MODELLING FOREST CARBON DYNAMICS IN TWO PHYSIOGRAPHIC REGIONS OF NEPAL

by

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Abstract

Forests play an important role in the global carbon cycle because of their large and dynamic carbon stocks. Improved understanding of the processes that affect the net ecosystem exchange of carbon are needed to conserve and enhance carbon stocks. In this dissertation, I addressed the impacts of forest disturbances on the forest carbon dynamics under a status quo scenario and a variety of managerial and policy assumptions in two physiographic regions of Nepal (Terai and Churia). I used a carbon dynamic modelling approach to: i) estimate the forest carbon stocks and changes; ii) assess the impacts of different forest management scenarios on forest carbon dynamics; and iii) examine the impact on carbon stocks and GHG emissions of different harvest rates and distributions of harvested wood products. I initially modelled the impact of forest disturbances on carbon stocks for 2010 to 2017 and then projected this forward to 2030 under a "business-as-usual" scenario. The carbon stocks were impacted more by human encroachment in Terai and by fire, landslides, and harvesting in Churia. However, the forest remained a carbon sink in both regions. I then explored the potential impact of management interventions on the carbon dynamics of forest of Terai region, where forests are experiencing the most population pressure. I used a multivariate imputation approach to provide a spatially explicit, wall-to-wall map of attributes to forecast alternative forest management scenarios. A scenario involving the highest investments and the lowest harvest level resulted in the most carbon sequestration and a scenario with higher disturbance levels reflecting the possible impacts of population pressure and climate change resulted in the least carbon sequestration. Lastly, I explored the combined impact of different harvest levels and harvested wood product mixtures (fuel wood vs. sawn wood products) in Terai on the overall carbon storage. Increasing the proportion of sawn wood products relative to fuel wood increased the carbon stock, allowing the possibility of higher harvest levels with a net increase in carbon storage compared to the status quo. Such an approach could convey economic benefits while retaining or enhancing the present rate of carbon sequestration.

Lay Summary

Globally, forests absorb about 30% of the atmospheric carbon dioxide emissions. To limit global warming below 2°C and to achieve net zero emissions, this proportion must be increased. However, increasing rates of disturbances limit this potential. Regular monitoring of forest carbon stocks and modifying forest management is necessary to maintain or enhance the role of forests in the carbon cycle. In this dissertation, I modelled the impact of disturbances on forest carbon stocks in Nepal to identify how carbon stocks might change under population pressures, climate change, and increased forest management. I also explored the impacts of increasing the proportion of harvest directed to solid wood products as opposed to fuel wood since solid wood products have a potential to store carbon over longer periods than fuel wood. My work provides specific evidence that actively managing the forests of Nepal can improve carbon sequestration while providing timber and economic benefits.

Preface

The research questions and objectives for this dissertation were originally formulated from discussions with my supervisory committee (Drs. Peter Marshall, Valerie LeMay, Werner Kurz, and Clive Welham). The forest inventory data required for this dissertation were provided by the Department of Forest Research and Surveys, Nepal, with some additional information downloaded from Food and Agriculture Organization (FAO) statistics. For each research chapter, the objectives, data preparation, statistical analysis, and writing, including tables and figures, were performed by me with very helpful feedback and editorial suggestions from my supervisory committee. The statistical analysis for the improvement of growth and yield curves required for all the research chapters and imputation for detailed inventory for Chapter 3 benefitted greatly from advice from Dr. Valerie LeMay. The dissertation chapters (1 and 5) were also written by me with feedback and suggestions from Dr. Peter Marshall.

Table of Contents

List of Tables

List of Figures

List of Abbreviations

AIC – Akaike's information criterion

°C – degree Celsius

CBS – Central Bureau of Statistics (of Nepal)

CH_4 – methane

CO – carbon monoxide

CO_2 – carbon dioxide

COP21 – United Nations Conference of Parties 21

DBH – diameter at breast height

DFRS/FRA – Department of Forest Research and Survey/Forest Resource Assessment

DOM – dead organic matter

FAO – Food and Agriculture Organization

FCPF – Forest Carbon Partnership Facility of the World Bank

FERL – forest emissions reference levels

FRA – forest resource assessment

GHG – greenhouse gases

HWP – harvested wood products

ICS – improved cooking stoves

IPPC – Intergovernmental Panel on Climate Change

KP – Kyoto Protocol

LPG – liquified petroleum gas

LRMP – Land Resource Mapping Project

LULUCF – Land Use, Land Use Change, and Forestry

MoFE – Ministry of Forests and Environment, Nepal

MoFSC – Ministry of Forests and Soil Conservation, Nepal

NBP – net biome productivity

NCS – natural climate solutions

NDVI - normalized difference vegetation index

NEP – net ecosystem productivity

NPP – net primary productivity

QMD – quadratic mean diameter

REDD+ – Reducing Emissions from Deforestation and Degradation

Rh – heterotrophic respiration

RMSE – root mean squared errors

SFMP – Scientific Forest Management Program (of Nepal)

SOC – soil organic carbon

SOM – soil organic matter

TPH – trees per hectare

UNFCCC – United Nations Framework Convention on Climate Change

WHO – World Health Organization

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This PhD would not have been possible without the financial and moral support of the Faculty for the Future (Schlumberger) Foundation and support of the Graduate and Postdoctoral Studies, University of British Columbia (UBC). I also want to express my profound gratitude to the Braham G. Griffith Memorial Graduate Scholarship in Forestry and the Special Scholarship provided by the Department of Forest Resources and Management during the Covid hardship. I would like to acknowledge that forest carbon models: CBM-CFS3 and CBM-FHWP were provided to me by the Canadian Forest Service. I am very grateful to Scott Morken, Stephen Kull, and Michael Magnan, from the Canadian Forest Service for providing computer programming knowledge and assistance on how to run the software for the carbon budget simulations. Special thanks to Mr. Jerry Maedel who provided valuable insights and kind guidance for spatial analysis using ArcGIS in multivariate imputation approach. A very sincere thank you to Department of Forest Research and Survey, Nepal for providing me with the forest inventory data necessary for my research. Special thanks to Mr. Basant Gautam, Mr. Rajesh Mall, Mr. Ananda Khadka and Mr. Shiva Khanal for helping me acquire and understand the forest inventory data.

My husband, Mr. Rudra Raya, encouraged me to pursue this PhD degree and he arranged my introduction to my eventual research supervisor, Dr. Peter Marshall. I am greatly thankful to him for the support, constructive criticism, and encouragement throughout the journey. I owe a big thanks to my adorable daughter, Ojaswi Raya Khatri, for her love and support throughout and for tolerating my PhD tantrums. I would like to thank my dear brothers for their kindness, love and support for my education and nephews and nieces who love me and always look forward to my PhD completion. Thanks to my dear friends in the biometrics lab. Lastly, I am happy that I didn’t give up!

Dedication

In loving memory of my late mother 'Netra Kumari Khatri', late father 'Prem Bahadur Khatri Chhetri', late sister-in-law 'Indra Kumari Khatri', and late brother 'NavRaj Khatri'. Thank you very much for all your immense love, care, and support: Ama, Ba, Thuli Vauju, and Maila Dai.

Chapter 1: Introduction

1.1 Background

Carbon dioxide (CO_2) is a greenhouse gas (GHG) that absorbs and emits infrared radiation as part of a system impacting the Earth's climate. An increased level of CO_2 in the atmosphere has resulted in climate changes, notably increased temperatures (Lindsey, 2020). Human activities that increase atmospheric CO_2, such as burning fossil fuels or reducing carbon sequestration by permanent removals of forest cover, are dominant causes of climate change (Ciais et al., 2011; IPCC, 2014). Friedlinstein et al. (2020) reported that fossil fuel burning, and cement manufacturing emit 86% of greenhouse gases, and deforestation and land-use changes emit much of the remaining 14% to the atmosphere. Climate changes resulting from increased GHG can severely impact ecosystems, human well-being, and livelihoods (IPCC, 2014). Consequently, international agreements are negotiated, the most recent being the International Paris Agreement (21st Conference of Parties (COP)[1]), where the targeted maximal allowable increase in global temperatures was set to 2°C. Many nations are adopting policies aimed at reducing CO_2 emissions and finding ways to mitigate emissions as a mechanism to reduce temperature increases to meet this target.

Apart from raising temperatures, a changing climate can change seasonality of precipitation, and increase the frequency, severity, or extent of natural disturbances to forests such as drought, wildfire, and forest pests and pathogens (Millar & Stephenson, 2015; Williams et al., 2016; Seidl et al., 2017). Both the Intergovernmental Panel on Climate Change (IPCC) reports (IPCC, 2014; IPCC, 2019) and the Paris Agreement (UNFCCC, 2015) recognized that forests play a substantial role in achieving climate change mitigation goals.

Forests form a major part the global carbon cycle (Bosworth et al., 2008; Turner, 2010; Pan et al., 2011). They sequester large amounts of carbon through photosynthesis, storing it in the biomass, soils, and harvested wood products (Kurz et al., 2002, Randerson et al., 2002; Eriksson, 2006; IPCC, 2007; Covey & Orefice, 2009). The global forest sink was estimated to be

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[1] https://www.cop21paris.org/about/cop21. (Accessed January 08, 2017)

approximately 1.1 Pg carbon $year^{-1}$ (Pan et al., 2011) and recent studies showed a potential carbon sink for forests as high as 2.0 Pg C $year^{-1}$ (Harris et al., 2021). Globally, forests have the capacity to absorb 25% to 30% of the annual anthropogenic CO_2 emissions, and this proportion needs to be maintained or increased to limit global warming below 2° C (Le Quéré et al., 2009; IPCC, 2018; Friedlingstein et al., 2020). However, monitoring the level at which forests impact the concentrations of atmospheric GHG is challenging (Harris et al., 2021).

Reducing the atmospheric CO_2 concentration requires both a reduction in emissions and removal of CO_2 from the atmosphere (Smyth et al., 2014); mitigation efforts involving land systems can contribute in both these ways (IPCC, 2007; Lemprière et al., 2013; Ontl et al., 2020). The amount of carbon sequestered in forests can be raised by increasing both the forest area and the stand and landscape-level carbon stocks (Nabuurs et al., 2007). The mitigation potential of forest ecosystems makes carbon management a basis for future natural climate solutions (NCS) (Griscom et al. 2017; Fargione et al., 2018). NCS are approaches, based on a suite of conservation, sustainable management, and restoration of forests, grasslands, and wetlands, that can provide additional climate mitigation beyond business-as-usual scenarios (Drever et al., 2021). The full implementation of cost-effective NCS activities could provide up to one-third of the global mitigation potential to keep global warming below 2° C by 2030 (Griscom et al., 2017). However, reduction of GHG emissions from fossil fuels and land sector activities is also necessary to achieve this goal (Anderson et al., 2019).

In a forested ecosystem, disturbances (anthropogenic or natural) generally interrupt the functioning of trees and stands by physical or chemical damage that impact growth and survival (Sturtevant & Fortin, 2021). Disturbances can change forest ecosystems from carbon sinks to sources (Baldocchi, 2003; Kurz et al., 2008), since they are one of the main drivers for transferring forest carbon stocks between the biomass and the dead organic matter carbon pools, contributing to GHG emissions to the atmosphere (Kurz et al., 2013). Disturbances can change the structure, patterns, processes, composition, and functioning of forests and possibly the dynamics of the landscape (Turner, 2010; Lindenmayer et al., 2017; Sturtevant & Fortin, 2021).

Disturbances can be either stand-replacing or non-stand replacing, based on the scale and magnitude of the disturbance and subsequent recovery (Turner, 2010). Stand-replacing disturbances that are followed by a change in land use (e.g., encroachment and deforestation) result in the permanent removal of trees (Franklin et al., 2007) and consequently impact the carbon cycle and the ecological processes (Lorenz & Lal, 2010). Stand-replacing disturbances that are followed by forest regrowth (e.g., clear cut harvest, wildfire) affect carbon stocks and fluxes but maintain the potential of the forest to remove carbon from the atmosphere (Kurz et al., 2008; Griscom et al., 2017). In contrast, non-stand replacing disturbances (e.g., less severe fire, partial harvest) are less intensive and impact the forest ecosystem less (Lorenz & Lal 2010). Disturbances often trigger a change in stand tree-species composition, age structure, biomass and productivity, and carbon cycling (Sturtevant et al., 2014; Gautam & Mandal, 2016). Deforestation and conversion to other land uses along with forest degradation are the most prominent negative outcomes of disturbances in many forests; these outcomes are posing the biggest threat to the forest worldwide, particularly in tropics (Allen & Barnes, 1985; Chaudhary et al., 2016).

Deforestation occurs when forests are converted to other uses such as agriculture, urbanization, etc. Forest degradation occurs when forests lose their ability to supply essential ecosystem services to people and nature[2]. Over 7,000,000 ha of forest per year were lost worldwide from 2000-2012 because of deforestation, forest degradation, and land-use changes (Hansen et al., 2013). Permanent forest losses have contributed significantly to global CO_2 emissions (Achard et al., 2014; Willcock et al., 2016). These losses also have severe implications for biodiversity and rural communities (particularly those in the tropics that are dependent on forests for food and income). According to IPCC (2014), annual net GHG emissions from land use and land-use change activities from 2000 to 2010 accounted for about 12% of global CO_2 emissions. This is the second-largest source of CO_2 emissions to the atmosphere after the burning of fossil fuels (IPCC, 2007; Spalding, 2009; Houghton et al., 2012). About 23% of GHG emissions come from agriculture, forestry, and other land uses (IPCC, 2019).

An estimated 420 million ha of forest was lost due to deforestation since 1990 and 90% of the loss was in tropical forests; however, the rate of forest loss has declined in the most recent five-year period (FAO, 2020). Deforestation and forest degradation are progressive processes in

[2] https://www.iucn.org/resources/issues-briefs/deforestation-and-forest-degradation. (Accessed November 28, 2021)

tropical regions because of the conversion of forest land to agricultural land, pasture for subsistence, infrastructure expansion, urbanization, etc.[3] Tropical regions had the highest forest cover loss globally from 2000-2012, at a rate of 6.2 million hectares per year (Hansen et al., 2013).

Emissions could be reduced by nine gigatons of CO_2 per year by 2030 if suitable forest areas are restored, and deforestation and degradation could be halted (Miles & Sonwa, 2015). Sustainable forested ecosystems management could help reduce global carbon emissions and stabilize atmospheric CO_2 (UNFCCC, 1992). It is equally essential to understand the primary sources of forest-related emissions and removals and reduce these, where possible, to increase forest carbon sinks for climate change mitigation (Lemprière et al., 2013; Birdsey et al., 2014). Adopting forest management policies that increase forest cover via reforestation quickly after disturbance can increase carbon sequestration rates while reducing human and natural forest disturbance impacts can reduce carbon emissions. These policies and resulting practices provide a fundamental mechanism as part of a climate mitigation plan (LeMay et al., 2008).

Forest harvesting operations transfer carbon out of the ecosystem as harvested wood products (HWP). Certain HWP, such as various timber products, may allow the carbon to remain stored for decades to centuries and limit emissions by substituting for carbon intensive materials such as concrete, steel, plastics, and fossil fuels (Sathre & O'Connor, 2010; Werner et al., 2010; Lempiere et al., 2013; Winkel, 2017). This longer carbon retention provides more time for forest regeneration and growth and provides a potentially cost-effective tool for mitigating greenhouse gas emissions (Sathre & O'Connor, 2010; Smyth et al., 2014). The use of one-third of all sustainable wood as substitutes could save up to 31% of global CO_2 emissions and 20% of global fossil fuel consumption (Oliver et al., 2014). However, it makes a difference what proportion of HWP is used for longer lived products such as sawn wood or short-lived products as fuel wood. The fuel wood component of HWP is rapidly oxidized and released to the atmosphere (IPCC, 2006). Nevertheless, the use of fuel wood is arguably a better alternative than using some other fossil fuels. For example, one ton of fuel wood can save 400 litres of oil and prevent 0.3 tons of fossil carbon emission (Schoene and Netto, 2005). The Kyoto Protocol (KP) recognized the role

[3] https://earthobservatory.nasa.gov/features/Deforestation/deforestation_update3.php (Accessed July 05, 2021)

of HWP in mitigating GHG emissions. It was assumed that the amount of carbon leaving the HWP pool was oxidized at the time of harvest during the first KP commitment period (2008–2012). For the second KP commitment period (2013–2020) the accounting rules were modified to explicitly include carbon stock changes in the HWP pool (UNFCCC, 2011).

To manage forest carbon stocks and sequestration successfully, managers must identify and regularly monitor the main drivers of human and natural disturbances, land use and land-use change, and climate and environmental changes which affect forest carbon dynamics (Birdsey et al., 2013a). It is important for the development of climate policy, and the various parties developing nature-based solutions, to understand the extent, and spatial distribution of carbon fluxes across the global forests, and how forests can be managed to reduce emissions and enhance removals (Griscom et al., 2017).

1.2 Forest Carbon Pools

Terrestrial forest carbon is divided into five different carbon pools: aboveground biomass; belowground biomass; litter; deadwood (litter and deadwood are collectively known as dead organic matter (DOM)); and soil organic carbon (SOC), also known as soil organic matter (SOM) (IPCC, 2006). Aboveground tree biomass includes stems, stumps, branches, and foliage. The belowground biomass pool is comprised of roots (fine and coarse). Carbon stored in fine roots is usually reported in other pools because it can be complicated to distinguish them from the soil organic matter or the litter pool (IPCC, 2006). Coarse roots dominate the belowground biomass pool.

Litter includes debris of leaves, fruits, flowers, twigs, and small branches, excluding larger diameter branches (>10 cm), and is decomposed into the soil organic pool (Brown & Lugo, 1982). The decay and decomposition of litter depend on temperature, root exudates and microbial activity, and it can take years to finally release carbon into the atmosphere (Lorenz & Lal, 2010). Deadwood consists of all the deadwood on the forest surface, including standing dead trees, stumps, dead logs, coarse woody debris, and dead roots that have a diameter larger than or equal to 10 cm (IPCC, 2006). The deadwood pool can be up to 20% of the aboveground carbon in mature forests (Lorenz & Lal, 2010). SOC is composed of different minerals and compounds from fine roots, litter, and plant residues (Price et al., 2012). Due to microbial decomposition and decay, carbon in the SOC pool also gets released into the atmosphere. IPCC recommended to include all live and dead fine roots and dead organic matter to a depth of at least 30 cm in the soil profile in this pool; however, these bounds can vary according to each country's specifications (IPCC, 2006).

1.3 Forest Carbon Monitoring

Climate mitigation plans using forests, current estimates of forest carbon stocks, and dynamics are greatly needed at a regional, landscape, national, and global scales (Kurz et al., 2013). Reliable and regular estimates of carbon stocks and emissions are essential (Oli & Shrestha, 2009). In addition, indigenous communities play a critical role in managing forestland globally. IPCC (2019) has recently recognized indigenous and community land rights to land ownership and their responsibility to help mitigate climate changes. Indigenous and community land rights are crucial for meeting the aims of the International Paris Agreement, Food and Agriculture Organization (FAO), International Union for Conservation of Nature (IUCN), United Nations' REDD+ (Reducing Emissions from Deforestation and Degradation), etc.

