et al., 2022), can further help refine our findings about delivery of material NCP.

There is an urgent need to develop policy and practise for a shared future for nature and people. Forest restoration strategies aimed at multiple objectives for the delivery of various outcomes will help us tackle the problems of climate change mitigation, biodiversity conservation and societal needs of energy, livelihoods, and housing (Donatti et al., 2022). However, forest restoration is only one of many conservation strategies for tackling challenges we face (Anderson et al., 2019; Griscom et al., 2020). Moving ahead integrated actions, combining protection and restoration in a variety of ecosystems, can pave the way for the delivery of multiple nature and people outcomes (Fastré et al., 2021; Leadley et al., 2022).

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5.7 Author Contributions

Conceptualization – TG, PY; Data Acquisition – TG, PV, GF ; Methodology - TG, PY, PV, EB; Formal Analysis - TG; Investigation – TG, PY, PV, EB, YM; Writing Original Draft - TG; Writing Review & Edition - TG, PY, PV, EB, YM, GF; Visualization - TG, PY; Supervision – PY

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5.9 Supplementary Information

5.9.1 Supplementary Methods

5.9.1.1 Area suitable for naturally regenerating natural forests or area of opportunity

5.9.1.1.1 Modelling the biophysical envelope of native forests at the pan-India scale

We extracted the data of the 11 environmental predictors for 10756 GPS- gathered points of presences (unpublished from (Roy et al., 2015)) of different forest types and 22453 pseudoabsences or background sites as random points where there is no current forest cover (Barbet-Massin et al., 2012). We parametrized the random forest algorithm by assessing the Area under the Curve (AUC) metric by spatial repeated cross validation (0.702) after comparing it to the AUC from repeated cross validation (0.930). In both validation analyses, we used 10 repetitions of 5 partitions of the data accounting for the variance introduced due to data partitioning (Schratz et al., 2018) (Fig S5.5). We used 830 trees, 6 nodes at each tree and 3 features to be considered at each node, resulting in the probability of native forests occurring. We calculated 10 accuracy metrics (false positive and negative rates, mean misclassification error, Kappa statistic, total positive and negative rates, accuracy, area under curve, balanced accuracy and balanced error rate). We ultimately used the threshold of 0.494 as the presence threshold corresponding to the least mean misclassification error of 0.069 (Fig S5.6), resulting in 54.58 Mha of the biophysical envelope.

5.9.1.1.2 Sequential exclusion of all land uses and covers that cannot be restored to forests

We excluded all land area classified as urban/built up, bare/sparse vegetation, snow & ice, permanent and herbaceous wetlands, moss and lichen and oceans and seas, resulting in 53.32 Mha remaining. Subsequently, all cultivated and manged land/ agriculture was excluded resulting in 35.42 Mha remaining. Finally, we excluded all area currently classified as natural forests, resulting in the final area of opportunity of 3.88 Mha (Fig S5.7).

5.9.1.2 NCP from natural regeneration of native forests in area of opportunity identified

5.9.1.2.1 Regulating NCP- climate change mitigation potential and habitat created for forest dependent mammals

We calculated the climate change mitigation potential as the total above and belowground carbon stocks that would naturally regenerate in the 3.88 Mha area of opportunity (Equation 1). We used aboveground and belowground sequestration rates as per (Cook-Patton, Leavitt, et al., 2020), which was estimated as a function of 66 environmental covariates and over 13000 georeferenced measurements of carbon accumulation for the first 30 years of natural forests regrowth globally. For India, the aboveground carbon sequestration rate has a range of 0.50 - 4.51 $MgCha^{-1}yr^{-1}$ and the belowground carbon sequestration rate has a range of 0.19 - 2.47 $MgCha^{-1}yr^{-1}$.

$$total\ carbon\ stocks\ to\ naturally\ regenerate\ from\ native\ forests\ (MgC) = (aboveground + belowground\ carbon\ sequestration\ rates)(MgCha^{-1}yr^{-1}) * area\ of\ opportunity\ (ha) * 30\ years \quad \text{(Equation 1)}$$

5.9.1.2.2 Material NCP- societal reliance for energy, housing construction material and livelihoods

We calculated the societal reliance on forests for three basic needs- energy for cooking, livelihood and housing construction material (Equation 2). We acknowledge that we do not account for the contentious issue of lack of accessibility of timber and non-timber-based forest products for basic needs, considering insecure land tenure and land rights of different peoples and communities in developing countries. To account for the varying reliance of people living in rural and urban areas, we weighted the population density reliant on nature by the time taken to reach the closest urban city centre as per (Weiss et al., 2018), such societal reliance on nature for the needs increases as the time taken to reach the closest urban city centre increases (Equation 2). Additionally, we assumed that (i) houses constructed partly or entirely with wood is more durable compared to other natural materials like thatch, mud, clay (ii) fuel wood has the highest calorific value per unit of consumption

for cooking purposes relative to charcoal, straw, animal dung etc and (iii) for livelihood, the societal reliance on agriculture will be more when compared to forests.

Lastly, we calculated the total people reliant on nature for each need.

$$societal\ reliance\ on\ nature\ for\ each\ need =$$
$$proportion\ of\ people\ reliant\ on\ nature\ for\ said\ need\ (\%) *$$
$$population\ density(peoplekm^{-2}) *$$
$$time\ taken\ to\ reach\ nearest\ urban\ city\ centre\ (unitless)\ \ (normalized\ 0-1) \quad \text{(Equation 2)}$$

5.9.1.3 Systematic conservation prioritization analyses considering different policy scenarios

We used the systematic conservation prioritization framework to determine optimum solutions of the ecosystem services delivered, for different proportions of the total area of opportunity naturally regenerating into native forests (in 1% increments) and constraints of the targets to be met for each ecosystem service and the different policy scenarios. This framework which includes multicriteria approach for optimizing outcomes, has successfully been used to identify priority areas for restoration (Strassburg et al., 2020). We used the integer linear programming approach because it identifies solutions closest to optimality (Ando et al., 1998; Beyer et al., 2016; Naidoo et al., 2008) and is hence is more advantageous to heuristics based algorithms used in conservation planning (Beyer et al., 2016; Brooks et al., 2006; Joppa et al., 2013; Montesino Pouzols et al., 2014).

5.9.1.3.1 Targets set for forest dependent mammals

For each of the 291 forest dependent mammals, we calculated the potential area of habitat and the potential area of habitat in the opportune area. We calculated the current area of habitat as the potential area of habitat outside the opportune area. We adapted the area based target setting protocol from (Jung et al., 2021) to calculate the absolute target (Table S5.1).

Table S5.1 Criteria for calculating the absolute area-based targets for each mammal considered in the study, in sqkm.

Potential area of habitat	Current area of habitat	Absolute target area of habitat
<2,200	<2,200	Potential AOH
<2,200	>2,200	min(max (2200, 0.8*potential AOH), 10^6)
>2,200	>2,200	min(max (2200, 0.8*potential AOH), 10^6)

From the absolute target, we deducted the current area of habitat as this area is already forested. Consequently, we considered a final 56 forest dependent mammals (Table S5.2).