Parties to the United Nations Framework Convention on Climate Change (UNFCCC) set up the Reducing Emissions from Deforestation and Degradation (REDD) program as a mechanism for mitigating the drivers of deforestation and forest degradation globally (UNFCCC, 2007). REDD+ was subsequently introduced as a forest-based climate-change mitigation approach that provides incentives to developing countries to reduce deforestation and forest degradation emissions, manage the forests sustainably, conserve, and enhance forest carbon stocks (UNFCCC 2009). The benefits are based on the "3Es", namely effectiveness (emissions reduced), efficiency (cost), and equity (benefit sharing) (Angelsen & Wertz-Kanounnikoff, 2008). Pilot projects have been implemented in many developing countries in readiness for REDD+ under the World Bank's Forest Carbon Partnership Facility, UN-REDD, and other bilateral aid schemes (Cerbu et al., 2011; UN-REDD, 2015).

Forest carbon management is an important activity in the context of GHG and climatic changes at national and international levels (Rabindranath & Ostwald, 2008). The REDD+ program was established by the parties to the United Nations Framework Convention on Climate Change (UNFCCC) to support developing countries to reduce emissions from deforestation (UNFCCC, 2007). Many participating countries have completed pilot programs, submitted their

Forest Emissions Reference Levels (FERL), and formulated their strategies for emission reductions (UNFCCC, 2007; UNFCCC, 2009). For example, Nepal received funds from the Forest Carbon Partnership Facility (FCPF) to reduce deforestation and forest degradation emissions in 2021[4]. Nepal is committed to REDD+ by reversing deforestation and forest degradation, conserving existing forests, enhancing forest carbon stocks, considering the livelihoods of poor and socially marginalized forest-dependent people, and incentivizing those who contribute to forest carbon conservation and enhancement (MoFE, 2018).

Estimates of the quantity of forest growing stocks and carbon stocks should be regularly updated at a national level to maintain reasonable estimates of carbon emission and carbon sequestration (Oli & Shrestha, 2009). Monitoring carbon sources and sinks are particularly critical in understanding the processes that affect carbon sequestration (MoFSC, 2013). Knowing the status of carbon stocks is useful when considering alternative management scenarios to achieve national GHG mitigation goals (Upadhyay et al., 2005). Thus, regular monitoring of climate mitigation activities to achieve emission reductions is needed. Monitoring forest cover stock, emission, and removal is often inadequate in developing countries like Nepal (Neupane & Sharma, 2014); however, a program like REDD+ has increased the importance of conducting such monitoring. Additionally, international agreements (UNFCCC, the Kyoto Protocol, etc.) require countries to monitor and report forest carbon stocks and changes.

1.4 Carbon Budget Modeling

Both developed and developing countries need to monitor and report on forest carbon stocks, emissions, and removals under international climate change agreements (UNFCCC, 2011). The IPCC requires countries to report on all five forest carbon pools: aboveground biomass (AGB), belowground biomass (BGB), deadwood (DW), litter (L), and soil organic matter (SOM), as well as on carbon stored in harvested wood products (HWP). Regular assessments of forests are fundamental to gain revenue from carbon trading and ensure that forest biomass extraction is sustainable (Upadhyay et al., 2005). For reporting, two alternative approaches are in use. The first

[4]https://www.forestcarbonpartnership.org/system/files/documents/FCPF%20Carbon%20Fund%20ERPA-Nepal%20Tranche%20B.pdf. (Accessed December 27, 2021).

is the stock-difference approach. Differences in forest inventory and other information between two or more points in time provide change estimates (GOFC-GOLD, 2015). Alternatively, the gain-loss approach focuses on estimating the balance between forest gains and forest losses using models informed by forest inventory, yield curves and annual disturbances (losses).

Science-based models can inform policy by quantifying the past and future impacts of human activities on GHG emissions and removals and assessing the effectiveness of climate change mitigation strategies designed to reduce GHG sources or increase sinks (Kurz et al., 2016). However, tracking carbon stocks and changes impacted by natural and human disturbances is challenging (Spalding, 2009). Estimating carbon stock and changes depends on the methodology, measurement time, and scale (Chapin et al., 2006; Petrokofsky et al., 2012) Although considerable progress has been made, challenges and limitations remain in estimating and monitoring terrestrial carbon. However, due to certain limitations in the methodological approaches used in estimating the net carbon fluxes, and limited scientific understanding of complex forest responses to climate change there still remain uncertainties in the size and future direction of the forest-based carbon balance (Hayes et al., 2012; Kurz et al., 2013).

Carbon models simulate terrestrial carbon dynamics and quantify forest carbon stocks and changes, integrating data from different spatial and temporal scales (Birdsey et al., 2013b). There are two types of modelling approaches used for carbon studies: empirical and process-based models. Empirical models simulate growth based on yield curves (e.g., EFISCEN: Nabuurs et al., 2000; CO2FIX: Masera et al., 2003; CBM-CFS3: Kurz et al., 2009, Kull et al., 2011; Metsaranta et al., 2011), while process-based models simulate growth based on the biological processes such as photosynthesis (CENTURY: Metherall et al., 1993; TEM: Tian et al., 1999; LUCA-CBM: Sleeter et al., 2022). Empirical models, which are yield-driven, explicitly simulate human and natural disturbances, but consider only those global change factors such as climate change that are expressed through changes in disturbances (e.g., increased wildfires or insect disturbances). In contrast, process-based models can simulate the impact of global change factors (Kurz et al., 2009). Since detailed biological data, such as photosynthesis rates, are not available for Nepal, I did not use a process-based model. Instead, I chose to use the empirical model, CBM-CFS3, because of its flexibility. Although yield predictions for Nepal were not available, it was possible to create such predictions using data from geographically similar regions.

The carbon budget model, developed for the Canadian forest sector (CBM-CFS3) is an empirical model which estimates forest carbon stocks and changes at the stand or landscape level (Kurz et al., 2009). This model uses algorithms to track the amount of carbon transferred to the five different carbon pools, the atmosphere, and harvested wood products. Litterfall and decomposition rates are simulated, and yield curves are used to simulate forest growth, mortality, and regeneration, determined by the forest type, stage of stand development and ecological characteristics (Kull et al., 2011). The model can assimilate the impacts of forest disturbance events on carbon stocks and allows the user to simulate alternative forest management and mitigation scenarios. Each disturbance event impacts carbon pools in different ways (Spalding, 2009). Natural or anthropogenic disturbances can turn forest ecosystems into sources of CO_2 emissions (Brown, 2002). The time that takes it to regrow and turn into a carbon sink can take years to decades (Kurz et al. 2013) and to take up all the carbon that was released in a disturbance can take decades to centuries as it depends on the regeneration of the forest, growth rates, and dead organic matter decay rates (Covey & Orefice, 2009). The model is flexible and has been adapted and applied to forests in Italy (Pilli et al., 2013), 26 EU countries (Pilli et al., 2015), Mexico (Mascorro et al., 2014), and Korea (Kim et al., 2017), as well as Canada (Stinson et al., 2011).

1.5 Forests in Nepal

Nepal is a small mountainous country situated between 26.022' N and 30.027' N latitude and 80.004' E and 88.012' E longitude. It is bordered by China to the north and India to the south, east, and west (Fig. 1.1). Nepal contains approximately 35 forest types due to variations in climate, topography, and soil conditions (Stainton, 1972; Chaudhary et al., 2016). The major forest types, according to altitude and climate, are tropical (up to 1000 m), sub-tropical (1000 - 2000 m), temperate (2000 - 3000 m), sub-alpine (3000 - 4100 m), and alpine (above 4100 m) (Stainton, 1972). There are five physiographic regions based on elevation, increasing from south to north namely: Terai (60-200 m), Churia (Siwalik) (200-1500 m), Middle Hills (1000-2500 m), High Mountains (2200-4000 m) and High Himalayas (>4000 m)[5]. Forests are one of the most essential natural resources in Nepal and the primary source of livelihood for people in rural areas; the

[5] http://dhm.gov.np/uploads/climatic/1935165359NAP_TrendReport_DHM_2017. (Accessed December 02, 2021).

forestry sector plays a pivotal role in sustaining Nepal's socio-economic development (Chaudhary, 2000).

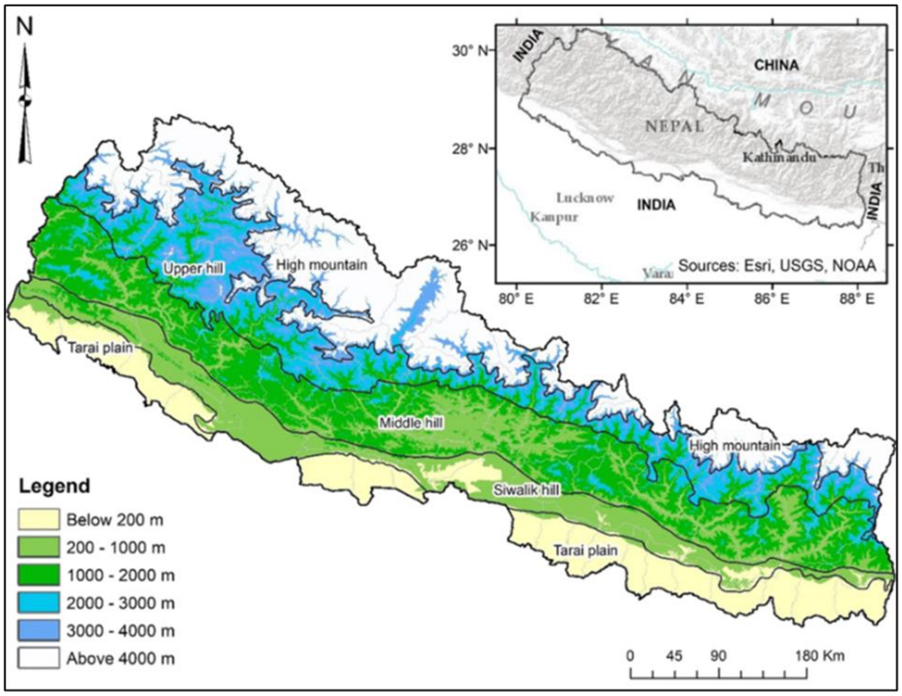

Figure 1.1: Map of Nepal showing the different physiographic regions (FRA, 2014)

Forests cover a total of 5.96 million ha (~40%) of the total land area of Nepal (FRA/DRFS, 2014c). The forested areas range from 60 to 5,000 m in elevation and extend across sub-tropical, temperate, sub-temperate, sub-alpine, and alpine eco-zones (MoFSc, 2014). Approximately 83% of the total forest land lies outside of protected areas. The Middle Hills physiographic region contains the largest percentage of Nepal's forest cover (~38%), followed by the High Mountains (~32%), Churia (~23%), and Terai (~7%) (FRA/DFRS, 2015). Forests are either owned by government (public) or privately owned. Public forests include:

1. government-managed forests, which are national forests managed by the Government of Nepal;
2. community forests, where management of national forests has been handed over to local forest users' groups for the management, protection, and utilization of forest resources;
3. collaborative forests, which are managed in partnership between the Government of Nepal, local governments, and local forest-user groups;

4. protection forests, where management is aimed towards protecting forests that are highly rich in biodiversity, cultural values and not covered under protected areas (Gautam et al., 2016);
5. Leasehold forests, managed by a group of marginalized people mainly to alleviate poverty and restore degraded land; and
6. Sacred forests are managed for religious purposes.

A large proportion of the HWP from Nepal's forests is used as fuel wood. More than 75% of the total energy used in Nepal is derived from fuel wood, and it is the primary source of carbon emissions (Baral et al., 2019). Furthermore, much of the forest area is affected by deforestation and forest degradation (FRA/DFRS, 2015; Bhusal et al., 2018).

The causes of deforestation and degradation in Nepal are high dependency on forest resources, unsustainable harvesting practices and illegal harvesting, permanent forest removal for infrastructure development, landslides, floods, encroachment, overgrazing, lack of good governance, and unclear forest policies (FRA/DFRS, 2015; Chaudhary et al., 2016). Deforestation is a concern in many developing countries, frequently caused by rapid population growth, expansion of cropland, as well as non-sustainable intensive harvesting of forests for fuel wood, and wood exports (Allen & Barnes, 1985). The disturbances rates in Terai and Churia are especially high because of population pressures due to migration from other regions of Nepal for better employment opportunities. The Forest Resource Assessment reports (FRA/DFRS, 2014a and b) indicated the rate of deforestation and degradation was 0.40% per year from 1991-2010 in Terai and 0.18% per year from 1995-2010 in Churia. Consequently, I have chosen to focus on those physiographic regions in this dissertation.

1.6 Objectives and Dissertation Structure

The overall goal of this research was to assess the carbon stocks and dynamics of the forests in the Terai and Churia regions of Nepal under a variety of managerial and policy assumptions. The motivation was to provide insight into how management of the carbon stocks in the forests of Nepal could be improved. To achieve this goal, three research chapters are included in this dissertation: modelling forest carbon dynamics in Terai and Churia (Chapter 2); impacts of alternative forest management approaches on forest carbon dynamics in Terai (Chapter 3); and carbon stored in different compositions of HWP in Terai (Chapter 4).

In Chapter 2, I compared forest carbon dynamics for the two regions of Nepal that have the highest deforestation and degradation rates and the highest populations: Terai, and Churia. I estimated the forest carbon stocks and stock changes due to the anthropogenic and natural disturbance rates from 2010 to 2017 and then projected these disturbances forward to 2030 under a "business-as-usual” scenario. I addressed the following specific questions:

1. What are the differences in carbon dynamics between Terai and Churia?
2. What might be causing those differences?
3. Are there differences in carbon stocks amongst administrative units in Terai and Churia?
4. How could this information be used to improve future forest management?

In Chapter 3, I analyzed how the impacts assessed in Chapter 2 for the forests of Terai might change under a variety of management scenarios related to possible population growth rates, climate change consequences, and possible forestry investment. I addressed the following specific questions:

1. What are the impacts on carbon stocks and dynamics resulting from altering the level of each forest disturbance type, specifically, increasing or decreasing harvesting, forest encroachment, landslides, and forest fires relative to the historic (2010 to 2017) baseline?
2. What are the impacts on carbon stocks and dynamics resulting from increased population pressure causing increased harvesting and encroachment, along with increased forest fires relative to the historic baseline (worst-case scenario)?
3. What are the impacts on carbon stocks and dynamics resulting from investments to reduce regeneration delay, suppress fire, institute landslide preventive measures, implement policies to minimizing encroachment relative to the historic baseline and decrease the harvest rate because of fuel wood substitution (best case scenario)?

In Chapter 4, my goal was to examine how HWP mixtures impact forest stocks and CO_2 emissions in Terai under different harvest rates. I addressed the following specific questions:

1. What are the impacts on carbon stocks associated with increasing the proportion of sawn wood in the HWP?
2. Can shifting the commodity proportions offset the carbon loss associated with higher harvest levels?

Chapter 2: Modelling Forest Carbon Dynamics in Terai and Churia

2.1 Introduction

Nepal has experienced considerable loss in forest cover over the last several decades (LRMP, 1986; Nepal Biodiversity Strategy and Action Plan, 2014). However, the most recent Nepal Forest Resource Assessment report showed an increase in forest area nationally, with approximately 40% of Nepal's total land area covered by forest in 2014, up from 29% in 1994 (FRA/DFRS, 2014c). This increase was attributed, in part, to better forest inventory data (e.g., a systematic sample of ground plots coupled with high-resolution imagery), but also because of community forestry interventions and natural regeneration that occurred on abandoned agricultural land, particularly in the mountainous region. The report also indicated increasing deforestation and degradation rates; 0.40% per year in Terai from 1991-2010 and 0.18% from 1995-2010 in Churia. The main drivers of deforestation and forest degradation were identified as illegal logging, fuel wood consumption, encroachment, road construction, forest fire, mining, and grazing.

The Nepalese Government committed to REDD+ after the 13th COP in 2007 and joined the United Nation's collaborative initiative on REDD+ in 2009 (UN-REDD, 2015). In 2012 and 2014, UN-REDD+ provided technical guidance to Nepal with respect to FERL (MOFE, 2015; MoFE, 2018) and the Forest Carbon Partnership Facility (FCPF) program of World Bank helped financially (MoFSc, 2014). The FERL for Nepal was 9.3 Tg CO_2e per year from deforestation and about 4.1 Tg CO_2e per year from forest degradation for 2000-2010 (MoFSC, 2016).

In this chapter, I compared forest carbon dynamics for the two most populous physiographic regions of Nepal, Terai, and Churia under the actual disturbance regime for 2010 to 2017 and then projected average disturbance forward to 2030 under a "business-as-usual scenario." Based on these forecasts, I asked the following questions:

1. What are the differences in carbon dynamics between Terai and Churia?
2. What might be causing those differences?
3. Are there differences in carbon stocks amongst administrative units in Terai and Churia?
4. How could this information be used to improve future forest management?

I expected higher biomass productivity in Terai since the growing conditions are better with alluvial soils, higher temperatures, and more rainfall. However, I expected lower accumulations of soil organic carbon due to higher decomposition rates for dead organic matter. Encroachment is higher in Terai, whereas fire, landslide, and harvest rates are higher in Churia. These disturbances release biomass carbon to the atmosphere, transfer biomass to dead matter that decomposes on-site and remove wood products, respectively. I expected these disturbances would impact the carbon dynamics of Terai more heavily than those of Churia. Administrative units vary in species compositions, temperature, elevation, and forest management. As a result, I expected the carbon stock densities would differ amongst different administrative units within each region. Finally, using this baseline information, if the forest ecosystems in either region or within administrative units were sinks, further interventions could be considered to sustain or enhance the carbon stocks. In contrast, if these forest ecosystems were a source of carbon emissions, management interventions to reduce carbon emissions could be recommended.

2.2 Methods

2.2.1 Study Area

As the most populated regions of Nepal with the highest forest use, Terai and Churia are the focus of this chapter (Fig. 2.1). The population densities were 392 and 173 people per square kilometer for Terai and Churia, respectively, over a decade ago (CBS, 2011). Although both regions are sub-tropical, they differ in altitudinal gradient, climate, precipitation, and magnitude of disturbances (FRA/DFRS, 2014; Nepal Biodiversity Strategy and Action Plan, 2014).

The Terai region occupies the southernmost part of Nepal, with a total area of 2.02 million ha. The sub-tropical climate in this region is characterized by hot and humid summers with heavy monsoon rains and dry winters. The maximum monthly mean temperature (35-40° C) occurs in April/May and the minimum (14-16° C) in January (Jackson, 1994). Average annual precipitation decreases from 2,680 mm to 1,138 mm from east to west. The mean monthly rainfall ranges from 8 mm in November to 535 mm in July (Department of Hydrology and Metrology, 2009)[6]. Forests

[6]http://dhm.gov.np/uploads/getdown/1837228842Existing%20Hdrometric%20Network%20of%20Nepal%20Project%20new.pdf. (Accessed June 27, 2018).

cover 20.4% (0.41 million ha) of the area, with approximately 76.4% outside protected areas, 17.0% in protected areas, and 6.6% in buffer zones between protected and unprotected regions (FRA/DRFS, 2014b). The primary forest type is mixed hardwoods, with the most common trees species being: *Shorea robusta*, *Syzygium cumini*, *Adina cordifolia*, *Terminalia alata*, *Tectona grandis*, *Dalbergia sissoo*, *Albizia procera*, and *Terminalia bellirica*. Of these, *Shorea robusta* is the most prevalent tree species (Stainton, 1972).