5.9.1.3.2 Problem formulation and optimization runs

This objective minimizes the overall shortfall for as many targets (t_j) (Equation 3 & 4) as possible, for each NCP (J_j) of all opportune area considered (I_j) for a given amount of NCP (r_{ij}) (Equation 3 & 4). We considered a proportional decision variable x_i, which specifies the proportion of the opportune area *i* to be selected (proportion of 0-1, where 0 means the restoration opportune pixel is not in the optimum solution and 1 means vice-versa), such that all the proportional areas (c_i in 1% increments) does not exceed total opportune area (B) (Equation 5). The strategies were implemented by assigning weights w_j for each NCP *j* (Equation 6).

$$Minimize \sum_{j=1}^{J} w_j \frac{y_j}{t_j} \quad (3)$$

subject to

$$\sum_{i=1}^{I} x_i r_{ij} + y_j \geq t_j \forall j \in J \quad (4)$$

$$\sum_{i=1}^{I} x_i c_i \leq B \quad (5)$$

$$w_j = \frac{1}{j} \quad (6)$$

5.9.2 Supplementary Tables

Table S5.2 Details of final forest dependent mammals considered in the study. Potential area of habitat (AOH) was calculated accounting for the habitat and elevation preferences of each mammal within its range as per (Brooks et al., 2019), potential AOH in the opportune area was used in the optimization runs, potential AOH not in the opportune area is the current AOH. Absolute target was calculated as per Table 1 adapted from Jung et al, 2020. Final target was calculated by deducting the current AOH from the absolute target. Percent target was calculated as the ratio of the final target and the potential AOH in the opportune area. All AOH information is in sqkm. Red list classification follows that of (IUCN, 2020).

Potential AOH	Current AOH	Potential AOH in opportune area	Total opportune area in species range	Absolute target	Final target	Mammal name	Red list classification	Percent target
2610.533	2190.842	420	473.0299	2200	9.15829	*Miniopterus pusillus*	LC	0.021805
16462.85	12824.62	3638.227	5608.267	13170.28	345.6592	*Macaca silenus*	EN	0.095008
12216.4	9493.608	2722.791	4325.853	9773.122	279.5145	*Platacanthomys lasiurus*	VU	0.102657
27353.14	21138.23	6214.909	11706.87	21882.51	744.2814	*Semnopithecus hypoleucos*	LC	0.119757
12732.59	9753.729	2978.864	3138.464	10186.07	432.3427	*Hypsugo affinis*	LC	0.145137
3748.598	2850.935	897.2727	962.9755	2998.879	147.9439	*Caracal caracal*	LC	0.164882
37067.43	27502.89	9564.545	14627.93	29653.95	2151.058	*Rhinolophus beddomei*	LC	0.224899
14939.18	10533.49	4405.7	5090.097	11951.34	1417.859	*Hipposideros pomona*	EN	0.321824
12708.18	5994.446	6713.736	13268.67	10166.55	4172.101	*Myotis peytoni*	DD	0.621428
10601.96	4742.543	5859.418	6564.653	8481.57	3739.027	*Viverra civettina*	CR	0.638123
168.809	152.3924	16.45455	16.41663	168.809	16.41663	*Myotis hasseltii*	LC	0.997695
1391.347	1380.097	11.27273	11.29039	1391.347	11.24972	*Cricetulus migratorius*	LC	0.997959
1017.018	1006.493	10.54545	5938.568	1017.018	10.52427	*Micromys minutus*	LC	0.997992
896.1173	663.8033	232.7273	276.7403	896.1173	232.3139	*Rhinolophus trifoliatus*	NT	0.998224
1073.857	1062.601	11.27273	12.34117	1073.857	11.25658	*Sicista concolor*	LC	0.998567
1797.304	1796.07	1.23636	14.81511	1797.304	1.23471	*Episoriculus leucops*	LC	0.998665
338.229	302.8002	35.45455	517.1508	338.229	35.42879	*Sorex minutus*	LC	0.999273
654.906	649.7638	5.14545	304.7258	654.906	5.14222	*Ochotona thibetana*	LC	0.999372
2100.645	2095.275	5.37273	76.29737	2100.645	5.37014	*Otomops wroughtoni*	DD	0.999518
1884.423	1856.254	28.18182	171.6578	1884.423	28.16837	*Apodemus rusiges*	LC	0.999523
1244.168	1223.086	21.09091	119.8626	1244.168	21.08254	*Alticola montosa*	VU	0.999603
249.7883	241.4455	8.34545	31.29618	249.7883	8.34276	*Mus famulus*	EN	0.999678
83.70929	83.40393	0.305455	895.109	83.70929	0.30536	*Rhinolophus subbadius*	LC	0.999689

386.7461	296.6823	90.09091	500.9803	386.7461	90.06382	*Rattus satarae*	VU	0.999699
1677.831	1672.268	5.56364	96.57099	1677.831	5.56224	*Niviventer brahma*	LC	0.999748
709.9824	703.1296	6.85455	528.0774	709.9824	6.85284	*Euroscaptor micrura*	LC	0.999751
47.21435	42.09704	5.11818	297.7262	47.21435	5.11731	*Chimarrogale himalayica*	LC	0.99983
143.6597	141.3207	2.33636	1186.235	143.6597	2.33906	*Ailurus fulgens*	EN	1
59.85035	56.21315	3.63636	48.49475	59.85035	3.6372	*Alticola stoliczkanus*	LC	1
241.6425	239.9697	1.67273	1.67288	241.6425	1.67287	*Capra falconeri*	NT	1
132.3157	123.0147	9.27273	581.3877	132.3157	9.30094	*Dacnomys millardi*	DD	1
1673.276	1671.039	2.23636	14.04306	1673.276	2.23668	*Eothenomys melanogaster*	LC	1
511.3766	494.6333	16.72727	30.24841	511.3766	16.74325	*Hadromys humei*	EN	1
2174.908	2145.32	29.54545	203.18	2174.908	29.58803	*Hyperacrius fertilis*	NT	1
1789.608	1760.145	29.45455	340.2448	1789.608	29.46274	*Hyperacrius wynnei*	LC	1
2170.774	1996.014	174.5455	1483.114	2170.774	174.7594	*Latidens salimalii*	EN	1
974.5008	972.4238	2.07273	10.68154	974.5008	2.07697	*Leopoldamys sabanus*	LC	1
1448.449	1411.17	37.27273	60.50815	1448.449	37.27918	*Phaiomys leucurus*	LC	1
1643.795	1633.7	10.09091	395.3791	1643.795	10.09484	*Neodon sikimensis*	LC	1
1353.163	1349.498	3.66364	144.4196	1353.163	3.66528	*Murina aurata*	DD	1
3.52297	3.51505	0.007918	871.4273	3.52297	0.00792	*Myotis sicarius*	VU	1
291.5217	143.9414	147.2727	1093.889	291.5217	147.5803	*Nesokia indica*	LC	1
158.3695	154.151	4.21818	764.5122	158.3695	4.21851	*Nyctalus montanus*	LC	1
4.46593	4.25846	0.207273	0.207	4.46593	0.20747	*Panthera leo*	VU	1
725.3597	624.3631	100.9091	228.9117	725.3597	100.9966	*Suncus montanus*	VU	1
1341.819	1321.987	19.81818	31.23734	1341.819	19.83131	*Trachypithecus geei*	EN	1
74.83304	58.07149	16.72727	230.9818	74.83304	16.76155	*Episoriculus macrurus*	LC	1
219.8541	219.1301	0.723636	5.52728	219.8541	0.72402	*Anourosorex squamipes*	LC	1
1966.094	1931.989	34.09091	1575.962	1966.094	34.10514	*Arielulus circumdatus*	LC	1
32.38139	32.34411	0.037273	37391.46	32.38139	0.03728	*Sus scrofa*	LC	1
298.2563	247.699	50.54545	404.1168	298.2563	50.55732	*Vandeleuria nilagirica*	EN	1
800.1285	743.4618	56.63636	92.24721	800.1285	56.66663	*Macaca munzala*	EN	1
277.5441	275.213	2.32727	73.59079	277.5441	2.33107	*Anourosorex schmidi*	DD	1
1753.81	1749.771	4.03636	321.2197	1753.81	4.03875	*Anourosorex assamensis*	LC	1