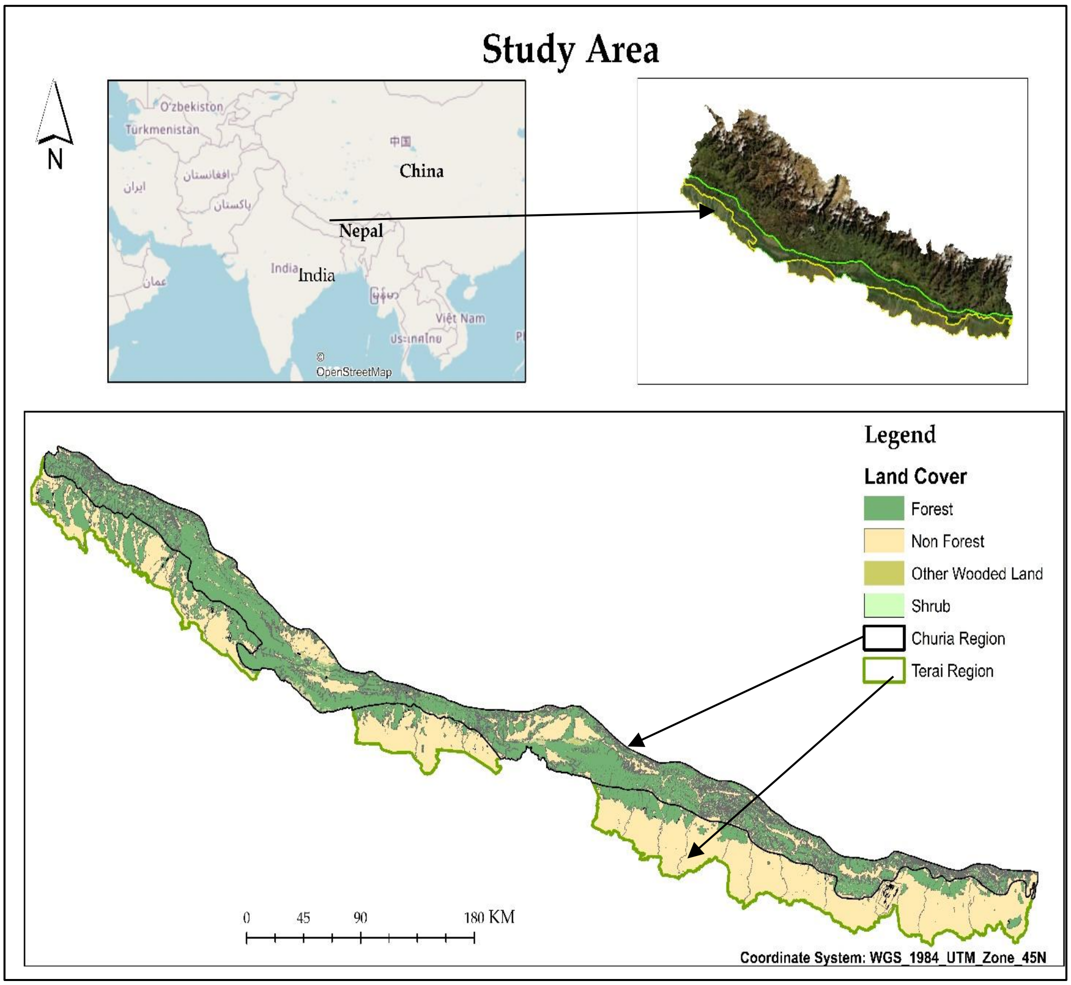

Figure 2.1: Map showing the study areas of Terai and Churia with different land cover categories (Data Sources: Open Street Map7: World Imagery8: and FRA/DFRS (2014c)).

[7] https://www.openstreetmap.org/search?query=Nepal#map=8/28.417/84.130. (Accessed Nov 23, 2020).
[8]https://maps.greenpeace.org/portal/home/webmap/viewer.html?layers=10df2279f9684e4a9f6a7f08febac2a9.(Accessed November 23, 2020).

The Churia region, also known as Siwalik, lies just to the north of Terai, covering an area of 1.9 million ha and containing the youngest mountain range in Nepal formed by accumulating fluvial sediments from the Himalayas during Neogene to Quaternary periods (Upreti, 1999). The climate ranges from sub-tropical to warm temperate with hot and sub-humid summers with heavy monsoon rains and cold, dry winters. The average annual minimum temperature ranges from 12^{o} C to 19^{o} C in January. The average yearly maximum temperature ranges from 22^{o} C to 30^{o} C in April/May (Department of Hydrology and Metrology, 2009)[9]. Churia's forests cover 72.4% (1.4 million ha), with 76% outside protected areas, 18% in protected areas, and 6% in buffer zones between these two (FRA/DRFS, 2014a). The most common tree species in Churia are *Shorea robusta, Terminalia alata, Adina cordifolia, Pinus roxburghii, Semecarpus anacardium, Acacia catechu, Dalbergia sissoo, Schima wallichii,* and *Castanopsis indica* (FRA/DFRS, 2014a). Similar to Terai, *Shorea robusta* is the dominant tree species (Stainton, 1972).

2.2.2 Carbon Budget Model-Canadian Forest Service (CBM-CFS3 Model)

CBM-CFS3 (Kurz et al., 2009; Kull et al., 2011; Metsaranta et al., 2011) was parameterized for Terai and Churia to quantify carbon pools and dynamics. This model uses the gain-loss method as described by the IPCC. The CBM-CFS3 model can be used at the stand and landscape levels to simulate biomass (above and below ground) and dead organic matter (soil, litter, and deadwood) carbon. The model estimates carbon stocks and emissions of CO_2, methane (CH_4), and carbon monoxide (CO); carbon amounts transferred between different pools are tracked. Further, annual changes caused by ecological processes, disturbances (human and natural), and land-use changes are estimated.

Along with calibrating the CBM-CFS3 model for use in Nepal, base forest inventory information, stand yields, historical disturbances, and other data and information were necessary inputs to the model. I followed approaches used in other countries for setting up CBM-CFS3 for Nepal (e.g., Pilli et al., 2013; Mascorro et al., 2014; Kim et al., 2017). The following subsections

[9]http://dhm.gov.np/uploads/getdown/1837228842Existing%20Hdrometric%20Network%20of%20Nepal%20Project%20new.pdf. (Accessed June 27, 2018).

provide detailed descriptions of the inputs to CBM-CFS3, model modifications, and how the model estimated and forecasted carbon stocks through time for Churia and Terai.

2.2.3 Forest Inventory Information

Nepal's most recent forest inventory, undertaken in 2010, used two-phase systematic sampling (FRA/DFRS, 2014c). In the first phase, grid locations, spaced 4 km by 4 km, were established and satellite images were used to classify each site as forested or not forested. In the second phase, a subset of the forested locations was systematically selected for ground sampling, resulting in 55 sample locations in Terai and 111 in Churia. At each chosen sampling location in Churia, a cluster of six plots spaced at 150 m in a two-by-three plot arrangement by cardinal directions was established. In Terai, a cluster of four plots spaced at 300 m in a two-by-two plot arrangement was used because of greater homogeneity in the forest. Four concentric circular plots were then established at each plot location within a cluster, namely: 1) 20 m radius for trees ≥ 30 cm diameter outside bark at breast height (1.3 m above ground, DBH); 2) 15 m radius for trees from 20.0 to 29.9 cm DBH; 3) 8 m radius for trees from 10.0 to 19.9 cm DBH, and 4) 4 m radius for trees from 5.0 to 9.9 cm DBH.

Plot-level, followed by cluster-level attributes were compiled for each ground-sampled location. For tree-level volume estimates, the species-specific models developed by Sharma & Pukkala (1990) for forest trees of Nepal were used. Aboveground stem biomass was obtained by multiplying the stem volume by the wood density (Sharma & Pukkala, 1990). Branch and foliage biomass estimates were obtained using branch-to-stem and foliage-to-stem biomass ratios as prescribed for Nepal (MoFSC, 1988). Average height (m), average quadratic mean diameter (QDBH; cm), trees per hectare, volume (m^3 ha^{-1}), aboveground biomass (tonnes ha^{-1}), and basal area per ha (m^2 ha^{-1}) values were calculated for each plot, along with the species composition by basal area per hectare. The plot-level attributes were then averaged for each cluster, accounting for any plots within the cluster with no trees.

The maximum volume (m^3 ha^{-1}) was higher for Terai than for Churia (Table 2.1). The maximum volume was also reflected in higher maximum biomass and average tree size (i.e., QMD shown in Table 2.1), but lower trees per hectare (TPH).

Table 2.1: Summary of the 2010 forest inventory for Terai and Churia (Data source: FRA/DFRS, 2014a, 2014b). (Min: minimum, Max: maximum, TPH: trees per hectare, Basal area ($m^2\ ha^{-1}$), Volume ($m^3\ ha^{-1}$), Biomass (tonnes ha^{-1}), QMD: quadratic mean diameter (cm), SD: standard deviation).

Estimates	Terai					Churia				
	TPH	Basal Area	Volume	Biomass	QMD	TPH	Basal Area	Volume	Biomass	QMD
Mean	592	18.33	169.95	197.61	25.0	782	18.64	150.63	170.71	18.8
Min	39	0.80	4.30	4.14	8.3	82	4.40	21.36	19.84	5.4
Max	2196	38.30	400.10	513.66	70.3	2999	33.71	304.19	366.66	41.8
SD	492	8.44	98.0	123.49	14.7	519	7.06	69.47	82.68	5.9

Each cluster was considered a "forest unit" in the CBM-CFS3 forecasts (i.e., 55 forest units in Terai and 111 forest units in Churia). The forest area associated with each of these forest units was determined using sampling probabilities along with the amount of forest cover in each administrative unit within Terai or Churia. The forest cover area in each administrative unit was determined for Terai and Churia based on land cover maps (FRA/DFRS, 2014c) using ArcMap (Version 10.8.1). I used the first and second stage selection probabilities for each cluster to calculate forest unit areas. The first stage probabilities were equal (systematic sampling with square spacing); the second stage probabilities differed, with higher probabilities for plots within a cluster labeled as forested in the first phase. The resulting forest unit areas varied from 947 to 14,413 ha in Terai and 2,515 to 29,936 ha in Churia.

2.2.4 Yield Tables

Based on an extensive literature search and contacting a few agencies in Nepal and several researchers on tropical forests, I found only one growth and yield model developed with Nepalese data from the two study regions (Rautiainen, 1999) for *Shorea robusta*. This model was based on 29 ground plots of varying density, spatial tree patterns, and stand ages measured only once. Permanent sample plots have only been recently established in Nepal and have only been measured once (FRA/DFRS, 2014c). Consequently, I constructed the yield tables needed for this study using published yield information from other countries for the most common tree species in the study regions (Table 2.2). This information was mainly for plantations under fully stocked conditions, except for Singh (1980) who provided yield values for three plantation densities and only high site quality class. The site quality of a site is dependent on several factors such as soil, rainfall, and water availability etc. Top height of the stand was an indicator of site quality in the plantation sites.

Table 2.2: Yield information sources by species, density classes (H: High, M: Medium, L: Low), and site quality classes (H: High, M: Medium, L: Low, Min: minimum).

Species	Source	Density class (Stems ha^{-1})	Site Quality (m)	Min. DBH (cm)
Shorea robusta	Singh, 1980	1400 (H), 1000 (M), 600 (L)	High Site plantation	5 cm
Terminalia alata	Singh, 1980	Fully stocked	33 (H)	Not reported
Syzygium cumini	Singh, 1982	Fully stocked	22 (H),18(M), 14 (L)	Not reported
Dalbergia sissoo	Sharma, 1979	Fully stocked	23 (H), 20(M), 17(L)	Not reported
Acacia catechu	Sharma, 1981	Fully stocked	26 (H), 23 (M), 7(L)	Not reported
Pinus roxburghii	Suri, 1984	Fully stocked	33 (H), 27 (M)	Not reported
Tectona grandis	Nunifu & Murchison, 1999	Fully stocked	19 (H), 14 (M), 10 (L)	Not reported

The yield tables for each forest unit required for forecasting using CBM-CFS3 were created according to the following steps:

1. Each forest unit was assigned a stand density class (High, Medium, or Low), based on a stand density index (SDI, no units) from fitting an SDI model. Also, a site productivity class (High, Medium, or Low) was assigned using an ecological classification approach.
2. A meta-model of the yield versus age was fit by species using published yield information for the high site and density classes only, representing yields of fully stocked, high site productivity conditions.
3. The fully stocked, high site productivity species-specific yield curves were then adjusted to create a table of yields by 10-year age classes for each forest unit by:
   a. Adjusting species-specific fully stocked yield tables for the density and site classes of the forest unit; and
   b. Prorating the adjusted species-specific yield by the species composition of the forest unit.

4. Using the yield for the ground cluster and the assigned yield table for each forest unit, a forest unit age was given by locating the age associated with the volume per ha for that unit on the yield table since age was not available in the forest inventory data.

For the first step, stand density index (SDI) models (Kershaw et al., 2017, p 261-263) were developed separately for Terai and Churia using the ground data summarized for each cluster. Specifically, a linear model of the logarithm (base 10) of trees per ha versus the logarithm of the average DBH was fitted (lm () function in R 3.6.2) for each study area, representing the average trend line considered as the 50th percentile (i.e., assuming a symmetric distribution around the trend line). By standardizing the residuals associated with each cluster, a percentile relative to the average line was obtained and then each cluster was assigned to one of three stand density (SD) classes, namely: low (L), 0 to 33%; medium (M), 33 to 66%; or high (H), above 67% (Fig. 2.2). To assign a site class (High (H), Medium (M), or Low (L)) to each forest inventory cluster, dominant/co-dominant species, slope, elevation, and soil type were used (Jackson, 1994).

The published yield data were primarily based on repeated measures of high-value plantations that represented yields of completely stocked stands (i.e., high SDI and high site conditions), with only one source showing yields at lower densities (Table 2.2). For the second step, a base model was fitted to the yield trajectories using only the subset of high site and high-density yields. For this, a Chapman-Richards' growth model was selected because this model is flexible and biologically meaningful (Clutter et al., 1983, p 124-125):

$$\text{Volume per ha} = \beta_1 \times (1 - \exp(-\beta_2 \times A))^{(1-\beta_3)^{-1}} + \varepsilon$$

where volume per ha is yield (m^3 ha^{-1}), β_1 is the asymptote or maximum achievable volume, β_2 and β_3 are the shape parameters, A is the age (years), and ε is the error.

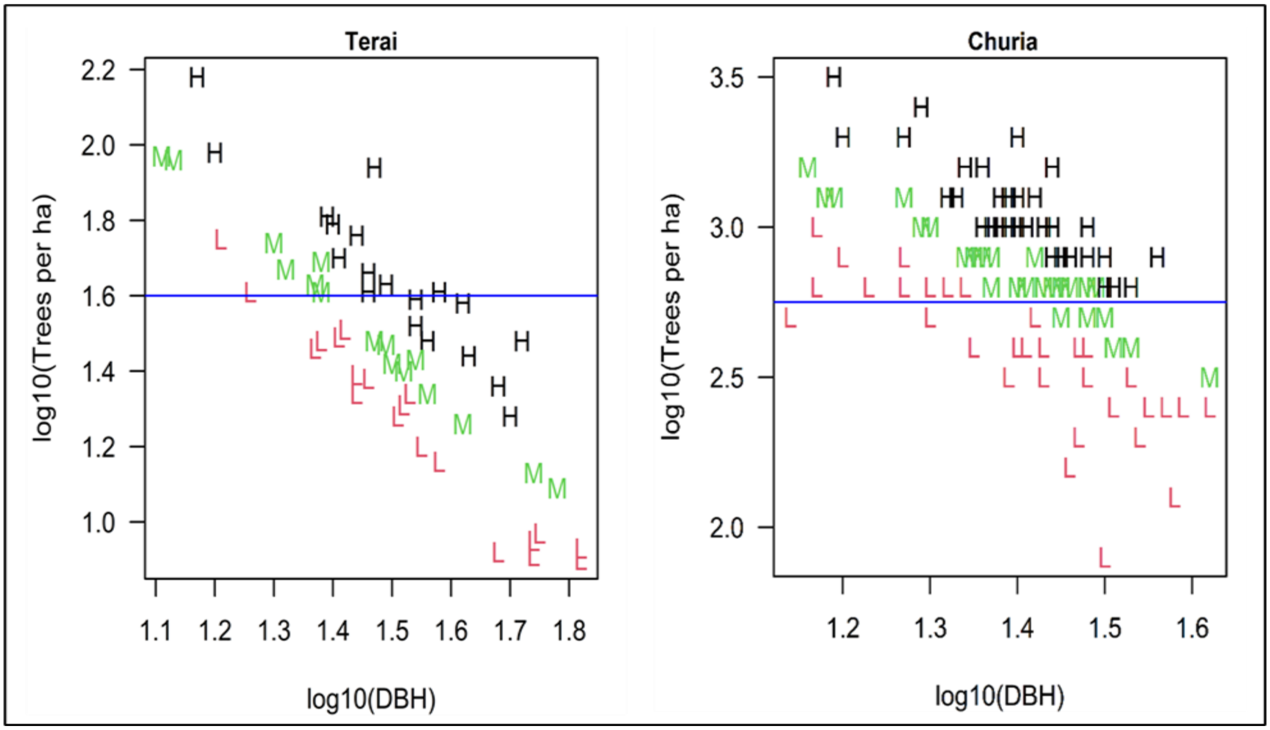

Figure 2.2: Stand density (SD) classes for cluster plots in Terai and Churia. Each point represents one cluster plot from the forest inventory, labeled with the SD class as low (L), 0 to 33%; medium (M), 33 to 66%; or high (H), above 67%.

This nonlinear model was fit using all species' high site and high-density yield information with published yield curves using the package "nlme" in R 3.6.2, varying starting parameters to ensure a global maximum solution. Then, each of the three parameters was allowed to change as a random effect with species (i.e., random coefficient). Next, more than one of the parameters was allowed to change as a random effect with species. Akaike's Information Criterion (AIC) and the log-likelihood (loglik) values were compared among models. Also, a graph showing the fitted model versus the yield data was used to indicate how well the model fits the data. The final model had random effects for each species for β_1 and β_3 only since no further improvements were obtained by allowing for a random effect on β_2 (Model 3 of Table 2.3; Table 2.4). This model also resulted in trends that mimicked the published yield information (Fig 2.3).