173.0565	171.7824	1.27273	61.82149	173.0565	1.2741	*Petaurista mishmiensis*	NT	1
22.15497	21.4237	0.730909	348.5442	22.15497	0.73127	*Murina tubinaris*	DD	1

5.9.3 Supplementary Figures

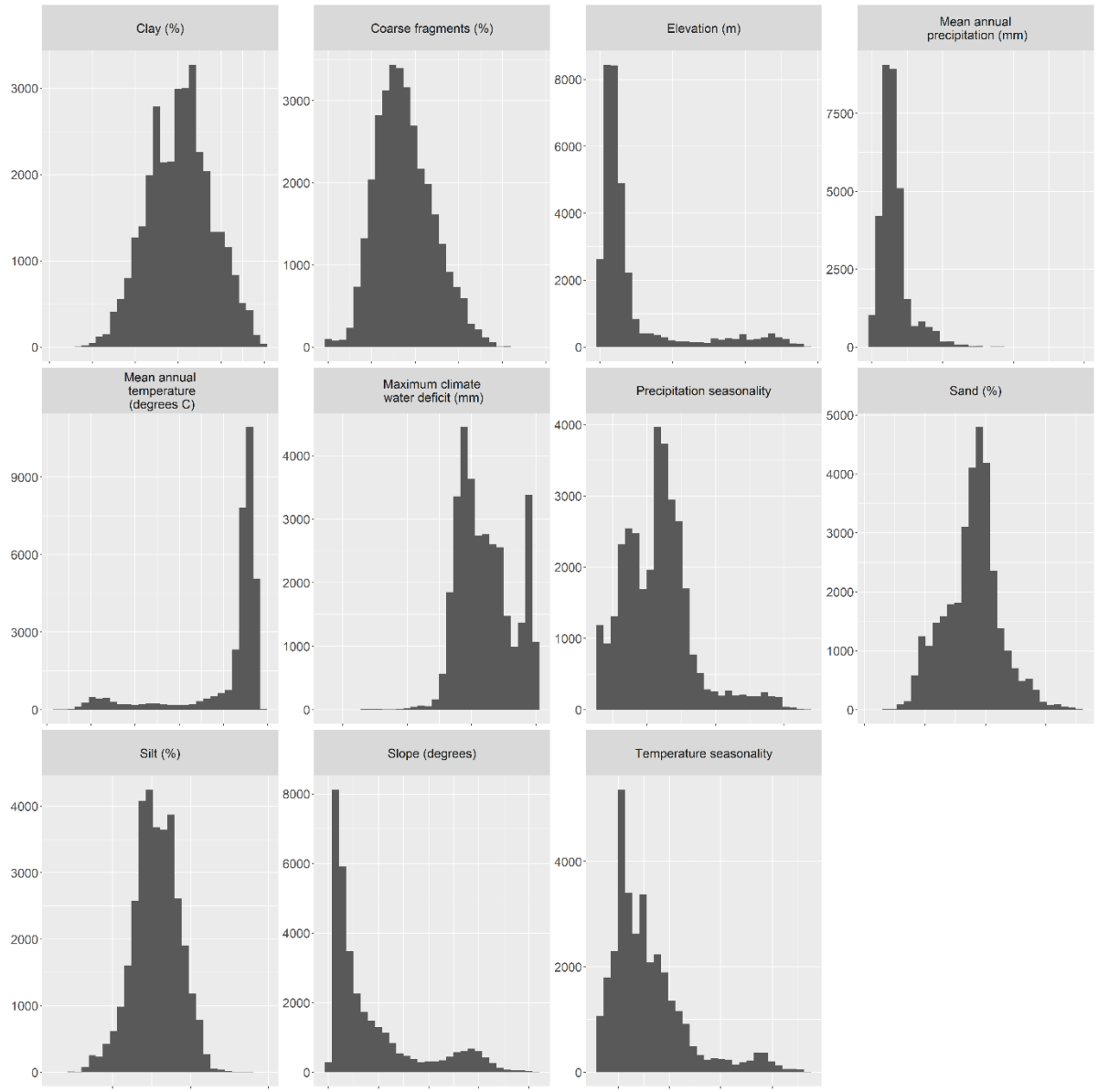


Figure S5.4 Distribution of the environmental variables considered across all 10756 presences and 22453 pseudoabsence points. The units of each environmental variable is mentioned in parenthesis.

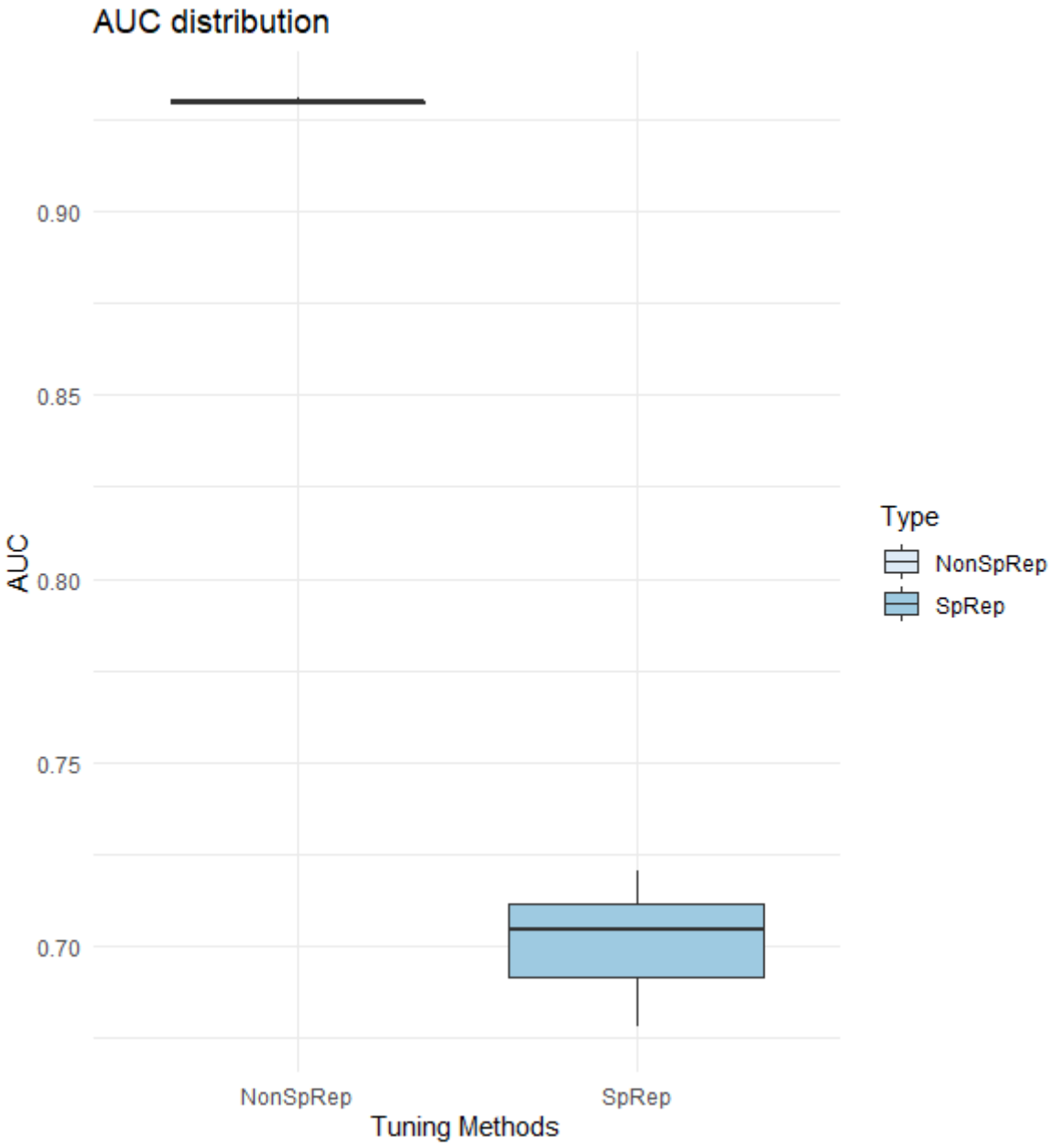


Figure S5.5 The random forest model was parameterized using spatial repeated cross validation (SpRep), which had a reduced AUC=0.702 versus non-spatial repeated cross validation (NonSpRep)

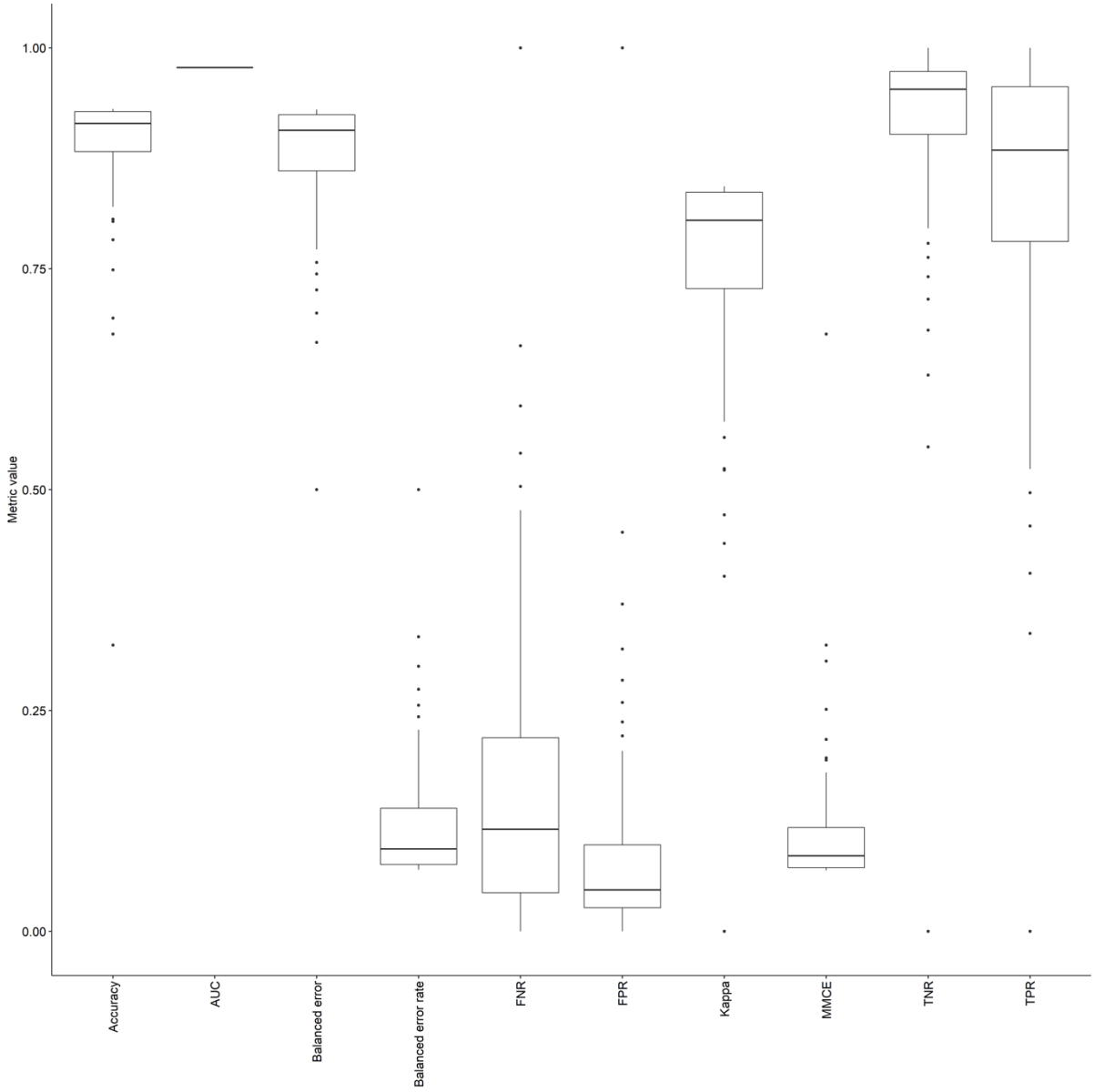


Figure S5.6 Distribution of the 10 accuracy metrics across all runs. The presence threshold= 0.494 was used as it corresponded to the least mean misclassification error (MMCE)= 0.069