Table 2.3: AIC and log-likelihood values for a selection of alternative high site and high-density yield models.

Models	Description	AIC	log likelihood
Model 1 (Base model)	$\beta_1, \beta_2,$ and β_3 were all fixed-effects parameters	945.2558	-468.628
Model 2	A random effect ($u1$) on β_1 was introduced	873.1874	-432.594
Model 3	Random effects, $u1$ and $u3$ for β_1 and β_3, respectively	827.407	-408.704

Table 2.4: The estimated parameters and adjustments by species for β1 (i.e., u1) and β3 (i.e., u3) for the chosen high density and high site yield model.

β_1	β_2	β_3	Species	$u1$	$u3$
504.3632	0.0389	0.4882	*Acacia catechu*	-288.744	-0.51975
			Dalbergia sissoo	-222.249	-0.39787
			Pinus roxburghii	-106.083	-0.05374
			Syzygium cumini	-59.4258	-0.26075
			Shorea robusta	243.1571	0.236994
			Terminalia alata	-134.159	0.387525
			Tectona grandis	358.3252	-0.03743

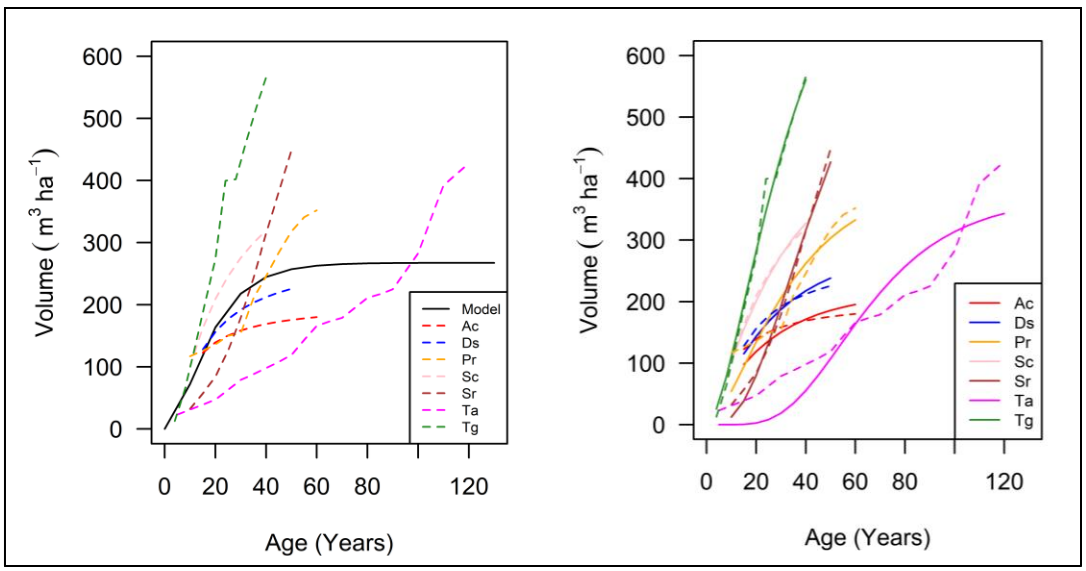

Figure 2.3: Yield trajectories for the published data by species (dashed) versus: (Left) the base model (solid line) and (Right) final models by species (solid lines). (Species: Ac: *Acacia catechu*, Ds: *Dalbergia sissoo*, Pr: *Pinus roxburghii*, Sc: *Scyzium cumini*, Sr: *Shorea robusta*, Ta: *Terminalia alata*, Tg: *Tectona grandis*).

In the third step, yield trajectories by species for high density and high site classes were adjusted for different stand density and site classes. Specifically, the yields were lowered by 33% and 67%, respectively, using published yield data. Then, using the forest inventory clusters attributes, a linear model of cluster volume per ha versus cluster mean height and site and stand density classes as factors were fitted. A mean height of 15 m was then input into the model, and an estimated volume per hectare value was obtained for the different site and stand density classes combinations. These were used to compute yield proportions for the medium and low site and stand density classes relative to volume per ha values for the high site and density class. These yield proportions were similar for the three stand density classes, at 0.78 and 0.64 for medium and low stand densities regardless of site class. Thus, for the medium and low stand density classes, the yields were lowered by 22% and by 36%, respectively. Nine different yield curves were obtained for each species with published yield information as shown for *Shorea robusta* and *Tectona grandis* (Fig. 2.4).

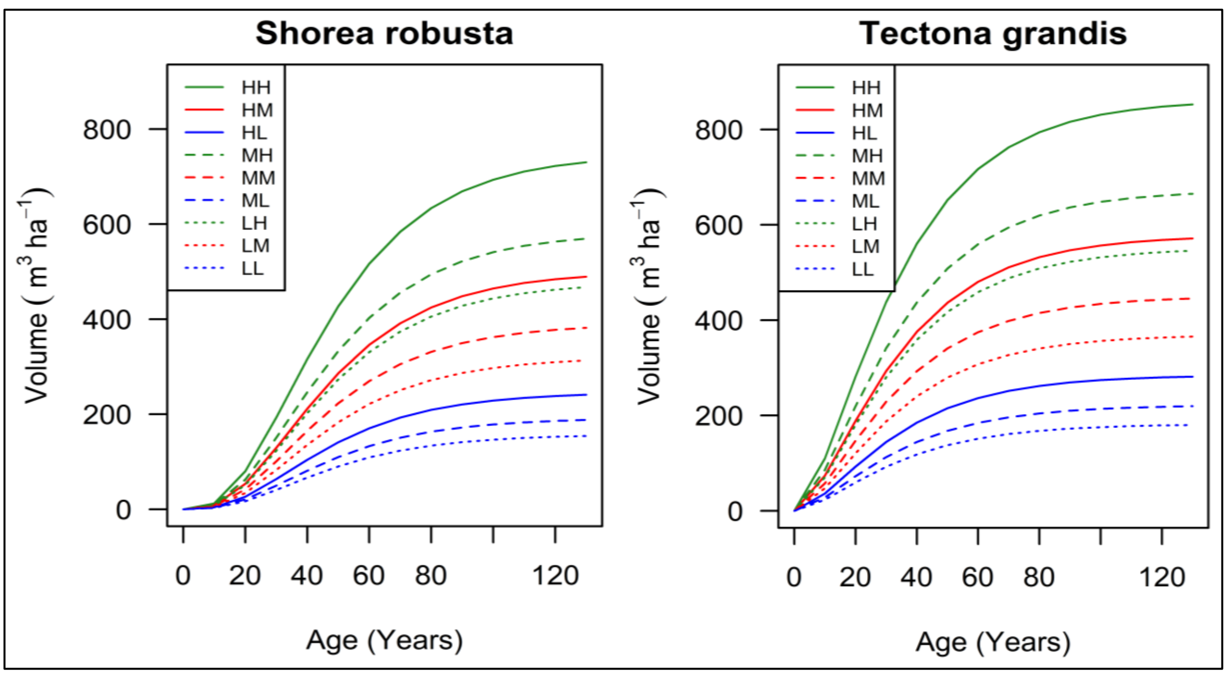

Figure 2.4: Yield curves by site class (H: High, M: Medium, L: Low) and stand density class (H: High, M: Medium, L: Low) for *Shorea robusta* and *Tectona grandis*.

A custom yield table was created for each forest unit by prorating (i.e., weighting) the species-specific yield tables for the forest unit stand density and site classes using the species composition. For clusters that contained species with no published yield curves, the yield table for the most common species of both regions, *Shorea robusta*, was used. Fifty-five local yield tables were constructed for Terai and 111 for Churia (i.e., one for each cluster). Finally, since age information was needed to access the yield curves and it was not available from the ground data for each cluster, the ground cluster yield associated with the forest unit was located on the assigned yield curve to determine the age to assign to the forest unit.

2.2.5 CBM-CFS3 Biomass Estimates and Dynamics Adjusted for Nepal

CBM-CFS3 applies species-specific conversion values reported in Boudewyn et al. (2007) for each eco-zone and province in Canada to estimate aboveground biomass from yield table volume per ha values. Each forest unit was matched with stand-level volume to biomass conversion values for Canada. Specifically, forest units with broadleaf species (i.e., *Shorea robusta*, *Terminalia alata*, *Syzygium cumini*, *Dalbergia sissoo*, and *Acacia catechu*) were "mapped" to *Quercus bicolor* Willd. *Pinus roxburghii* was "mapped" to Pinus spp. Mixed stands of broadleaves and conifers were mapped to "Mixed Woods." This mapping was based on air-dried wood densities obtained from the Global Wood Density Database[10].

Some parts of trees, such as fine roots, foliage, and branches, are transferred to the DOM carbon pools in CBM-CFS3. This transfer is estimated by turnover rates specific to each biomass component in each eco-zone (Kull et al., 2011). For these study areas in Nepal, the default turnover rates for the eco-zone Pacific Maritime in British Columbia province, the warmest region in Canada, was used to estimate the amount of biomass that annually turns into DOM. The decay rate of dead organic matter differs with temperature, with the base decay rate being at 10^{o} C (Kurz et al. 2009). The average annual temperature of both Terai and Churia was customized in the Archive Index Database to estimate the decomposition rate in CBM-CFS3.

[10] http://www.datadryad.org/handle/10255/ dryad.235. (Accessed July 20, 2019).

2.2.6 Attributed Disturbances

Three disturbance types (i.e., encroachment, forest fires, and landslides) were identified as the most commonly occurring disturbances in the recent forest resource assessment (FRA). High-resolution global forest cover change maps (Hansen et al. 2013) were used to quantify annual historical forest losses. Annual forest-cover loss data from 2011 to 2017 were first retrieved and then intersected with the administrative units in each study area using ArcGIS (Version 10.6.1). Then, these losses were prorated by disturbance type based on their intensity of occurrence as reported in the FRA (FRA/DFRS 2014a and b), leading to area disturbed by disturbance type in each study region by year (Fig. 2.5). The number of hectares was converted to forest area percentages to run in the CBM-CFS3 from 2011 to 2017. All three disturbance types were higher in the earlier years and were decreasing in Terai. The disturbances were variable over time for Churia. The encroachment rate was higher in Terai than Churia from 2011-2017. The proportional area affected by forest fire was higher from 2011 to 2013 in Terai and in Churia from 2014-2017. Except for 2012, landslide impacts were higher in Churia.

To obtain disturbance levels for the 2018 to 2030 forecasts, the 2011-2017 disturbances were averaged to obtain one value for each disturbance type in each study region. Relative to forest areas, the resulting disturbance percentages were: 0.0637% forest fire, 0.0325% encroachment, and 0.0103% landslide in Terai; and 0.0841% forest fire, 0.0023% encroachment, and 0.0281% landslide in Churia. In the model area targets (hectares per year) for each forest unit were used.

A fourth disturbance, harvest, was also included as harvests are regularly scheduled in these forests. The average annual harvest amounts over the 2010-2017 period were retrieved for Nepal[11]; this varied from 13.2 million m^3 yr^{-1} to 12.6 million m^3 yr^{-1}. Annual harvest amounts were first averaged and then prorated to Terai and Churia based on the proportion of forest area available for harvest in these two regions compared to the country. Forests in protected areas (17% for Terai and 18% for Churia) were excluded since harvesting is not scheduled in these areas. The average annual harvest levels were 1.5% for Terai and 1.7 % for Churia. Consequently, these were the percentages of the eligible area that were harvested by CBM-CFS3 each year.

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[11] http://www.fao.org/faostat/en/. (Accessed December 10, 2019).

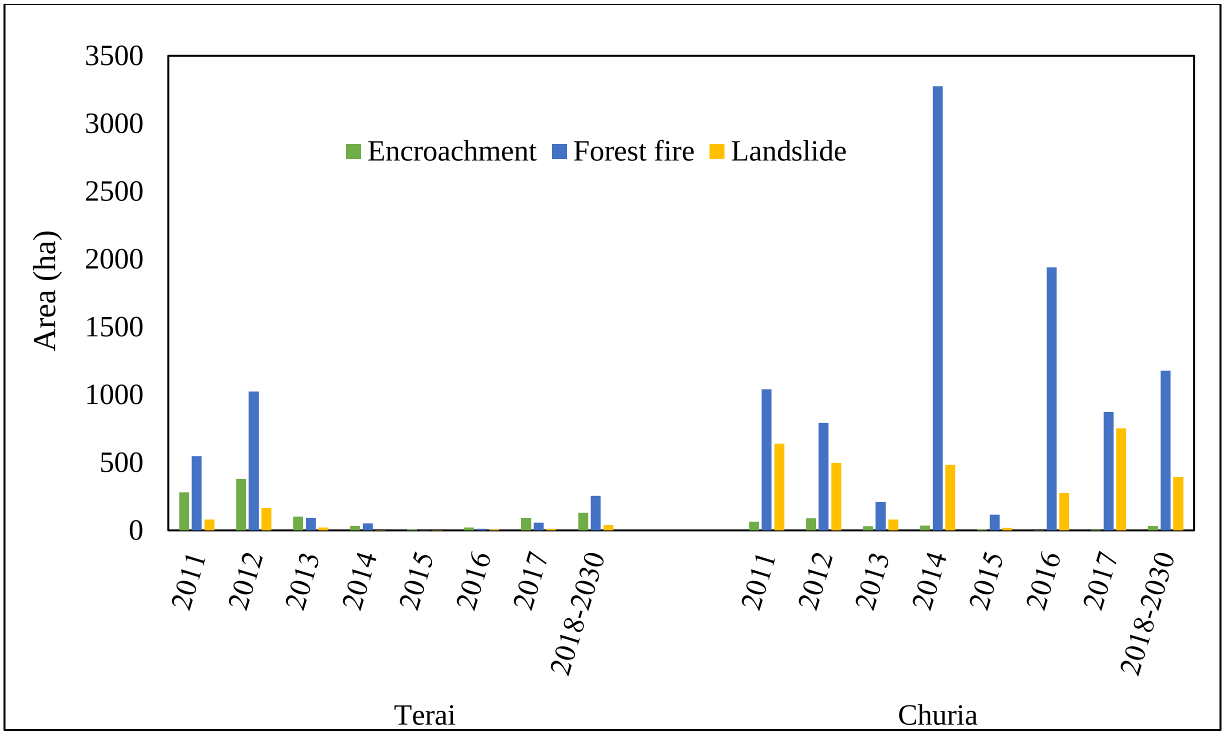


Figure 2.5: Forest cover losses (2011-2030) attributed for Terai and Churia (Data from FRA/DFRS, (2014) and Hansen et al., (2013)).

Disturbance matrices outline the effects on the carbon pools for each disturbance type and specify the amount of carbon transferred from the biomass to the DOM pools or released into the atmosphere following a disturbance (Kurz et al., 2009; Kull et al., 2011). Customization required matching these four major disturbance types for the study areas with those specified for Canada in CBM-CFS3. Specifically, harvesting was mapped to "clear cut without salvage," forest fires to "wildfires," encroachment to "deforestation," and landslides to "deforestation." Encroachment and landslides were considered as permanent losses. While landslides might regenerate over time, the delay is longer than the forecast period in this study. For forest fires and harvesting, a regeneration delay was applied to each forest unit depending on the species and type of regeneration (plantation or natural). Post-harvest regeneration delays varied by species. *Shorea robusta* and *Terminalia alata* regenerate naturally and were assigned a regeneration delay of 2 years (Stainton, 1972 (pp 58-78); Jackson, 1994; Rautiainen et al., 1999). Species that are generally planted, such as *Tectona grandis* and *Syzygium cumini*, were assigned a regeneration delay of 3 years given administrative delays in obtaining adequate stocks and other uncertainties. A longer regeneration delay of 5 years was applied post-fire because the predominant species, *Shorea robusta*, is adversely affected by severe fire (Rautiainen et al., 1999; Malla et al., 2018). Nevertheless, *Shorea robust*a has excellent potential for natural regeneration. It is resistant to forest fires and other external factors through a die-back mechanism (Rautiainen et al., 1997).

2.3 Results

2.3.1 Carbon Stocks and Dynamics in Terai and Churia

The outputs for the business-as-usual runs using CBM-CFS3 indicated that total ecosystem carbon stocks in Terai were projected to increase from 2010 to 2030 by 6.1%, of which 3.0% was in biomass and 3.1% in DOM (constituted of soil, litter, and deadwood) (Table 2.5). In 2010, the highest percentage composition of carbon was in soil (43.0%) followed by aboveground biomass (38.9%). However, the percentage composition for the aboveground biomass increased to 39.5% while it decreased for soil organic carbon to 40.2% by 2030. The percentages for litter and deadwood and belowground biomass increased by 2030. In Churia, the total ecosystem carbon stock was projected to increase by 4.8% from 2010 to 2030, with a 2.0% increase in biomass and a 2.8% increase in DOM (Table 2.6). Unlike Terai, the percentage of carbon in aboveground biomass (41.6%) was highest, followed by soil carbon (38.0%) in 2010. As was the case for Terai, the aboveground biomass percentage increased, while the soil carbon percentage decreased by 2030. The composition by litter increased by almost 2%, while it increased only slightly for deadwood and increased slightly for belowground biomass.

In 2010, the total ecosystem carbon stock density (carbon stocks per ha) was higher for Terai (220.0 Mg ha^{-1}) than Churia (180.5 Mg ha^{-1}), with higher above ground (85.5 Mg ha^{-1} in Terai vs. 75.1 Mg ha^{-1} in Churia) and dead organic matter carbon (116.1 Mg ha^{-1} in Terai, comprised of 94.5 Mg ha^{-1} soil carbon, 3.1 Mg ha^{-1} deadwood carbon and 18.5 Mg ha^{-1} litter carbon versus 88.3 Mg ha^{-1} in Churia, comprised of 68.7 Mg ha^{-1} soil organic carbon, 4.7 Mg ha^{-1} deadwood carbon and 15.0 Mg ha^{-1} litter carbon) (Fig. 2.6). Below ground carbon stock densities were 18.3 Mg ha^{-1} in Terai and 17.1 Mg ha^{-1} in Churia. By 2030, the total ecosystem carbon stock density remained higher for Terai (233.5 Mg ha^{-1}) than for Churia (189.3 Mg ha^{-1}), with higher above ground (92.2 Mg ha^{-1} in Terai versus 79.2 Mg ha^{-1} in Churia) and dead organic matter carbon

Table 2.5: Annual carbon stocks (Tg C) for Terai (0.41 million ha; percentage composition for each pool is in brackets).

		Biomass Carbon		Dead Organic Matter		
Year	Total Ecosystem	Aboveground	Belowground	Soil C	Deadwood	Litter
2010	86.5	33.7	7.08	37.2	1.2	7.3
2011	87.1	33.9	7.08	37.2	1.4	7.5
2012	87.6	34.1	7.06	37.2	1.5	7.7
2013	88.0	34.3	7.07	37.2	1.5	7.9
2014	88.3	34.5	7.08	37.1	1.6	8
2015	88.7	34.8	7.10	37.1	1.6	8.1
2016	89.0	35.0	7.11	37.1	1.6	8.2
2017	89.3	35.1	7.13	37.1	1.7	8.3
2018	89.6	35.3	7.13	37.1	1.7	8.4
2019	89.9	35.4	7.14	37.1	1.7	8.6
2020	90.2	35.6	7.14	37.0	1.8	8.7
2025	91.2	36.0	7.17	37.0	1.9	9.1
2030	91.9	36.3	7.21	36.9	2	9.5

Table 2.6: Annual carbon stocks (Tg C) for Churia (1.4 million ha; percentage composition for each pool is in brackets).

		Biomass Carbon		Dead Organic Matter		
Year	Total Ecosystem	Aboveground	Belowground	Soil C	Deadwood	Litter
2010	229.0	95.3	21.7	87.1	5.9	19.0
2011	230.4	95.6	21.7	87.1	6.4	19.6
2012	231.4	95.9	21.7	87.1	6.7	20.0
2013	232.5	96.3	21.9	87.1	6.9	20.3
2014	233.2	96.3	21.9	87.1	7.4	20.5
2015	234.0	96.7	22.0	87.1	7.6	20.6
2016	234.7	97.0	22.0	87.1	7.9	20.7
2017	235.2	97.2	22.1	87.1	8.1	20.7
2018	235.9	97.5	22.1	87.1	8.4	20.8
2019	236.3	97.7	22.1	87.1	8.6	20.8
2020	236.8	97.9	22.1	87.2	8.8	20.8
2025	239.1	99.1	22.2	87.2	9.8	20.8
2030	240.7	100.4	22.3	87.2	10.0	20.8

(33.0 Mg ha^{-1} in Terai, separated as 3.8 Mg ha^{-1} soil carbon, 5.1 Mg ha^{-1} deadwood carbon and 24.1 Mg ha^{-1} litter carbon versus 93.5 Mg ha^{-1} in Churia, separated as 68.8 Mg ha^{-1} soil carbon, 8.4 Mg ha^{-1} deadwood carbon and 15.5 Mg ha^{-1} litter carbon). Below ground carbon densities increased to 18.4 Mg ha^{-1} in Terai and 16.6 Mg ha^{-1} in Churia by 2030. As expected, Terai had a higher rate of biomass increase due to better soil, temperature, and precipitation conditions. The DOM rate of change was also higher in Terai. This might be due to a higher rate of heterotrophic respiration (decomposition) because of the higher temperatures in Terai (Smyth et al., 2010).

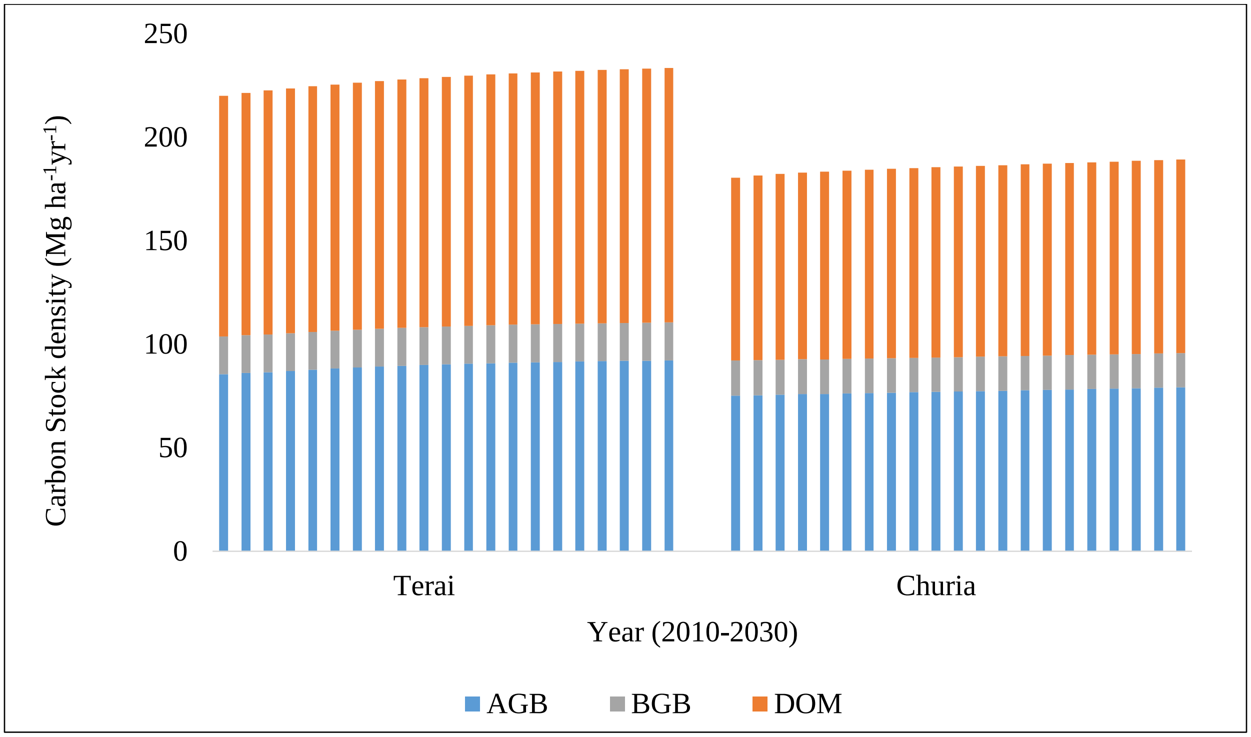
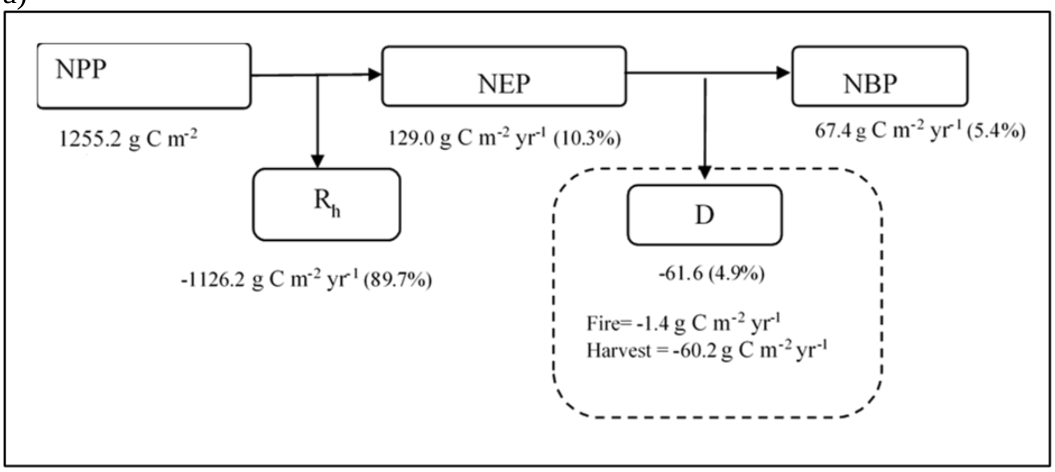


Figure 2.6: Predicted change in carbon stock densities from 2010 to 2030 for Terai and Churia (AGB: aboveground biomass carbon, BGB: belowground biomass carbon, DOM: dead organic matter).

The largest carbon fluxes were associated with net primary productivity (NPP) and heterotrophic respiration (Rh). Gross primary productivity is the amount of biomass produced by photosynthesis of trees in an ecosystem in a given period of time while NPP is the sum of net accumulation of new biomass plus the replacement of annual turnover. Through heterotrophic respiration, carbon is lost by organisms due to the decomposition of dead organic matter. On average, during the 2010-2030 period, a higher percentage of NPP remained in the ecosystem as net ecosystem production (NEP) for Churia than for Terai (Fig. 2.7), indicating that a higher rate of carbon was lost due to Rh in Terai. The estimated net forest ecosystem carbon balance (a.k.a., net biome productivity, NBP) was positive for both the regions, meaning they both remained a carbon sink. The average was higher for Terai. The most substantial disturbance transfers were out of the ecosystem to HWP, followed by forest fires that emitted carbon directly into the atmosphere in both regions. Disturbance transfers from encroachment and landslides were minimal (data not shown) for both the regions.

a)



b)

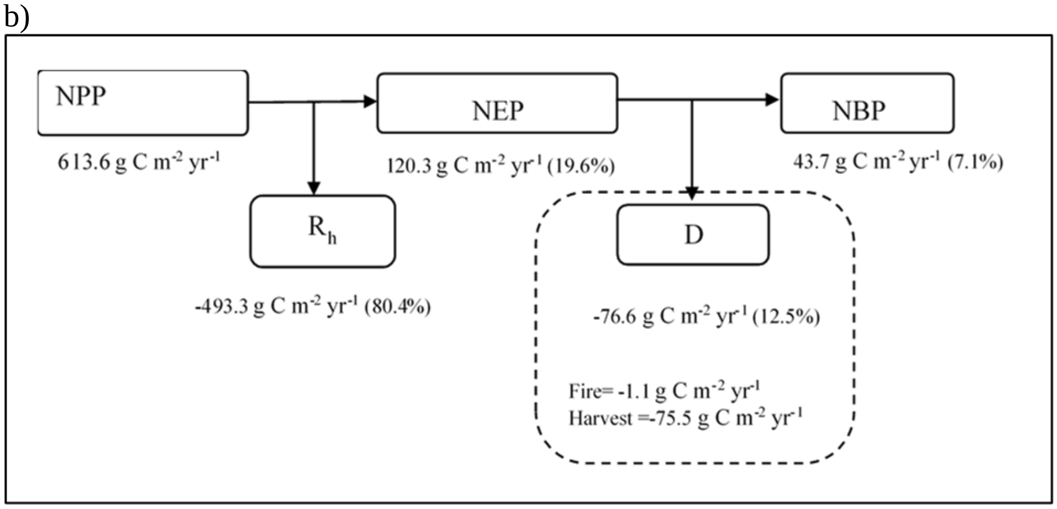


Figure 2.7: Estimated average ecosystem C fluxes (percentages of NPP in brackets) for the period of 2010-2030 for (a) Terai and (b) Churia. (Net primary production (NPP), heterotrophic respiration (Rh), net ecosystem production (NEP), disturbance transfers out of the ecosystem (D), and net biome production (NBP)).

2.3.2 Annual Carbon Stock Changes

The estimated annual net changes in ecosystem carbon stocks are shown in Figure 2.8, with positive numbers indicating a carbon removal from the atmosphere resulting in increased carbon stocks. Although carbon fluxes changed from one year to another, showing shifts in years with high disturbance rates, the forests of Terai and Churia both remained carbon sinks throughout the 20-year forecast period. The inter-annual changes in biomass and dead organic matter carbon were variable until 2017 for both the regions since there were a varying number of disturbances each year.

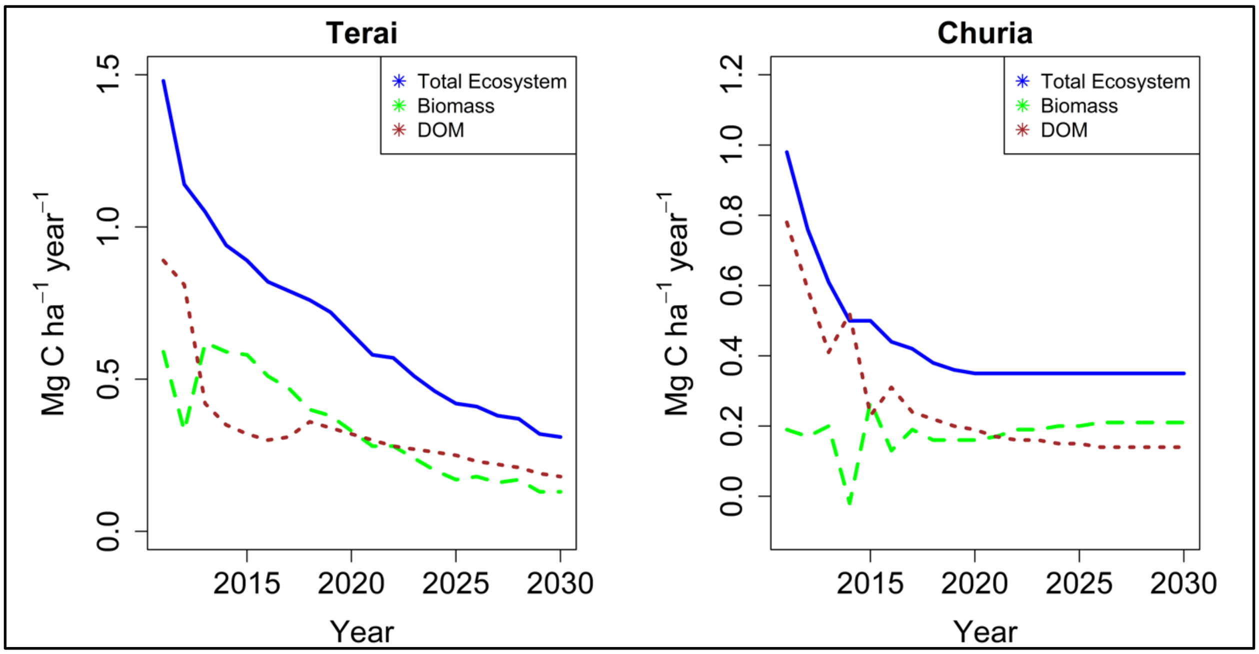


Figure 2.8: Annual carbon stock changes (Total Ecosystem, Biomass, and Dead Organic Matter (DOM)) for Terai and Churia.

In Terai, I found a sink of -3.0 $TgCO_2e\ yr^{-1}$ (negative sign indicates a carbon sink) in 2011 which decreased to -1.4 $TgCO_2e\ yr^{-1}$ by 2030. In Churia, the forest provided a carbon sink of -7.7 $TgCO_2e\ yr^{-1}$ in 2011 which decreased to -5.4 $TgCO_2e\ yr^{-1}$ by 2030 (Table 2.7).

Table 2.7: Net CO_2 removal from the atmosphere (Tg yr^{-1}) for the forests in Terai and Churia.

	Net CO_2e	
Year	Terai	Churia
2011	-3.0	-7.7
2015	-2.1	-5.6
2020	-1.8	-5.2
2025	-1.5	-5.3
2030	-1.4	-5.4

2.3.3 Carbon Stocks by Administrative Unit

The carbon stock densities varied among districts within the regions for 2010 (Fig. 2.9). For Terai, the Illam district had the lowest AGB carbon (49.4 Mg ha^{-1}) and BGB carbon (13.3 Mg ha^{-1}), while the Bara district had the highest AGB carbon (95.2 Mg ha^{-1}) and BGB carbon (198 Mg ha^{-1}). The Siraha district had the lowest DOM carbon (95.7 Mg ha^{-1}) and the highest was found for the Rupandehi district (111.7 Mg ha^{-1}). In Churia, the Palpa district had the lowest AGB carbon (44.6 Mg ha^{-1}) and BGB carbon (12. 5 Mg ha^{-1}), while the Chitwan district had the highest AGB carbon (96.9 Mg ha^{-1}) and BGB of 20.1 Mg ha^{-1} (Fig. 2.10). The Mahottari district had the lowest DOM carbon (68.8 Mg ha^{-1}), and the highest was found for the Salyan district (95.2 Mg ha^{-1}).

2.4 Discussion

The sub-tropical forests of Terai and Churia are variable, with various forest types, stocking densities and site qualities, and local climates contributing to differences in carbon stock densities in these regions. Although the two regions are similar in size, Terai has less forest area, with 0.4 million ha compared to 1.4 million hectares for Churia (FRA/DFRS, 2014a and b). The proportionally lower forest area of Terai is likely due to higher human population densities, with 392 and 173 persons per km^2 for Terai and Churia, respectively (Central Bureau of Statistics, 2011)[12], resulting in more human-caused forest disturbances (e.g., encroachment due to agriculture

[12] http://cbs.gov.np/nada/index.php/catalog/54/download/465. (Accessed July 03, 2021).

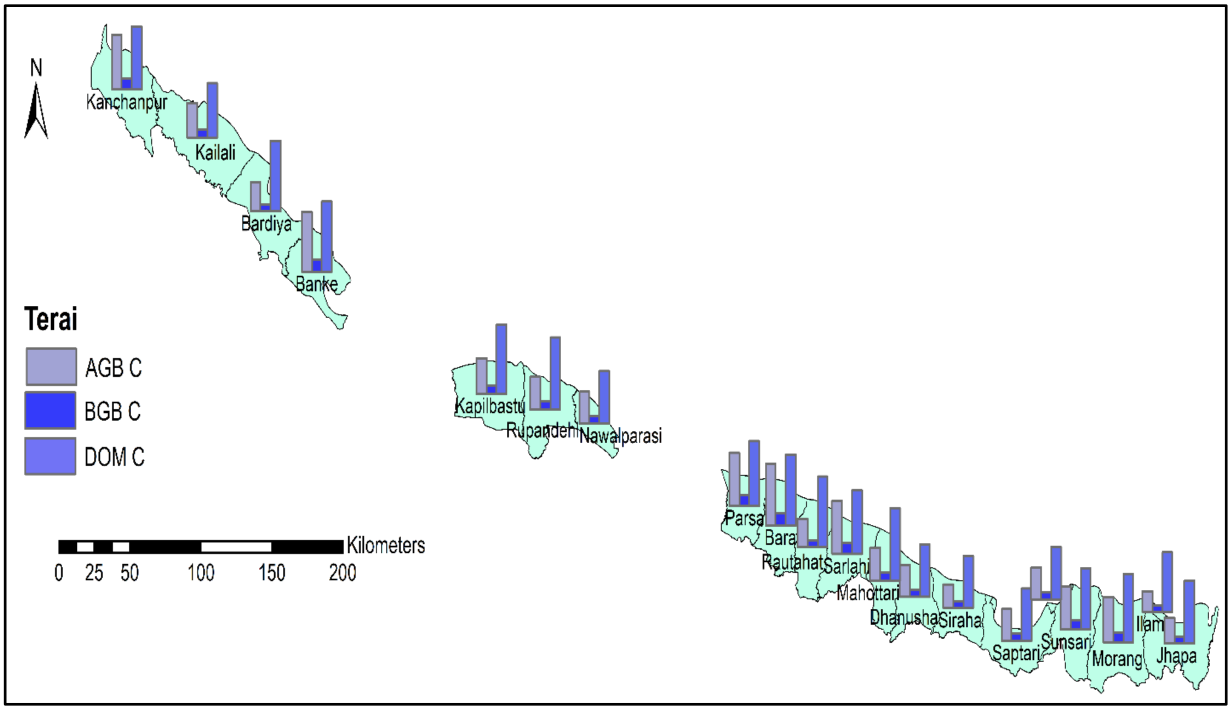


Figure 2.9: Aboveground biomass (AGB), belowground biomass (BGB), and Dead Organic Matter (DOM) carbon (C) stocks by the district for Terai.