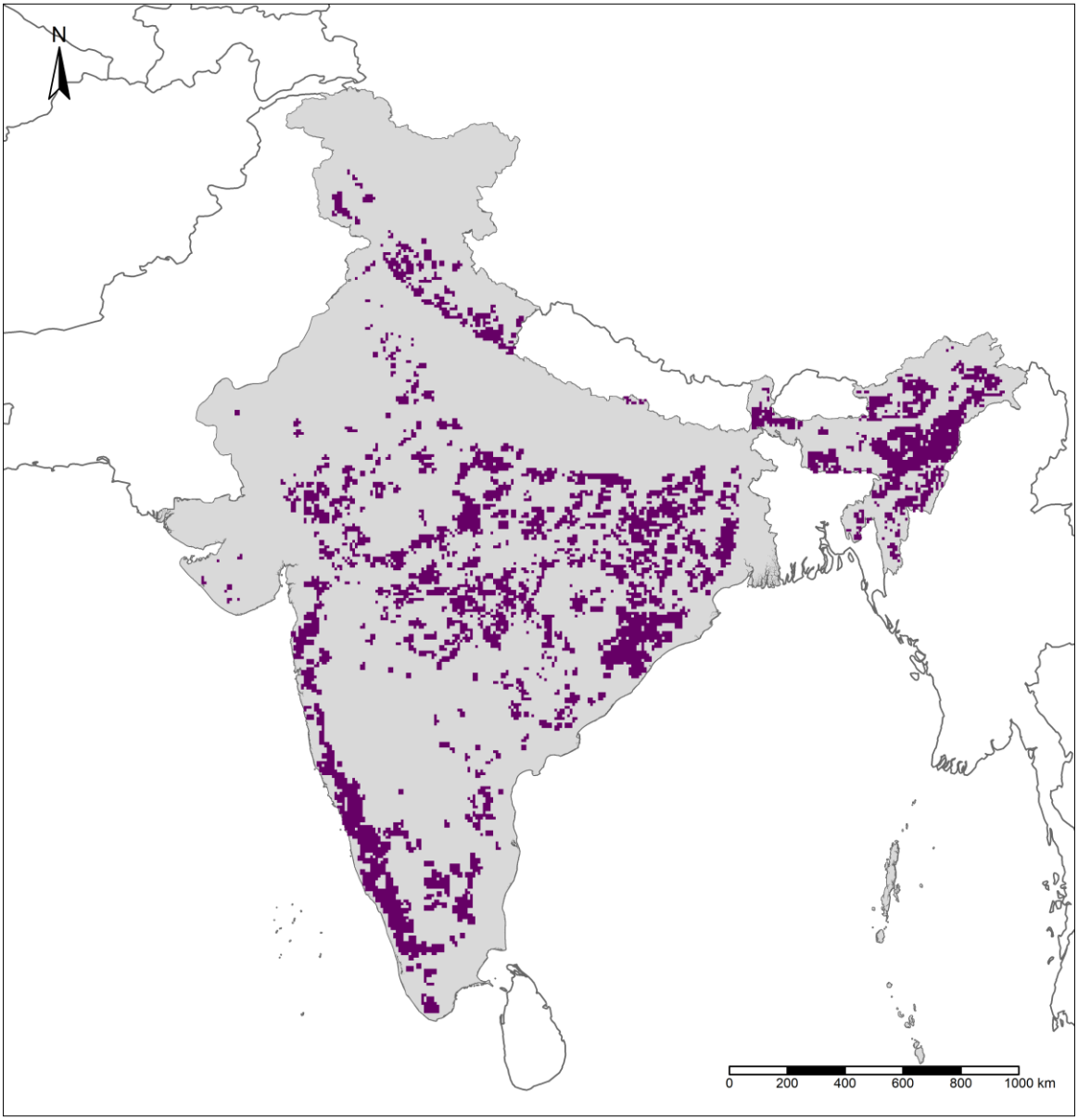


Figure S5.7 3.88 Mha of opportune area suitable for forest restoration across India considered in the study (purple). All areas in grey were initially considered, from which the opportune area was determined.

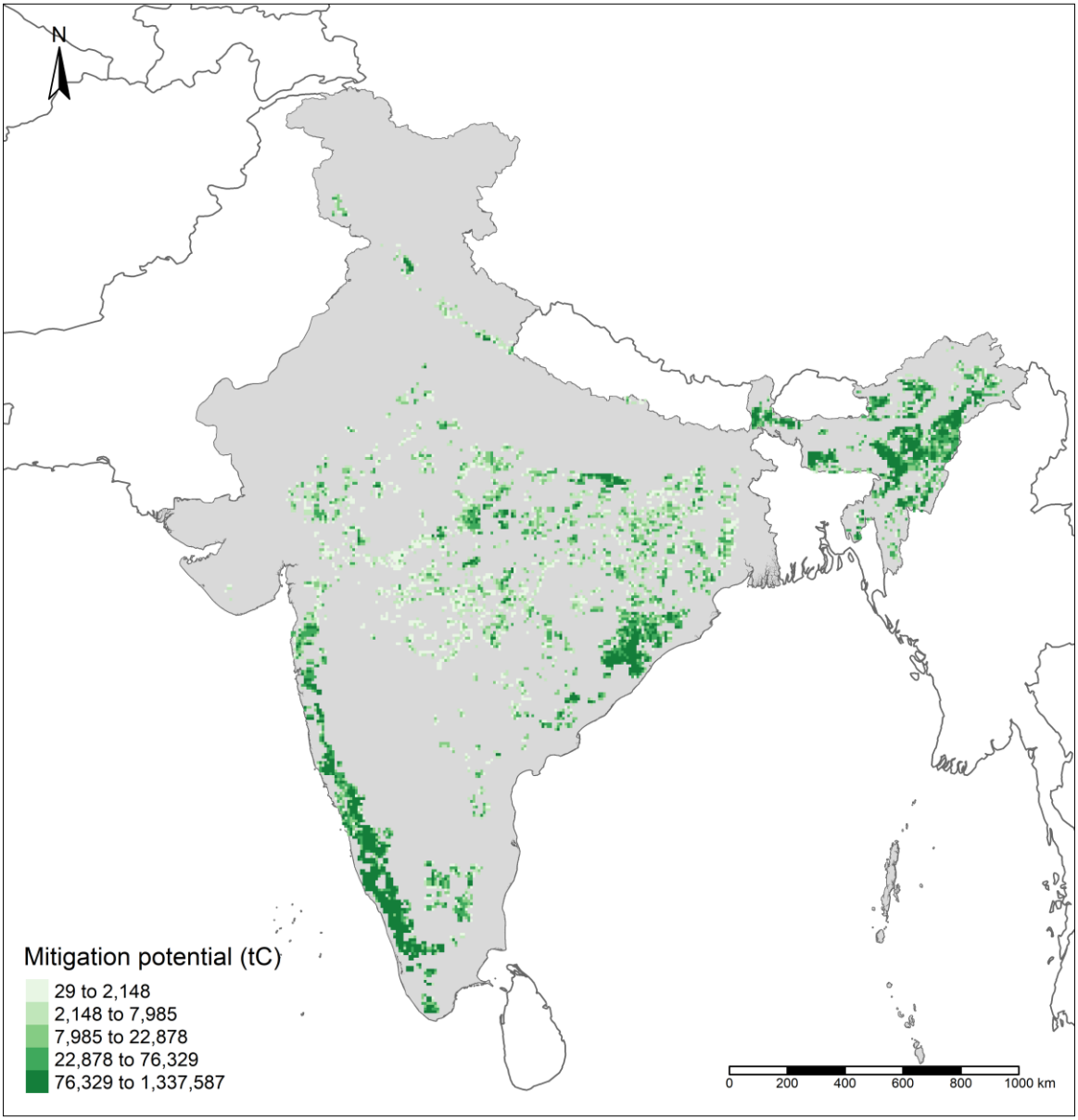


Figure S5.8 Regulating nature's contribution to people (NCP) of climate change mitigation potential was calculated across the opportune area (Fig S4). The total mitigation potential was calculated as the product of above and belowground carbon sequestration rates (Cook-Patton, Leavitt, et al., 2020) and opportune area, considering a 30 year time period

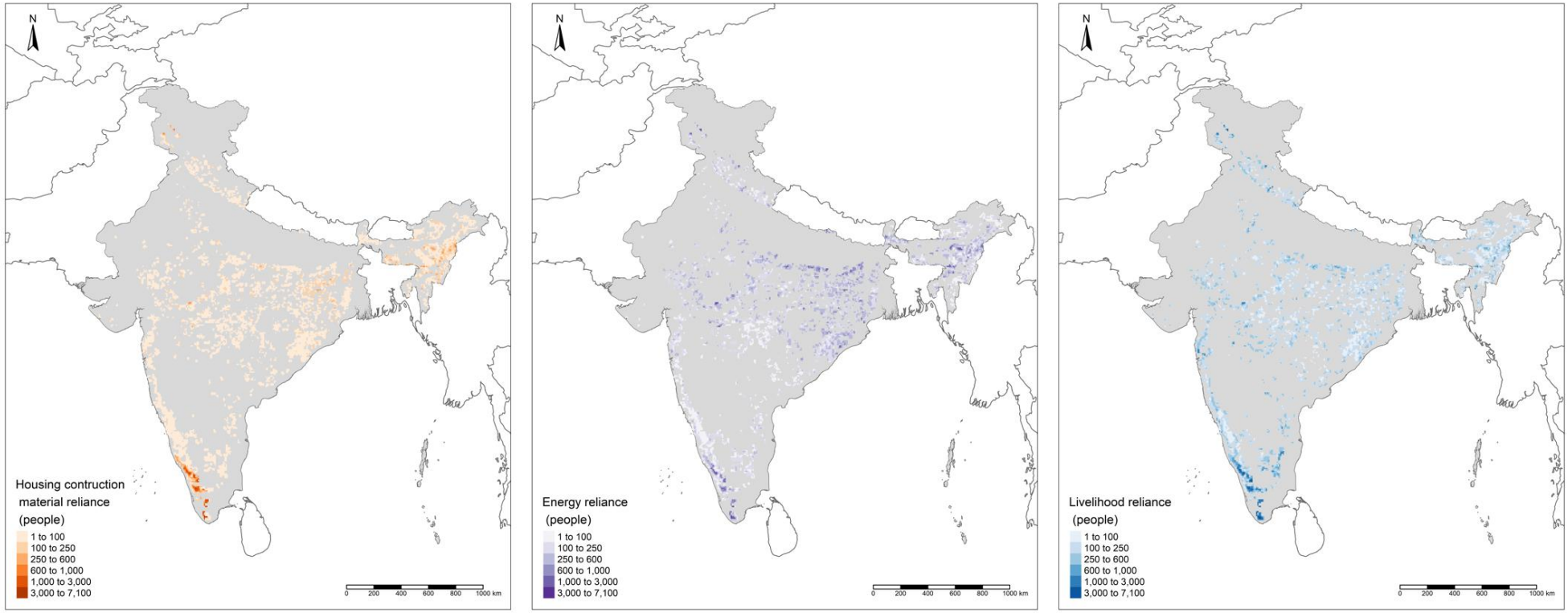


Figure S5.9 Material NCP was calculated as the total number of people reliant on nature for key needs of housing construction material, energy and livelihoods (left to right). Each NCP was calculated as the product of the percentage reliance for a respective key need from (Fedele et al., 2021), population density and time taken to travel to the closest urban centre (Weiss et al., 2018). The last term was normalized to vary between 0 and 1, such that a value of 0 meant living in an urban centre and a value of 1 meant living furthest away from the closest urban city centre

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Chapter 6 Synthesis and Conclusion

My thesis disentangles the complexities of forest restoration, considering the country of India. I focused on three important science advancements that are needed to improve the science, policy and practise of forest restoration (briefly summarised below; Fig 6.1). I focused on naturally regenerating native forests as the forest restoration technique and I completed a country wide analysis (except *Chapter 3 (Research Paper 1)* focused on the sub-jurisdiction scale).

In the remainder of this chapter, I elaborate the significance and novelty of the contributions made in this thesis. I then provide an outlook of this research, followed by future steps needed for the progression of the study of the complexities of forest restoration.

6.1 Main conclusion, significance and novelty of this thesis

6.1.1 Conclusion 1- "Existing land uses constrain climate change mitigation potential of forest restoration in India"

Where should forests be restored in India? What is the resulting climate change mitigation potential?

Findings- I estimated that there is 1.58 Mha of opportunity area available at the pan- India scale. The central Indian states have the highest opportunity area, while the western states have the least opportunity area. The cumulative climate change mitigation potential is 61.3 TgC, again with maximum mitigation in the central states and the least mitigation potential in the north eastern Indian states. Overall, 33.2% of the identified opportunity area is currently classified as 'degraded forests', followed by 28.8% as scrub and 81% as barren land, again with immense variation across all Indian states. Consequently, I determined that at the pan-India scale, there is 14.67 Mha of opportunity for agroforestry in current agricultural lands, delivering 98.1 TgC climate change mitigation nationally.

Significance- These estimates are lower than the India specific estimates from global studies such as Bastin et al., (2019) and Griscom et al., (2017) (see *Table 3.1* for additional details). Hence, my findings support the overall claim that the potential of forest restoration to mitigate climate change

is overestimated in India. By accounting for fine scale variation in land uses and covers that cannot be restored to forests and accounting for India's large agricultural footprint, it is apparent that forest restoration is not the most beneficial strategy to be pursued. Agroforestry, on the other hand, delivers considerably higher climate change mitigation potential. With India being the first country in the world to adopt a national agroforestry policy (Chavan et al., 2015), there is great opportunity for agroforestry to be a primary ecosystem based climate change mitigation strategy that India pursues. This specific finding of greater climate change mitigation potential of agroforestry when compared to forest restoration, might apply to other countries with large agricultural footprints as discussed in section *3.5.3*. Lastly, the cumulative climate change mitigation potential of forest restoration and agroforestry is only small sliver of India's ambitious pledge LULUCF pledge to the Paris Agreement (19.5- 23.4%). This brings the reality of the need to phase out the use of fossil fuels to the forefront of climate change action.

Novelty- There are three main aspects of this scholarship that makes it novel. Firstly, this is one of the few studies that identifies opportunity area and climate change mitigation potential for each sub jurisdiction comprehensively i.e. each of the 28 Indian states and six out of eight Indian Union Territories. By using India specific data, where possible, I expect that the evidence generated can be directly used for sub jurisdiction and national level decision and policy making. Secondly, on the methodological front, a great advancement made in this research is the estimation of the biophysical envelope of natural forests from which opportunity area was determined. This method provides a novel way to overcome the problems associated with selection of a baseline, based on historical distributions of natural forests (Holl, 2020). Lastly, again on the methodological front, the use of inventory data of the carbon stocks improves upon the limited data on carbon fluxes available via extensive literature reviews, that has been used commonly in global studies.

6.1.2 Conclusion 2- "Novel factors such as topography and disturbance regimes are to be accounted for when delineating areas where forest is not the climax ecosystem"

What is the distribution of tree cover across the forest and savanna biomes in India? What drivers maintain the distribution of tree cover and hence the biomes?

Findings- I delineated four distinct climatic zones of tree cover and its determinants across India- a low and predominantly high tree cover zone where climate is the main driver, a core savanna zone that consists of endemic savanna understorey plants and where climate limits maximum tree cover and lastly a mixed forest- savanna zone that has evidence of savanna understory plants, but climate does not control maximum tree cover. Novel physical factors such as topography and soil sand fraction limit tree cover from reaching its climatic maximum potential. Additionally, tree cover is limited by anthropogenic disturbances and high herbivory pressure, especially that of sheep. However, contrary to global evidence, there is no clear evidence of the effect of fire on tree cover across India.

Significance- This is the first study that examines the pattern of tree cover and its determinants across savannas and forests, at the landscape scale in India and indeed the first of its kind study in south Asia. Hence, this scholarship fills the missing piece in the global puzzle of biome distribution of savannas and forests, as majority of the evidence is from Africa, South America and Australia. This is crucial because of the continued threat of afforestation and forest cover expansion that global open ecosystems including savannas, grasslands and woodlands continue to face due to ambitious forest restoration schemes. The distinct patterns of tree cover shortfall in varying topographies paint a rich picture of the interplay of micro temperature gradients, soil moisture and ground water dynamics, which determine grass and tree dynamics and hence biome distribution. Lastly, the unclear evidence of the effect of fire on tree cove is important because it shows a different aspect of fire regimes in biome distribution, in a region with a long history and contemporary views and policies supporting fire suppression.