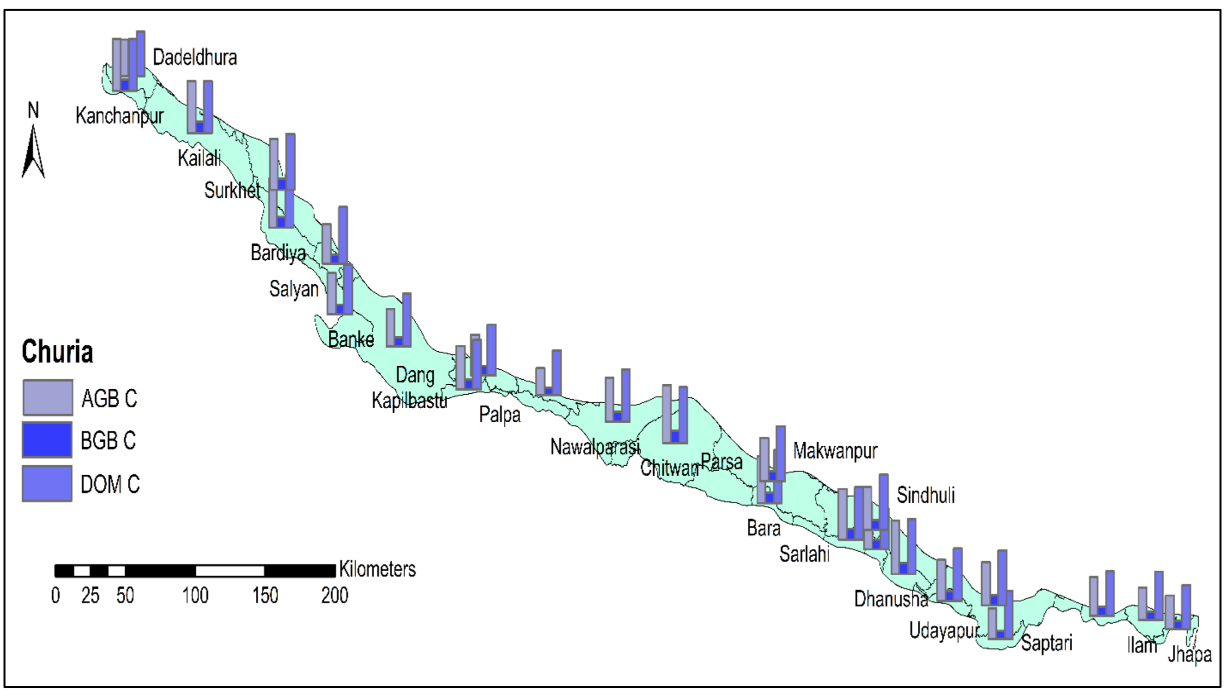


Figure 2.10: Aboveground biomass (AGB), belowground biomass (BGB), and Dead Organic Matter (DOM) carbon (C) stocks by the district for Churia.

and housing). At the same time, the forest fire rate was higher in the beginning years of the simulation in Terai, but in later years, forest fire and landslide rates were higher in Churia (Hansen et al., 2013; FRA/DFRS, 2014a and b). This variability in forest demographics, disturbance patterns, species compositions, and temperature, among other factors, impacts carbon dynamics (Stinson et al., 2011). Carbon stocks and fluxes vary with species compositions and management systems due to differences in natural growth rates (Jackson, 1994; Smith et al., 1997). Although genetics was not explicitly part of this study, variations between and within species also affect growth rates of trees (Bradshaw & Stettler, 1995), and this might have ultimately affected carbon quantities and rate of changes in forests. Overall, the two regions were expected to have different carbon dynamics.

As expected, the Terai carbon stock densities associated with above and below ground biomass (103.8 Mg ha^{-1} in 2010 and 110.6 Mg ha^{-1} in 2030) were higher than those of Churia (92.2 Mg ha^{-1} in 2010 and 95.8 Mg ha^{-1} in 2030; Fig 2.6). Soil organic carbon content of mineral forest soils (to 1 m depth) varies greatly depending on the forest type and climatic conditions (Jobbágy & Jackson, 2000). Soils in Terai are alluvial, with textures that vary from sandy to clay depending on the parent materials (Jackson, 1994). In contrast, the soils in Churia originated from soft rocks, with textures changing from fine-grained sediments, multistoried sandstones, and coarse sediments from lower to higher elevations (Upreti, 1999). Terai has hot and humid summers and dry winters. The minimum annual daily temperature is 14-16° C with a maximum of 35-40° Celsius (Nepal Biodiversity Strategy and Action Plan, 2014). The climate of Churia varies from sub-tropical to warm temperate with hot and sub-humid summers and cold, dry winters. The minimum and maximum daily temperatures range from 12 -19° C and 22-30° C, respectively (Nepal Biodiversity Strategy and Action Plan, 2014). Tree growth rates in the tropics vary spatially and temporally because of the wide variability of available water, nutrients, and light resources (Toledo et al., 2011). Tree growth rates are higher in Terai leading to higher aboveground biomass per ha because of the alluvial soils with more nutrients and greater soil moisture coupled with more sunlight at these lower elevations (Woodruff & Meinzer, 2011). These higher growth rates produce larger trees and, therefore, larger dead and fallen trees as well as higher litter rates. The higher encroachment rate in Terai would also lead to more dead and fallen trees, however encroachment may also result in DOM removal to facilitate agriculture or other activities. Consequently, the

DOM carbon density was also higher in Terai (116.0 Mg ha^{-1} in 2010 and 123.0 Mg ha^{-1} in 2030) than in Churia (88.3 Mg ha^{-1} in 2010 and 93.5 Mg ha^{-1} in 2030).

Using the forest inventory data for 2010, FRA/DRFS (2014 a and b) reported 89 Mg ha^{-1} (Terai) and 85 Mg ha-1 (Churia) of aboveground carbon, with soil organic carbon estimated at 33.6 Mg ha^{-1} (Terai) and 32 Mg ha^{-1} (Churia), and litter and deadwood carbon densities of 0.28 Mg ha^{-1} (Terai) and 0.31 Mg ha^{-1} (Churia). For the Terai Arc landscape covering 12 of the 19 districts of Terai, Gurung et al., (2015) reported carbon stock densities for aboveground biomass as 105.58 Mg ha^{-1}, belowground biomass as 25 Mg ha^{-1}, and soil organic carbon as 97 Mg C ha^{-1}. In that study, they used one-time field measurements and estimated carbon values using allometric models. These reported aboveground carbon values are similar to those for the forecast period of this study. However, the DOM pools (i.e., soil, litter, and deadwood) amounts were higher in this study than those reported in these other studies. DOM estimates using the gain-loss approach of the CBM-CFS3 model are based on turnover rates and do not account for litter and deadwood collection. The other studies may have taken place in areas where litter and deadwood collection are permitted. Litter is used as cattle bedding material and deadwood is used as fuel wood (Adhikari et al., 2007). These practices do not allow litter and deadwood to accumulate and ultimately decompose to soil organic matter (Pandey et al., 2014); removal of woody debris for fuel wood can greatly reduce forest carbon stores (Harmon et al., 2020).

Sharma et al. (2010) reported 128.63 Mg ha^{-1} of aboveground carbon, based on one-time tree measurements, for the moist Bhabar *Shorea robusta* forests of Garhwal Himalaya in India. These estimates are comparable to those reported for *Shorea robusta* forests in Terai (121 Mg C ha^{-1} in biomass; Pandey et al., 2014). However, they are higher than those reported in this study since pure *Shorea robusta* stands have higher biomass than the mixed species stands of Terai and Churia. FAO (2020) reported the carbon densities of 79 Mg ha^{-1} in biomass (AGB+BGB), 3.3 Mg ha^{-1} in deadwood and litter, and 57.8 Mg ha^{-1} in soil for Southeast Asia, including Nepal. These values are less than those reported for Terai and Churia in this study.

The higher percentages of DOM carbon stocks than AGB stocks found for these two regions of Nepal were also found in other studies that used CBM-CFS3 to study forest carbon dynamics under a gain-loss approach. For example, studies in Italy (Pilli et al., 2013) and South

Korea (Kim et al., 2017) reported similar carbon composition percentages in aboveground biomass, belowground biomass, soil, deadwood, and litter pools. Similarly, research on carbon dynamics in Canada's managed forests showed lower carbon in living biomass pools and more in DOM (Stinson et al., 2011).

Stand age, nitrogen deposition, water, and temperature substantially affect NEP (Yu et al., 2014). For both regions in this study, nearly half of the NEP remained as a carbon balance in the ecosystem (as positive NEP). Wood harvested was captured as carbon transference from the forest ecosystem to the harvested wood pool and fire disturbances resulted in carbon emissions to the atmosphere. However, this source was relatively small, and the impact of the other disturbances considered in this study were minimal.

The NEP estimates in this study were lower than those estimated for East Asian monsoon forests using eddy covariance measurements (Yu et al., 2014). Those forests were relatively young, and experienced higher temperatures and more precipitation than the forests in this study. However, the NEP estimates of this study were much larger than those estimated for Canada's boreal forest (Stinson et al., 2011) with older stands and colder climate. My analyses indicated that more than 70% of the forest cover in both Terai and Churia was comprised of stands less than 60 years of age. Most of the stands were *Shorea robusta* dominant; this species has a rotation age of 80 years (MoFSC, 2014). Carbon fixation in the aboveground biomass of *Shorea robusta* forests is higher for new growth than the old growth (Rana *et al.*, 1989). Forest productivity is known to decline with age (e.g., Ryan et al., 1997; Yu et al., 2014). NPP surpasses Rh in young forests resulting in higher NEP; however, it depends on the forest disturbance types and forest can show a net loss in carbon for some time after disturbance (Köhl et al., 2015). In contrast, NPP declines in older forest stands, and Rh increases because of the accumulation of deadwood and soil organic matter from earlier production (Chen et al., 2003).

There were variations in the carbon stocks in the various pools across the different administrative units in Terai. Illam district had the lowest biomass carbon stock density because sparse forests at higher elevations resulted in lower productivity. Conversely, Bara district has dense stands with highly productive species, including *Terminalia* sp. and *Shorea* sp., supported by alluvial soils, higher temperatures, and lower elevations with good sunlight (Stainton, 1972) and consequently higher biomass carbon stock density. The DOM was higher in Rupandehi district, most likely because of a decrease in the forest area resulting from deforestation and urbanization (FRA/DFRS, 2014b). Similarly, there were variations in carbon stocks among administrative units in Churia. Palpa district lies at higher elevations, and species found in this region have lower productivity than those found at lower elevations in Churia. Conversely, most of the forest areas of Chitwan district are protected as conservation areas. This district also lies at a lower elevation, and the soil productivity is higher. The higher DOM in Salyan district could be related to forest loss in the recent past years (1990-2010) (FRA/DFRS, 2014a). Having information at the district level could help in choosing management regimes to conserve stocks and improve carbon sequestration appropriate for the ecosystem and disturbance rates.

Overall, carbon stock estimates for Terai and Churia in this study were similar to those of other studies in similar tropical forests for Nepal and elsewhere. However, other forecasts for Nepalese forests were based on one-time measurements, while the gain-loss approach of the CBM-CFS3 model used in this study simulates carbon dynamics over time. CBM-CFS3 has been shown to provide reliable estimates of carbon stocks and changes for a variety of forests. For example, Shaw et al. (2014) noted that their model estimates of forest ecosystem carbon stocks of Canada were similar to ground plot values. They also showed a percent error of 7.5% for aboveground biomass and 30.8% for deadwood pools, relative to the standards specified in the IPCC-Good Practice Guidance of 8% and 30%, respectively (IPCC, 2006).

This approach simulates different disturbance rates under alternative management strategies and provides the flow of carbon through the system for assessing these alternatives. In this chapter, only a business-as-usual scenario with historic disturbance rates and yields was used. Accurate information on historic forest disturbances was quite challenging to obtain. The forest cover loss retrieved from Hansen's (2013) high-resolution global map was attributed to three of the four disturbance types using assessments conducted during the ground-based phase of the most recent forest inventory. This approach might not accurately depict the actual amount of loss by disturbance type. For harvest rates, yearly harvest volumes were assigned to the study regions based on reported values for Nepal as a whole, determined from each regions' proportion of accessible (i.e., non-protected) forest land. Consequently, the harvest levels may not be accurate and, in any case, only capture the legally harvested and reported volumes. However, the best available information was used for this study in all cases. Regular monitoring and reporting of disturbances to improve disturbance rate estimates are of utmost importance since these disturbance levels highly influence carbon dynamics. Finally, the yield tables used in this study were based on published yield values from geographically similar regions. Nepal's relatively new permanent sample plot program (FRA/DFRS, 2014c) should provide the data needed to model yields for a variety of stand types more accurately.

I recommend measures to reduce landslides in Churia and to reduce encroachment, particularly in Terai, as well as increasing fire suppression funding in both regions. Preventive measures such as afforestation, proper surface water drainage system, retention walls, etc. could be increased to reduce landslides. Fire suppression awareness campaigns and training at the community level could save forests and prevent casualties. Increasing migration into Terai leads to land fragmentation, forest encroachment, and hence has direct impacts on forests. Stronger legislation and enforcement are required to stop forest encroachment. With the increasing population, the demand for timber and wood products is undoubtedly growing. Nepal has not yet extracted the potential benefits from the forestry sector in terms of timber and value-added products, although scientific forest management program (SFMP) was reinstated in 2014. I recommend extensive commercial plantations to meet the growing demand for wood.

2.5 Conclusions

As expected, there were differences in the carbon stocks in Terai and Churia forests. These two regions vary in species composition, elevation, soils, and climate, resulting in higher productivity and decomposition rates in Terai. Further, disturbance rates differed, which directly impacts on carbon dynamics. Specifically, the encroachment rate was higher in Terai with higher human population densities, whereas landslide and forest fire rates were higher in Churia. However, the forests in both regions were carbon sinks and were projected to remain sinks over the next decade using historical averages of disturbances and harvesting amounts. Total ecosystem carbon stocks were expected to increase by 6.1% for Terai and 4.8 % for Churia by 2030 from their values in 2010.

Prior estimates of carbon stocks and sequestration rates for Nepal were primarily based on stock-difference approaches (Tier 2), which principally requires forest inventory data and allometric models. Using the gain-loss (Tier 3) in this study allowed for examining changes over time to forecast future carbon dynamics. This approach provided detailed carbon dynamics at the district level for both regions. With these detailed carbon dynamics, it is possible to forecast alternative management scenarios that ultimately could be important in implementing successful climate change mitigation policies. Management interventions could sustain or enhance the carbon stocks and sequestration rates. I explore the potential impacts of such interventions on the carbon dynamics of Terai in the next Chapter.

Chapter 3: Impacts of Alternative Forest Investments on Forest Carbon Dynamics in Terai

3.1 Introduction

Natural and human-caused forest disturbances play a crucial role in the carbon balance of forest ecosystems, as well as directly or indirectly impacting human livelihoods and natural resources. Although forests sequester atmospheric carbon via photosynthesis, they can become a net source of carbon through the emissions associated with disturbances and thereby contribute to climate change (Lorenz & Lal, 2010). As a result, forest management is increasingly a component of climate mitigation strategies (Nabuurs et al., 2007; Smyth et al., 2014).

Natural climate solutions (NCS) could provide extra climate mitigation beyond business-as-usual scenarios based on a suite of conservation, sustainable management, and restoration of forests, grasslands, and wetlands that could provide extra climate mitigation beyond business-as-usual scenarios (Drever et al., 2021). There are co-benefits of NCS to people and ecosystems beyond mitigation such as habitat improvement, reduction of wildfire risks, augmentation of soil fertility and water-holding capacity and decrease of air and water pollution (Anderson et al., 2019). The full implementation of cost-effective NCS activities could provide up to one-third of the global mitigation potential required to keep global warming below 2°C by 2030 (Griscom et al., 2017). However, NCS are not only means of keeping temperatures below 2°C, reduction of GHGs emissions from fossil fuels and land sector activities are equally important because delaying emissions reduction can drastically accelerate the challenges of meeting the Paris goal (Anderson et al., 2019).

Increasing GHG emissions have contributed to changes in the patterns, frequencies, and intensities of natural disturbance events in forest areas (IPCC, 2014). Excessive rainfall has led to flooding and slope instabilities, whereas higher temperatures coupled with low rainfall have led to more frequent and larger forest fires (Seneviratne et al., 2012). The risks are higher in the tropics where forests and other land areas are more vulnerable to climate change (Baccini et al., 2017). In 2015, about 98 million ha of forests were impacted by natural or human-caused fires, mainly in the tropics (FAO, 2020). At the same time, tropical forests have had higher deforestation and degradation rates (Cosgrove et al., 2017). People living in the tropics are often highly dependent on natural resources for subsistence (Population Action International, 2010) resulting in permanent deforestation via conversion for agriculture, ranching, and infrastructure projects, as well as temporary changes to forest stocks from removals for fuel wood and timber (Carr et al., 2006; Barlow et al., 2018). Further, rapid population growth in developing countries increases these impacts as increasing numbers of people need more land and more forest resources (FAO, 2009). Overall, this growing human population and increased natural resources use further contributes to increased GHG in the atmosphere leading to further climate changes (Geist & Lambin, 2002).

Since natural and human disturbances play a crucial role in the carbon balance of forest ecosystems, estimates of disturbance rates are critical inputs for simulating carbon sequestration or losses from forests under different management scenarios (Harris et al., 2016). Fire alters the distribution of live and dead carbon pools, along with the associated carbon fluxes, through mortality of live trees and burning of dead materials (i.e., coarse woody debris and standing dead trees), and causes direct pyrogenic carbon emission through combustion (Amiro et al., 2001; Campbell et al., 2007; Bormann et al., 2008). These impacts of fire on carbon storage and emissions increase proportionally with severity (i.e., spatial extent and fire intensity), but are followed by carbon removals if forests successfully regenerate naturally or are replanted following fires (Paul et al., 2006). Other natural disturbances may result in a temporary or permanent loss of forests. Anthropogenic disturbances may result in permanent forest losses through conversion to other land uses (e.g., agriculture, urban expansion), resulting in direct releases of carbon to the atmosphere (FAO, 2020). Fuel wood and timber extraction can alter the structural attributes of a forest and reduce the biomass and carbon sequestration potential (Mir et al., 2021). However, carbon storage losses to land conversion and biomass removals can be curtailed or even reversed through management strategies that increase forest area and woody biomass retention (Nabuurs et al., 2007; Pihlainen et al., 2014; Heinonen et al., 2017), increase carbon sequestration rates, or both. Specifically, variations in harvest intensities, rapid regeneration following forest harvest, increased growth rates via improved genetic stocks, reforestation of previously cleared lands, and investments in combating natural disturbances, can substantially increase carbon sequestration rates as well as increase and retain existing carbon stocks.

As a developing country, about 87% of the total energy in Nepal comes from fuel wood, making fuel wood the primary source of carbon emissions (Nepal Second National

Communication, 2014[13]; Baral et al., 2019). High levels of fuel wood extraction have led to deforestation and forest degradation near populated areas. To reduce fuel wood extraction, an organization named the "Alternative Energy Promotion Center" has been developing renewable technologies for reliable and sustainable sources of energy in Nepal. Nepal initiated a REDD+ program in 2007 resulting in subsequent reviews that identified strengths and weaknesses in the major forest-related policies in Nepal. A strategy (called the "Scientific Forest Management Program" (SFMP)) to reduce carbon emissions, enhance forest carbon stocks, and enhance harvested wood products supply was then formulated (MoFSC, 2013; MoFE, 2018). Under SFMP, specific actions planned for 2018-2022 included implementing measures to control drivers of deforestation and forest degradation, strengthening fire control capabilities of local authorities and community groups, rehabilitating degraded land through natural regeneration and planting, and increasing the supply of harvested timber (MoFE, 2018). The SFMP was piloted in one of the collaborative forests of Terai in 2012 and was extended in 2014 to other collaborative forests, community forests, and government-managed forests (Cadman et al., 2016; Poudyal et al., 2020).

Terai's forest has great commercial as well as subsistence value (Webb & Sah, 2003). However, its wellbeing and sustainability has been of concern since the 1950s due to increasing population. In the 10-year period from 2001-2011, the population grew by 1.75 % per year (CBS, 2011); however, the trend has slightly decreased to 1.56% per year in the 10-year period from 2012-2021 (CBS, 2021). People from the hills and mountains of Nepal have migrated to the lower elevations of Terai for job opportunities, health and school facilities, and better agricultural land (FRA/DFRS, 2014b). As a result, Terai contains about half of the total population of Nepal (CBS, 2011). Hence, there is a high pressure on forests and other natural resources (Allen & Barnes, 1985; Goll et al., 2014).

Human activities have resulted in degradation and fragmentation of historically contiguous landscapes, creating threats to both biodiversity and livelihoods (Timilsina et al., 2007). The annual rate of decrease in forest cover in the Terai region was 0.44% from 2001–2010 (FRA/DFRS, 2014b). Causes of deforestation and forest degradation are expansion of agriculture

[13] https://unfccc.int/resource/docs/natc/nplnc2.pdf. (Accessed January 05, 2019).

land, illegal timber harvesting, livestock grazing, forest fires, fuel wood extraction, development, and conflicting government policies (Chaudhary et al., 2016).

Forest conservation efforts and clearing forests for agriculture and settlements have been in continuous struggle (Shrestha & Conway, 1996). The demand for land has been high because it is flat and fertile and easily accessible. As well as legal settlements, there are illegal encroachments where people clear forests and practice subsistence agriculture to survive, exacerbating the conflicts between conservation efforts and agricultural expansion (Bhusal et al., 2019).

Encroachment is an ongoing problem in Terai and the government's approach towards solving this issue has been ineffective (Bhusal et al., 2019). The principal reasons for this failure are lack of livelihood options, the high cost of legislation, the weakness of forest authorities, and political lobbying (Regmi et al., 2015). Although fuel wood demand will likely be reduced to some extent with the introduction of more efficient cook stoves, given the increasing population in Terai, the need for fuel wood and timber is projected to increase for the 2020 and 2030 period by Kanel et al. (2012). Fire is also one of the critical causes of forest cover reductions in Terai. Forest fires occur in Terai due to deliberate burning by cattle ranchers to promote grazing opportunities, by poachers of valuable timber, by hunters, collectors of valuable non-timber forest products such as medicinal plants, as well as by accidental events (Kunwar, 2006; Matin et al., 2017).

In Chapter 2, I determined that Terai's forests remained a sink for the forecast period under historic disturbances and harvest rates. However, how might this change under future population pressures and expected climate changes? Also, could increase in investments mitigate or even reverse impacts of population pressures and climate changes? To investigate this, I assessed how alternative forest management strategies might alter the carbon dynamics of Terai's forests. I used the CBM-CFS3 model calibrated for Nepal, the historic human and natural disturbance rates, and the growth and yield tables from Chapter 2. However, I also created a spatially explicit wall-to-wall map of imputed forest attributes for Terai. For all scenarios, I used the reported human and natural disturbance rates for 2010 to 2017. Then, the averages of the human and natural disturbance rates were used to project forward to 2030 under a "business-as-usual" scenario. For other scenarios, I altered the disturbance rates and regeneration delays for the 2018-2030 forecasts to provide insights into the relative effectiveness of various interventions, investments, and strategies on carbon storage and emissions. In this analysis, I addressed the following questions:

1. What are the impacts on carbon stocks and dynamics resulting from altering the level of each forest disturbance type, specifically, increasing or decreasing harvesting, forest encroachment, landslides, and forest fires relative to the historic (2010 to 2017) baseline?
2. What are the impacts on carbon stocks and dynamics resulting from increased population pressure causing increased harvesting and encroachment, along with increased forest fires relative to the historic baseline (worst-case scenario)?
3. What are the impacts on carbon stocks and dynamics resulting from investments to reduce regeneration delay, suppress fire, institute landslide preventive measures, implement policies to minimizing encroachment relative to the historic baseline and decrease the harvest rate because of fuel wood substitution (best case scenario)?

I expected that the best-case scenario would conserve the highest amount of carbon in the forest ecosystem and followed by the less harvest scenario, while the worst-case scenario would turn the forest from a carbon sink to a source of carbon.

3.2 Methods

3.2.1 Forest Inventory Data

The ground cluster data, Landsat, and map information described in detail in Chapter 2 were used in a multivariate imputation approach to provide a spatially explicit, wall-to-wall map of attributes for input to CBM-CFS3 to forecast the alternative forest management scenarios. For this, all map layers were projected using WGS 84 / UTM zone 45N to match the Landsat mosaic and then rasterized into 9 ha (i.e., 300 m X 300 m) tiles to spatially match the ground cluster data (i.e., clusters spaced 300m X 300 m) using Arc GIS v. 10.7.1 (ESRI, 2020). Then, only tiles with 50% or more area with forest were retained, leaving 0.4 million ha. Attributes derived from Landsat data and map information were used as potential x-variables to impute the ground-measured forest attributes as the y-variables (Table 3.1; see Chapter 2 for details on ground sampling, Landsat, and map data sources, data preparation, and attributes).

Table 3.1: Landsat, map, and forest inventory variables.

Variables	Description	Source
Land use map for Terai	Forest cover, shrubland, other wooded and non-forest	FRA/DFRS (2014b)
Forest cover	>=50% forest	FRA/DFRS (2014b)
Landsat Bands	B1, Blue, (0.45 - 0.52 μm) B2, Green, (0.52 - 0.60 μm) B3, Red, (0.63 - 0.69 μm) B4, NIR, (0.76 - 0.90 μm) B5, SWIR, (1.55 - 1.75 μm)	https://espa.cr.usgs.gov/ (Accessed on January 10, 2019)
UTM map projection	(WGS 84 / UTM zone 45N)	https://epsg.io/32645 (Accessed on January 22, 2019) _
Vegetation Index	Normalized Difference Vegetation Index (Tucker, 1979) NDVI = (NIR - Red) / (NIR + Red)	
Soil classes	FAO/IIASA/ISRIC/ISSCAS/ JRC, 2012.	https://worldmap.harvard.edu/data/geonode:DSMW_RdY (Accessed on January 12, 2019)
Topographic Metrics	Elevation above sea level (m) Slope (degrees) Aspect (degrees) transformed to cosine of aspect	https://search.earthdata.nasa.gov (Accessed on January 17, 2019)
	Distance to roads (m) Distance to water bodies (m) Distance to towns/villages (km)	https://mapcruzin.com/free-nepal-country-city-place-gis-shapefiles.htm (Accessed on January 14, 2019)
	UTM coordinates: Northing and Easting (m)	https://epsg.io/32645
Ground Cluster Variables (for tiles with ground samples only)	Volume (m^3/ha) Age (years) Stand density class (High, Medium, Low) Site quality class (High, Medium, Low) Percentage composition of primary tree species.	FRA/DFRS (2014b)

Variables that were available for a smaller spatial extent (e.g., band values and the normalized difference vegetation index (NDVI)) were averaged for each tile. A subset of these tiles also had ground cluster attributes from the forest inventory data. One of the 55 ground clusters in Terai fell outside of the forest area, leaving ground attributes information on 54 of these tiles for the imputation.

3.2.2 Wall-to-Wall Forest Maps

Imputation was used to create wall-to-wall maps of estimated forest attributes using each 9-ha tile, following approaches documented elsewhere (e.g., LeMay et al, 2007; Tomppo et al., 2008; Nilsson et al. 2017 Lochhead, et al., 2018). This approach enabled spatial displays of simulated management outcomes. The choice of imputation method varies among studies, with some choosing to use univariate imputation, and others using multivariate imputation where a vector or matrix of forest attributes was simultaneously estimated (Eskelson et al. 2009). In this study, all forest attributes were imputed simultaneously using the yaImpute R package 3.6.2 (Crookston et al., 2020). The "RandomForest" method was selected within this package since it allows for a mixture of continuous and categorical forest variables.

To assess the accuracy, differences between measured and imputed y-variables for the 54 ground clusters were summarized into root mean squared errors (RMSE, Eq. 1, Crookston et al., 2020) by forest attribute:

$$RMSE = \sqrt{\sum_{i=0}^{n} \frac{(y_i - \hat{y}_i)^2}{n}} \quad (1)$$

where n is the number of plots, y_i is the measured ground variable $\hat{y}_i$ is the predicted variable. The RMSE were then used to compare alternative choices of x-variables, along with graphs showing meaured versus imputed y-variables. From this, x-variables such as forest cover maps, landsat bands (B1, B2, B3, B4, and B5), NDVI, soil classes, elevation, and aspect were used to impute y-variables such as volume (m^3/ha), stand age (years), stand density class (High, Medium, Low), site quality class (High, Medium, Low), and percent composition of the primary species. The RMSE values for each of the imputed variables were: volume: 119.4 m^3ha^{-1}; age: 26 years; percent composition for *Shorea robusta*: 33.0%; percent composition of *Terminalia alata*: 19.0%; percent composition of *Dalbergia sissoo*: 15.4%; percent composition of *Syzyium cumini*: 4.8%; and percent composition of *Acacia catechu*: 2.2% and percent composition of other species: 34.9%. Fig. 3.1 shows the relationship between the measured ground y variables and the imputed y variables.

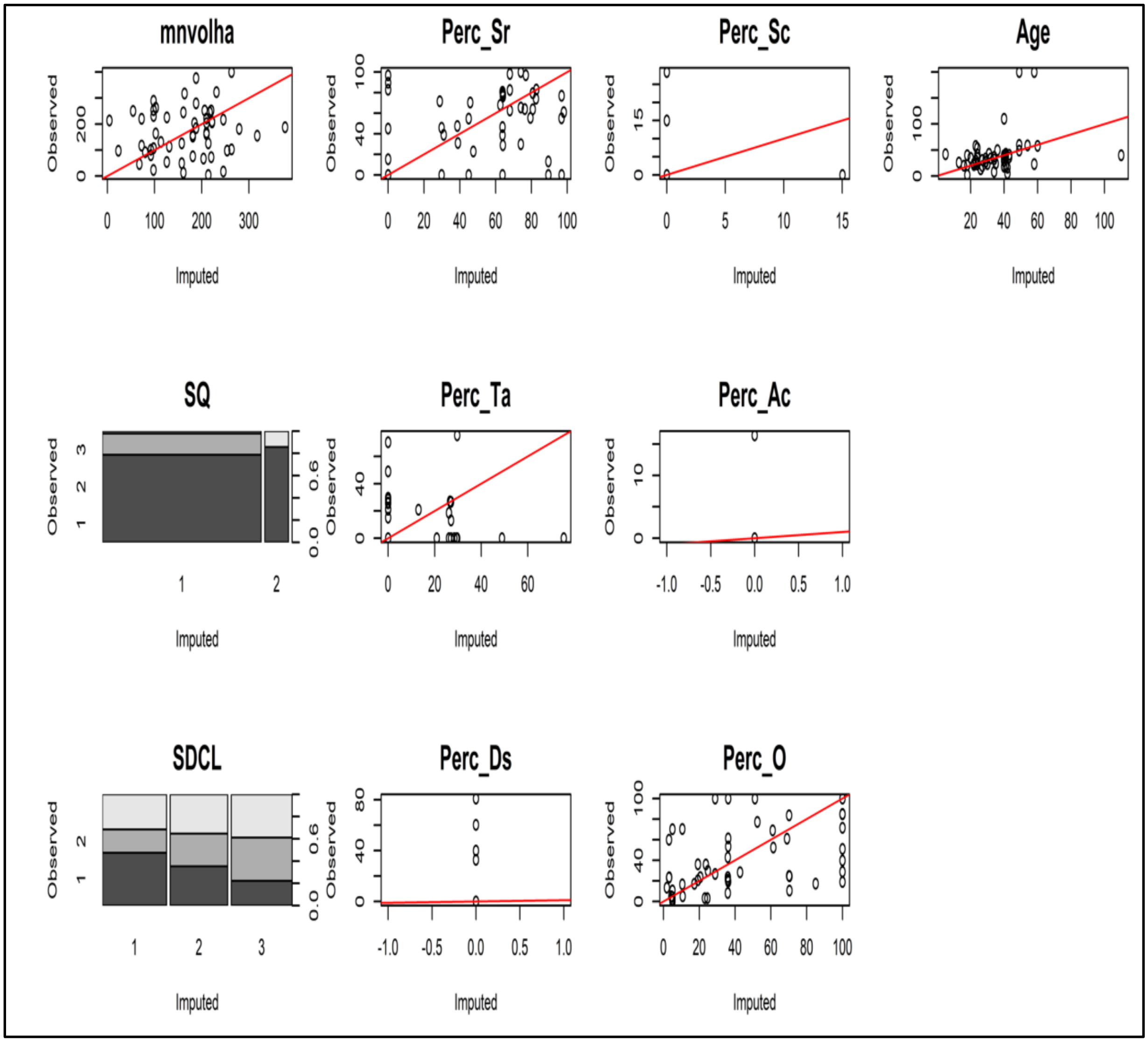


Figure 3.1: Measured versus imputed volume (m^3 ha^{-1}), species composition, age (years), and site quality class, and stand density class for the 54 plot clusters. (mnvolha: ground cluster volume m^3 ha^{-1}; Perc_Sr: Percentage composition of *Shorea robusta*; Perc_Sc: Percentage composition of *Sygium cumini*; Age in years; SQ: Site quality classes (1=high site class, 2=medium site class); Perc_Ta: Percentage composition of *Terminalia alata*, Perc_Ac: Percentage composition of *Acacia catechu*, Perc_Ds: Percentage composition of *Dalbergia sissoo*, Perc_O: Percentage composition of other species; SDCL: Site Density classes (1=high density class, 2=medium density class, 3=low density class).

To ensure logical consistency between the the design-based estimated average volume per ha for Terai (Chapter 2) and the model-based estimate in this chapter, a ratio adjustment of 0.93 was applied to each tile to obtain the volume per ha values used in the forest management scenarios simulations. The imputed volumes ranged from 3.9 m^3/ha to 370.6 m^3/ha with the majority of the tiles having volumes between 140.9 m^3/ha and 171.1 m^3/ha. The average imputed volume was 169.3 m^3/ha. The higher volume areas tended to be found in the north of Terai (Fig. 3.2).

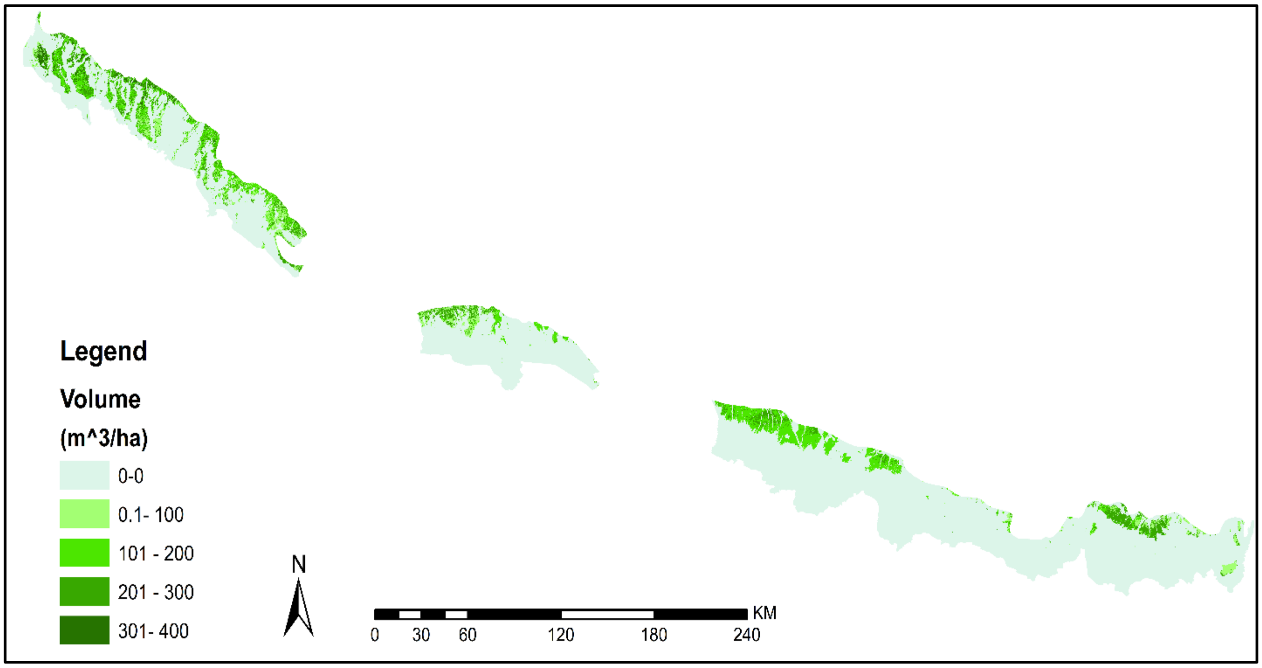


Figure 3.2: Map of imputed volume (m^3 ha^{-1}) values for each 9 ha tile. NOTE: non-forest areas appear as 0.0 m^3 ha^{-1}.

3.2.3 Forecasting Alternative Forest Management Scenarios

The imputed forest attributes volume (m^3 ha^{-1}), site class (High, Medium or Low), stand density class (High, Medium or Low), primary species composition (%’s), and age (years) were used to select a yield curve for each 9-ha tile (see Chapter 2 for details on yield curves). Then, alternative forest management scenarios (Table 3.2) were simulated using CBM-CFS3. The baseline scenario used the same growth and yield models, disturbance rates, and other inputs as the business-as-usual scenario for Terai from Chapter 2, except that the spatially explicit 9-ha tiles were used as the forest units. These same business-as-usual inputs were used for the 2010 to 2017 period, and then altered for the 2018 to 2030 period for other scenarios. Scenario 1 simulated increased reforestation investments to reduce regeneration delay. Scenario 2 simulated a decrease in the harvest rate assuming a switch from fuel wood to alternative energy sources. Increasing harvest rates reflecting an increased demand for wood products under population increases were simulated in Scenario 3. Scenario 4 assumed decreased disturbance from fire frequency due to increased fire suppression which contrasted with Scenario 5 that assumed increased fire disturbance due to adverse climate change impacts. Scenario 6 simulated reduced landslides due to increased investments in physical barriers while high single-event rainfall due to climate change may increase landslides and this was the focus of Scenario 7. As noted previously, forest encroachment had been high in Terai over the last decade. The decreased encroachment rates, possibly related to increased penalties and stronger enforcement were simulated as Scenario 8. A further increase in encroachment was simulated as Scenario 9. Finally, three more complex scenarios were simulated. I applied a best-case scenario that included decrease in regeneration delay, fire disturbance, landslide, and encroachment (Scenario 10) and a best-case plus scenario (Scenario 11) that also included a decrease in harvesting rate due to fuel wood substitution. Lastly, a worst-case scenario (Scenario 12) was simulated that included increases in harvesting, encroachment, fire disturbance, and landslides.