Novelty- The novelty in this research primarily lies in the innovative application of global evidence of drivers of tree cover, to the landscape of India. The evaluation of the effect of herbivory pressure as a disturbance regime that regulates tree cover is a significant advancement, as evidence from field based experiments is the norm. Similarly, the use of remotely sensed products to evaluate the effects of fire frequency and severity indicates the promise of the use of a variety of satellite based data products in evaluation of disturbance regimes at landscape scales.

6.1.3 Conclusion 3- "Multi-objective forest restoration strategies have the least trade-offs in environmental and societal outcomes with flexibility in options for on the ground implementation and are equitable"

What are the trends in environmental and societal benefits from single and multi-objective forest restoration strategies in India? What are the spatial patterns in the delivery of these benefits from the different strategies? What are the equity consequences on different societal groups from the different strategies?

Findings- I determined that forest restoration strategies designed to deliver multiple objectives have the least trade-offs in environmental and societal outcomes of climate change mitigation, habitat created for forest dependent mammals and societal reliance of human basic needs of energy, livelihoods and housing construction material. Such multi-objective forest restoration strategies have no spatial pattern in the delivery of the above listed outcomes, providing many on-the-ground options for implementation, ultimately being flexible. Multi-objective forest restoration strategies deliver societal outcomes to the highest number of socioeconomically backward Indian people, when compared to forest restoration strategies aimed at sole climate change mitigation and biodiversity outcomes. On evaluation of single objective strategies, I concluded that there are very few stronghold areas, such as the Western Ghats along the western Indian coast, that can provide both climate and biodiversity benefits in India. Lastly, inclusion of people's needs when designing forest restoration strategies provides a reality check of how different the priority areas can be from priority areas when focusing on climate change and biodiversity.

Significance- The findings from this scholarship provides the evidence that forest restoration strategies designed to meet multiple objectives can be impactful to meet the numerous global challenges we face today (Donatti et al., 2022). Secondly, I expect this research to have direct implications to policy integration, specifically addressing crosscutting societal and environmental problems (Biesbroek, 2021). By using a transdisciplinary lens to evaluate forest restoration strategies, this research provides the path to understand how actions can be designed to integrate climate change mitigation, resilience, and adaptation. Additionally, this research clearly highlights the significant difference in outcomes and options for site selection when accounting for people's needs. It underscores the relationship between humans and nature that should be the core of environmental policy formulation and decision making. Lastly, this scholarship provides an example of integration of equity and justice issues when designing conservation actions.

Novelty- The main novelty of this research is that it marries the concepts of strategy design, spatial optimization and equity and justice, when focusing on forest restoration. From the methodological perspective, the use of spatial optimization which is traditionally rooted in protected area delineation and reserve design (Moilanen et al., 2009; Villarreal-Rosas et al., 2020), has been applied to the context of forest restoration. Another novelty of this study is the estimation of distributional equity of the resulting outcomes from different forest restoration strategies. It is an exemplar showcase of integration of key ideas core to the social and ecological sciences.

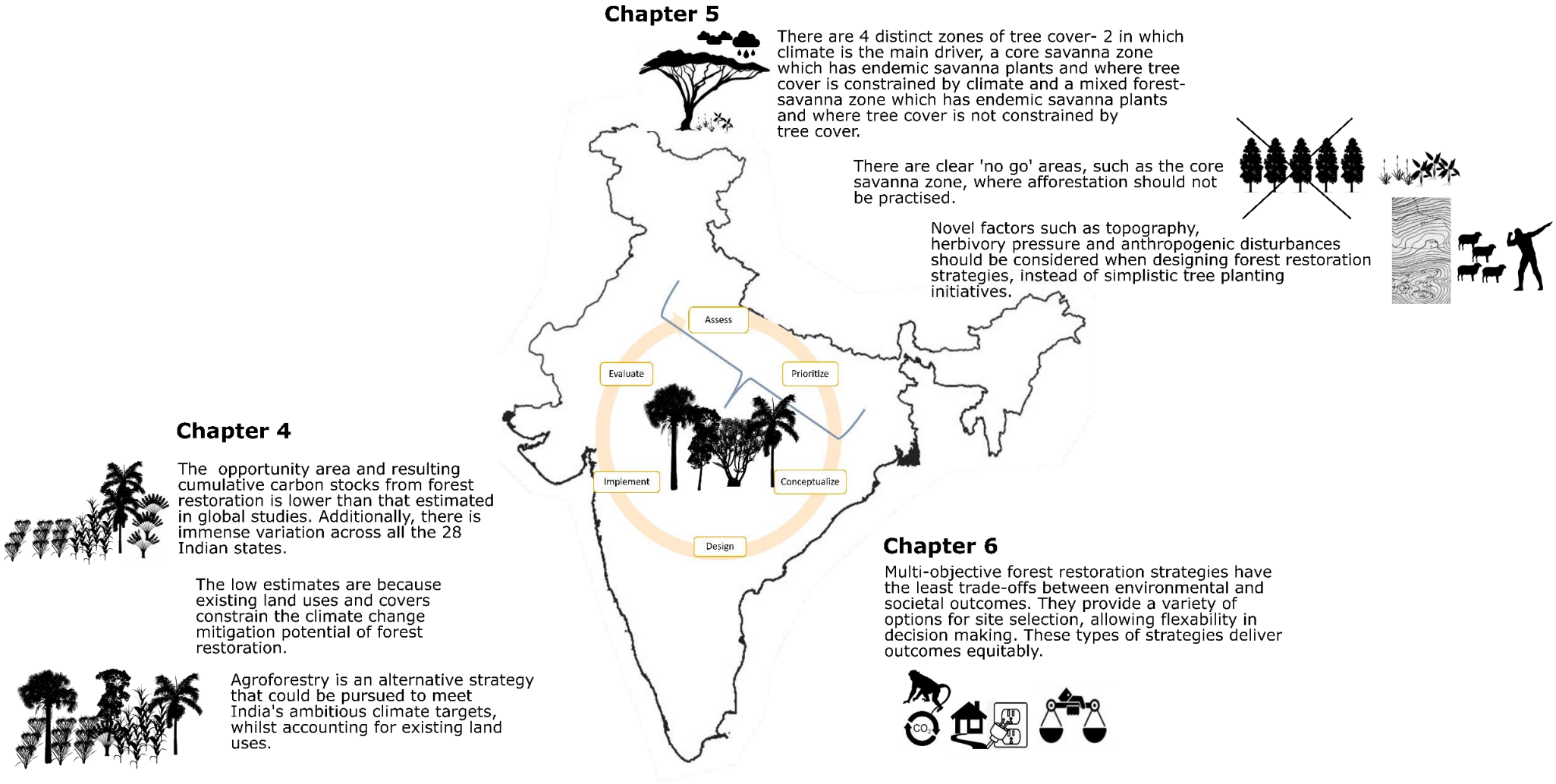


Figure 6.1 Synthesis of *Chapters 4, 5 & 6* of this thesis highlighting the main conclusions from each chapter. Silhouette images are by David Orr (*Homo sapiens sapiens*), Gabriela Palomo-Munoz (*Sabal palmetto*), Katy Lawler (*Ovis aries*), Mason McNair (*Oryza sativa, Zea mays mays*), and Seraina Lisa Cappelli (*Anthoxanthum odoratum*) All illustrations are not drawn to scale and are meant to be representative only. Designed by Trisha Gopalakrishna

6.2 Outlook

The UN Decade on Ecosystem Restoration provides a crucial policy window for accelerated science, policy and practise of tropical forest restoration (Dudley et al., 2020). My thesis clearly demonstrates that there are various nuances, issues and intricacies that are to be addressed for successful and impactful action, in India.

In *Chapter 3 (Research Paper 1)***,** I demonstrated the limited opportunity and climate change mitigation potential of forest restoration in India. This is the trend that is increasingly being demonstrated, such as in Southeast Asia (Zeng et al., 2020) and Canada (Drever et al., 2021), but there is contrasting evidence from Indonesia (Basuki et al., 2022) and the USA (Fargione et al., 2018). Hence, I conclude that the evidence base for the case of forest restoration is still arguable, globally. However, I suspect that there is strong enough of an evidence base supporting the need to temper the global and country specific ambitions for forest restoration. Integrated actions of conservation, restoration and improved management of ecosystems is a key strategy to be championed with acknowledgment of the need to phase out the use of fossil fuels (Anderson et al., 2019; Griscom et al., 2019).

In *Chapter 4* (*Research Paper 2)*, I demonstrated a method of delineating forest and savanna biomes to guide appropriate forest restoration in India. The key drivers of tree cover of topography, anthropogenic disturbances and a threshold response of herbivory pressure, at the landscape scale of analyses is new information from South Asia. This information holds promise (i) in deciphering the resilience of tree cover in the face of climate change (Hirota et al., 2011; Staal et al., 2018) (ii) in understanding the reasons for alternative states of forests and savannas (Pausas & Bond, 2020, 2022) and relatedly (iii) critical thresholds and tipping points beyond which savannas and forests may transition to a novel ecosystem state (Buisson et al., 2022; Kéfi et al., 2016; Suding et al., 2004).

In *Chapter 5 (Research Paper 3)***,** I provide evidence of how multiple areas that have the biophysical potential for forest restoration can be prioritized to provide multiple environmental and societal benefits. Most importantly, this research shows how priority areas are different when

integrating both environmental and social outcomes. It emphasizes the important relationship between nature and humans (Díaz et al., 2018; Ellis et al., 2019), with an increasing need to provide wholistic conservation strategies (Chazdon & Brancalion, 2019; Donatti et al., 2022). Hence, this research provides a stepping stone to understanding the linkages between climate change mitigation, adaptation and resilience.

Lastly, though this thesis focused largely on area-based assessments of the three science advancements of forest restoration addressed, it supports the need and importance of ecosystem restoration focused on ecosystem complexity (Bullock et al., 2022) and restoration of ecosystem functioning and processes (Carlucci et al., 2020). Also, this thesis supports the notion that the immediate need to address climate change warrants a range of recovery strategies that include ecosystem restoration (Gann et al., 2019) and rewilding (Pettorelli et al., 2019), leading to an ecologically functioning, complex and resilient world.

6.3 Future Research Steps

Although I have addressed three key science advancements required for further development of the science, policy and practise of forest restoration in India, there are potential research avenues that could be undertaken. Below, I list these potential research avenues, grouped under the three science advancements addressed in this thesis-

6.3.1 Where should forests be restored in India? What is the climate change mitigation potential of forest restoration in India?

(1) I focused only on naturally regenerating native forests as the forest restoration technique in this thesis. Hence, it would be useful to estimate the climate change mitigation potential of different forest restoration techniques, such as active restoration including planting of native plants. Active restoration techniques have been shown to be a viable forest restoration technique, especially in the fragmented landscapes such as the Western Ghats (Osuri et al., 2019). There is also evidence of improved bird community composition from active

restoration techniques in comparison to natural regeneration in fragmented landscapes of India (Hariharan & Raman, 2021).

(2) Considering the climate change mitigation of agroforestry demonstrated in *Chapter 3*, it would be useful to complete an in-depth analyses. This could include (i) mapping of the area of opportunity for agroforestry considering different systems and crops across the different agroecological zones of India (Ahmad et al., 2017) (ii) evaluation of different agroforestry systems of India, such as agri-silvicultural, silvo-pastoral and agro-silvo-pastoral systems including traditional agroforestry practises such as home gardens (Sharma et al., 2017).

(3) Lastly, it would be beneficial, especially for global and national policy fora, to understand the opportunity area, climate change mitigation potential and uncertainties of forest restoration against different scenarios of future climate change.

6.3.2 What is the distribution of tree cover across the forest and savanna biomes in India? What drivers maintain the distribution of tree cover and hence the biomes?

(1) Overall, we need more information about the savanna ecosystem across South and Southeast Asia. This includes answering key questions such as (i) extent of the ancient savanna lands in India, as proven by the empirical evidence of endemic understorey savanna plants (Nerlekar et al., 2022) (ii) extent and intensity of degradation in savannas (iii) drivers of degradation of Indian savannas and (iii) knowledge about the ecological processes and functioning of the Indian savanna biome.

(2) Specifically focusing on the last point made above, it would be useful to understand the effect of resource based drivers beyond those analysed in *Chapter 4*. For example, soil nutrient availability, not analyses in this chapter, is a crucial factor in savanna and forest biome distribution globally, with the overall consensus that savannas are found in nutrient poor soils, while forests are more likely to be present in nutrient rich soils (Oliveras & Malhi, 2016; Sankaran et al., 2004, 2008).

(3) Similarly, more information about the role of disturbance drivers of herbivory and fire would be useful to understand the distribution of forests and savannas in India. For example, improved characterization of the role of different severities of fire would be useful in explaining the unclear evidence I have discussed in *Chapter 4*. Lastly, it would be very useful to compare the role of wild and domestic herbivores on biome distribution, considering the unique herbivore diversity across South and Southeast Asia.

6.3.3 What are the trends in environmental and societal benefits from single and multi-objective forest restoration strategies in India? What are the spatial patterns in the delivery of these benefits from the different strategies? What are the equity consequences on different societal groups from the different strategies?

(1) Future research involving multi-criteria analyses for forest restoration, could warrant from including additional criteria. For example, inclusion of the cultural nature's contributions to people (NCP), such as nature-based tourism and heritage landscapes (Pascual et al., 2017), especially when working in India, would be important for informed decision-making.

(2) Overall, there is a need for inclusion of information about the people that will be impacted from forest restoration strategies. Further to the equity aspects discussed in *Chapter 5*, delineation of priority areas in India will be wholistic by inclusion of additional social, institutional and cultural criteria such as forest governance and land tenure (Choksi et al., 2023).

(3) In addition to the use of the lens of NCP as completed in *Chapter 5*, economic criteria such as opportunity and implementation costs (for example labour, see source, supply chains) would provide additional insight into the trade-offs and synergies between multiple environmental and societal outcomes from forest restoration.

(4) Lastly, further research of additional criteria of feasibility and probability of success will help delineate priority areas where there is maximum return on investments. For example, when

considering probability of success of natural regeneration, proximity metrics to the closest natural forest patch (Crouzeilles et al., 2020), could be included in the optimization analyses.

6.4 Concluding remarks

In this thesis, I have added to the growing scientific literature of the intricacies of forest restoration as a wholistic environmental strategy, considering the relatively understudied case of the country of India. Clearly, there are many opportunities for forest restoration, including refined estimates of suitable land area available for implementation activities and that forest restoration strategies can be designed to deliver multiple environmental and societal outcomes equitably. However, the realities of the potential of forest restoration to mitigate climate change, the consequences on non-forest land such as savannas and the role of factors such as topography, herbivory and anthropogenic disturbances when designing strategies are to be seriously considered. These opportunities and realities have implications for India and other countries, and every entity (person, indigenous and local community, private company), striving for a world in which humans and nature thrive.

6.5 References

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