3.3 Results

3.3.1 Carbon Stocks Under Alternative Forest Management Scenarios

Carbon stocks were projected from 2010 to 2030 for the business-as-usual baseline as in Chapter 2 but using the spatially explicit 9-ha tiles. For other scenarios, changes were implemented for the 2018 to 2030 period. The total carbon stocks increased for all scenarios except for the worst-case and the more harvest scenarios (Fig.3.3). Below the baseline are the worst-case and more harvest scenarios which included doubled disturbances and higher harvest rates. They also show a decreasing carbon stock. Above the base line are the best case plus and less harvest scenarios which included halved disturbances and lower harvest rates. They conserved more carbon with an increase over time. The other scenarios which included doubled or halved disturbances rate did not show much variation in carbon stock from the baseline (Fig. 3.3).

Table 3.2: Alternative Forest management scenarios involving varying assumptions on investment, wood utilization, and natural disturbances (Regen. delay: regeneration delay; Encroach: encroachment).

Scenarios	Harvest	Regen. delay	Fire	Landslide	Encroach.	Description
0 Baseline	**1.5%**	**3-5 years**	**0.064%**	**0.010%**	**0.033%**	Historic disturbance rates
1 Shorter regen delay	Baseline	**(1-2) years**	Baseline	Baseline	Baseline	Regeneration delays decrease under increased reforestation investments.
2 Less harvest	**0.75%**	Baseline	Baseline	Baseline	Baseline	Decreased harvest by half from baseline under fuel substitution from wood to other fuels.
3 More harvest	**2.25%**	Baseline	Baseline	Baseline	Baseline	Increased harvest by half the amount of baseline under a population increase and increased fuel and timber products use.
4 Less fire	Baseline	Baseline	**Halved**	Baseline	Baseline	Decreased fire rates under increased suppression investments.
5 More fire	Baseline	Baseline	**Doubled**	Baseline	Baseline	Increased fire rates under climate changes causing increasing temperatures.
6 Less landslide	Baseline	Baseline	Baseline	**Halved**	Baseline	Decreased landslides under investments in physical barriers.
7 More landslide	Baseline	Baseline	Baseline	**Doubled**	Baseline	Increased landslide rates under climate changes with high single-event rainfall.
8 Less encroachment	Baseline	Baseline	Baseline	Baseline	**Halved**	Decreased encroachment rates under increased penalties for encroachment.
9 More encroachment	Baseline	Baseline	Baseline	Baseline	**Doubled**	Increased encroachment rates under increasing population pressure.
10 Best case	Baseline	**Halved**	**Halved**	**Halved**	**Halved**	Heavy investment in carbon stocks conservation
11 Best case plus	**0.75%**	**Halved**	**Halved**	**Halved**	**Halved**	Heavy investment in carbon stocks conservation and fuel substitution.
12 Worst case	**2.25%**	Baseline	**Doubled**	**Doubled**	**Doubled**	Baseline investment under population pressures and climate changes

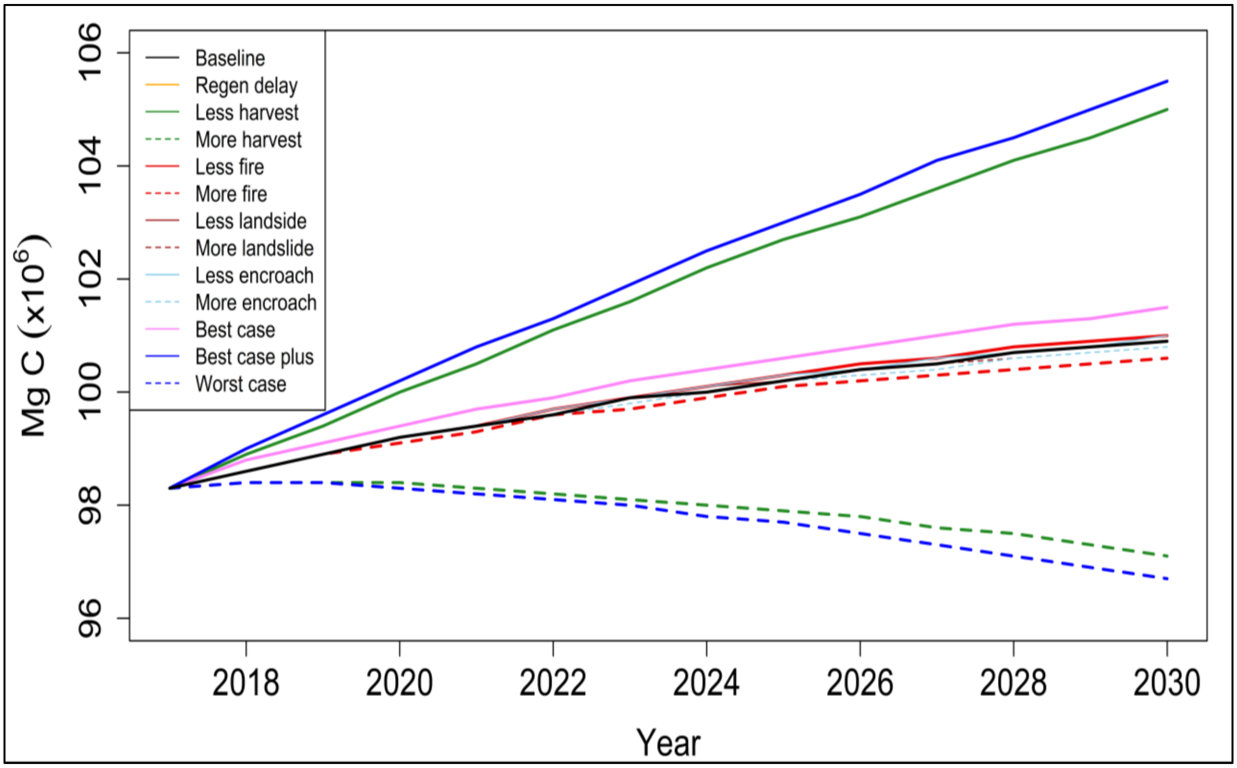


Figure 3.3: Total carbon stocks for different scenarios (encroach: encroachment, regen: regeneration).

The biomass carbon in 2030 for the best-case plus, less harvest, best-case, less encroachment, less fire, and less landslide scenarios were higher than for the baseline scenario (Table 3.3); while the DOM carbon was less for these scenarios relative to the baseline. The largest increase in biomass carbon was for the best-case plus scenario, while it showed the smallest increase in DOM carbon. The largest decrease in biomass carbon occurred for the worst-case scenario. The total carbon stocks decreased for the more harvest and for the worst-case scenarios, but the DOM carbon increased for these two scenarios.

Table 3.3: The percentage increase (+ve) or decrease (-ve) of biomass carbon (aboveground + belowground) and dead organic matter carbon (DOM: Soil + Litter + Deadwood) in 2030 relative to 2018.

Scenarios (Number in brackets)	**Biomass**	**DOM**
(11) Best-case plus	12.3%	2.7%
(2) Less harvest	11.1%	2.8%
(10) Best-case	3.4%	2.8%
(8) Less encroachment	2.5%	2.9%
(4) Less fire	2.7%	2.8%
(0) Baseline	**2.3%**	**2.9%**
(1) Shorter regeneration delay	2.3%	2.9%
(6) Less landslide	2.4%	2.9%
(7) More landslide	2.2%	2.9%
(9) More encroachment	1.9%	3.0%
(5) More fire	1.5%	3.1%
(3) More harvest	-5.8%	2.9%
(12) Worst-case	-6.9%	3.2%

The best-case plus scenario yielded the highest positive difference in total ecosystem carbon stocks compared to the baseline scenario, followed by the less harvest and less fire scenarios (Fig. 3.4). The worst-case scenario resulted in the largest negative difference followed closely by the more harvest scenario. The more fire scenario also resulted in less total ecosystem carbon being stored than the baseline scenario. Decreasing the regeneration delay did not produce much difference from the baseline scenario, since the historic regeneration delays was assumed to be relatively short. The total carbon stocks given more landslides, less landslides, less fire, more encroachment, and less encroachment varied only slightly from the baseline scenario.

The patterns of higher and lower biomass carbon stocks differences from the baseline scenario were similar to the patterns for total ecosystem carbon differences (Fig. 3.4). The best-case plus scenario conserved the most biomass carbon, while worst-case scenario followed closely by the more harvest scenario conserved the least.

The highest positive difference in dead organic carbon (DOM) compared to the baseline scenario was found for the worst-case scenario followed by the more harvest scenario. It both cases, the differences rose until 2022, but then started to decrease. The more fire scenario had more carbon in DOM than the baseline scenario and this difference continued to increase with time. The best case plus and the less harvest scenarios had lowest DOM carbon compared to the baseline scenario initially, but they almost approached the baseline scenario by the end of the simulation period. The DOM carbon from the best-case scenario was slightly below that of the baseline scenario throughout the simulation period, with the difference initially increasing and later decreasing with time. Finally, the less fire scenario also had slightly less DOM carbon than the baseline scenario, with the difference increasing slowly through time. The DOM carbon dynamics for other scenarios were quite similar to that of the baseline scenario.

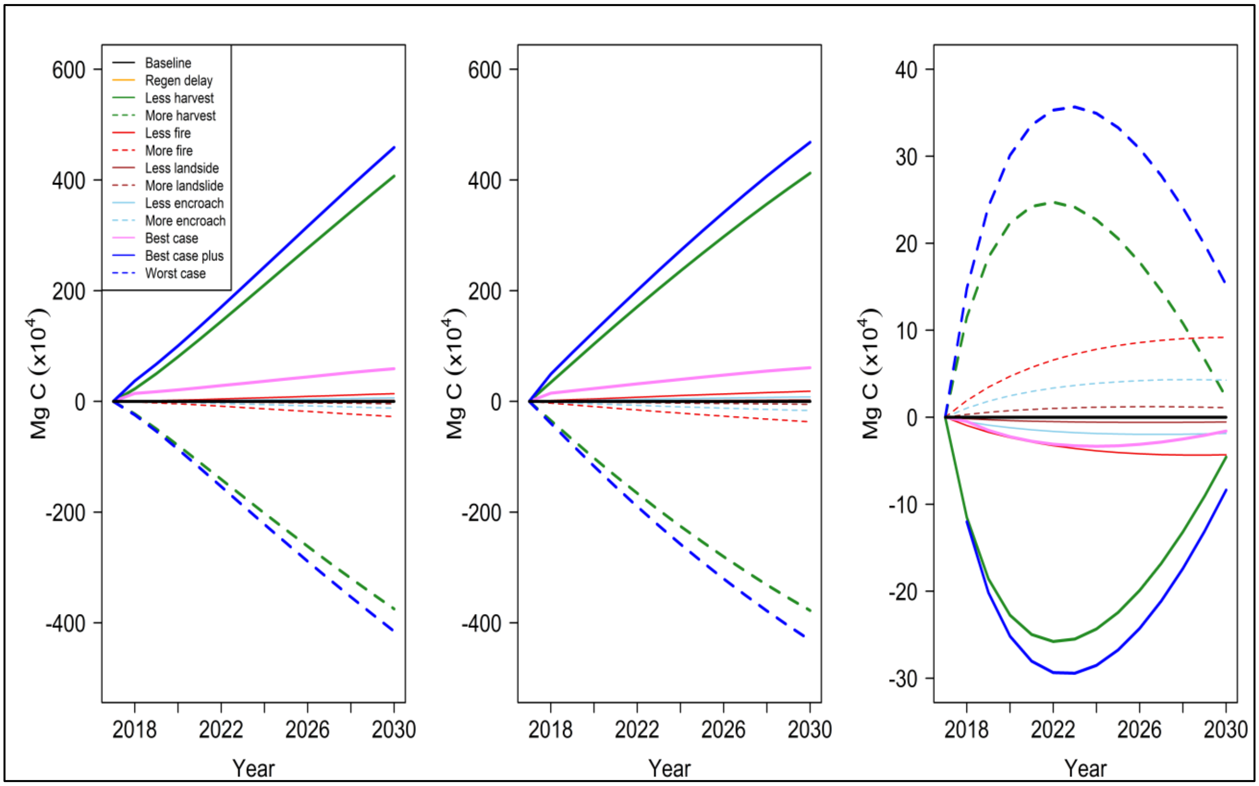


Figure 3.4: The carbon stock differences between baseline and alternative scenarios for total ecosystem carbon stocks, biomass carbon stocks, and dead organic carbon stocks from left to right. Positive numbers denote higher carbon stocks than the baseline and the negative number denoted lower carbon stocks than the baseline).

The worst-case had the lowest carbon stocks in total biomass carbon (both above and below ground), while the percentages of carbon in the soil, litter and deadwood carbon pools were the highest (Table 3.4). The next lowest percentages occurred for the more harvest scenario followed by the more fire scenario. The highest percentage of total biomass carbon was found for the best-case plus scenario. This was followed by the less harvest, which had second highest percentage biomass carbon and lowest percentage soil and deadwood carbon. The more fire scenario had a similar percentage of deadwood carbon as the more harvesting and the more encroachment scenarios. The other scenarios differed only slightly in the percentage composition of the different carbon pools.

Table 3.4: The carbon stocks (Tg) for the various scenarios for 2017 and 2030 (Total: Total ecosystem carbon; AGB: aboveground biomass; BGB: belowground biomass; Regen.: regeneration; encroach.: encroachment).

Scenarios	Year	Total	Biomass		DOM		
			AGB	BGB	Soil	Litter	Deadwood
	2017	98.3	39.0 (39.6%)	7.8 (8.0%)	40.5 (41.2%)	9.2 (9.4%)	1.8 (1.8%)
0 Baseline	2030	100.9	40.0 (39.7%)	7.8 (7.8%)	40.3 (39.9%)	10.5 (10.4%)	2.2 (2.2%)
1 Shorter Regen. delay	2030	100.9	40.0 (39.7%)	7.8 (7.8%)	40.3 (39.9%)	10.5 (10.4%)	2.2 (2.2%)
2 Less harvest	2030	105.0	43.6 (41.5%)	8.4 (8.0%)	40.3 (38.4%)	10.5 (10.0%)	2.2 (2.1%)
3 More harvest	2030	97.1	36.8 (37.9%)	7.3 (7.5%)	40.3 (41.5%)	10.5 (10.8%)	2.3 (2.3%)
4 Less fire	2030	100.9	40.1 (39.7%)	7.8 (7.8%)	40.4 (40.0%)	10.5 (10.4%)	2.2 (2.2%)
5 More fire	2030	100.8	39.9 (39.6%)	7.8 (7.8%)	40.3 (40.0%)	10.5 (10.4%)	2.3 (2.2%)
6 Less landslide	2030	101.0	40.2 (39.8%)	7.9 (7.8%)	40.3 (39.9%)	10.5 (10.4%)	2.2 (2.1%)
7 More landslide	2030	100.6	39.7 (39.5%)	7.8 (7.7%)	40.3 (40.0%)	10.5 (10.4%)	2.3 (2.3%)
8 Less encroach.	2030	100.9	40.1 (39.7%)	7.8 (7.8%)	40.3 (39.9%)	10.5 (10.4%)	2.2 (2.2%)
9 More encroach.	2030	100.8	40.0 (39.7%)	7.8 (7.8%)	40.3 (39.9%)	10.5 (10.4%)	2.2 (2.2%)
10 Best case	2030	101.5	40.5 (39.9%)	7.9 (7.8%)	40.3 (39.7%)	10.5 (10.4%)	2.1 (2.1%)
11 Best case plus	2030	105.5	44.0 (41.7%)	8.5 (8.1%)	40.3 (38.2%)	10.5 (10.0%)	2.1 (2.0%)
12 Worst case	2030	96.7	36.3 (37.6%)	7.2 (7.5%)	40.3 (41.6%)	10.4 (10.8%)	2.4 (2.5%)

The net primary productivity (NPP) varied for different scenarios. Relative to the baseline scenarios such as best case plus, less harvest, best care and less fire had higher NPP,. while scenarios such as more encroachment, more fire, more harvest, and worst case had lower NPP (Table 3.5). Only 8.8% of the NPP, (averaged over the 2018-2030 period), remained in the ecosystem as net ecosystem productivity (NEP) for the baseline scenario. The best-case plus scenario had the highest NEP (12.1% of NPP) and the less harvest scenario had the second highest (11.7% of NPP). The worst-case scenario had the lowest NEP, followed by the more harvest scenario. For the baseline scenario, only 3.9% of the NPP remained in the ecosystem as NBP. The best-case plus retained the highest NBP (9.7% of NPP), closely followed by the less harvest scenario. The worst-case scenario and the more harvest scenario yielded negative NBP values (-2.0% and -1.4% respectively).

Table 3.5: Net primary productivity (NPP) and the percentages of net primary productivity (NPP) as net ecosystem productivity (NEP) and net biome productivity (NBP) for the various scenarios.

Scenarios (Number in brackets)	NPP (Tg)	NEP (% of NPP)	NBP (% of NPP)
(11) Best-case plus	5.24	12.1%	9.7%
(2) Less harvest	5.20	11.7%	9.2%
(10) Best-case	5.05	9.4%	4.5%
(8) Less encroachment	5.01	8.9%	4.0%
(4) Less fire	5.02	8.9%	4.1%
(0) Baseline	**5.01**	**8.8%**	**3.9%**
(1) Shorter regeneration delay	5.01	8.8%	3.9%
(7) More landslide	5.00	8.8%	3.8%
(6) Less landslide	5.01	8.8%	3.9%
(9) More encroachment	5.00	8.7%	3.7%
(5) More fire	4.99	8.6%	3.5%
(3) More harvest	4.82	5.9%	-1.4%
(12) Worst-case	4.80	5.4%	-2.0%

The estimated cumulative net forest ecosystem carbon balance during the 2018-2030 period for the baseline scenario was 2.7 Tg C (an average net sink of 0.2 Tg C yr^{-1}), while the best-case plus scenario had the highest cumulative net carbon balance of 7.1Tg C (an average net sink of 0.6 Tg C yr^{-1}) (Fig. 3.5). The worst-case scenario produced a cumulative carbon source of -1.4 Tg C (an average net source of -0.1 Tg C yr^{-1}) and the more harvest scenario also produced cumulative carbon source of -1.0 Tg C (an average net source of -0.07 Tg C yr^{-1}) (Fig 3.5).

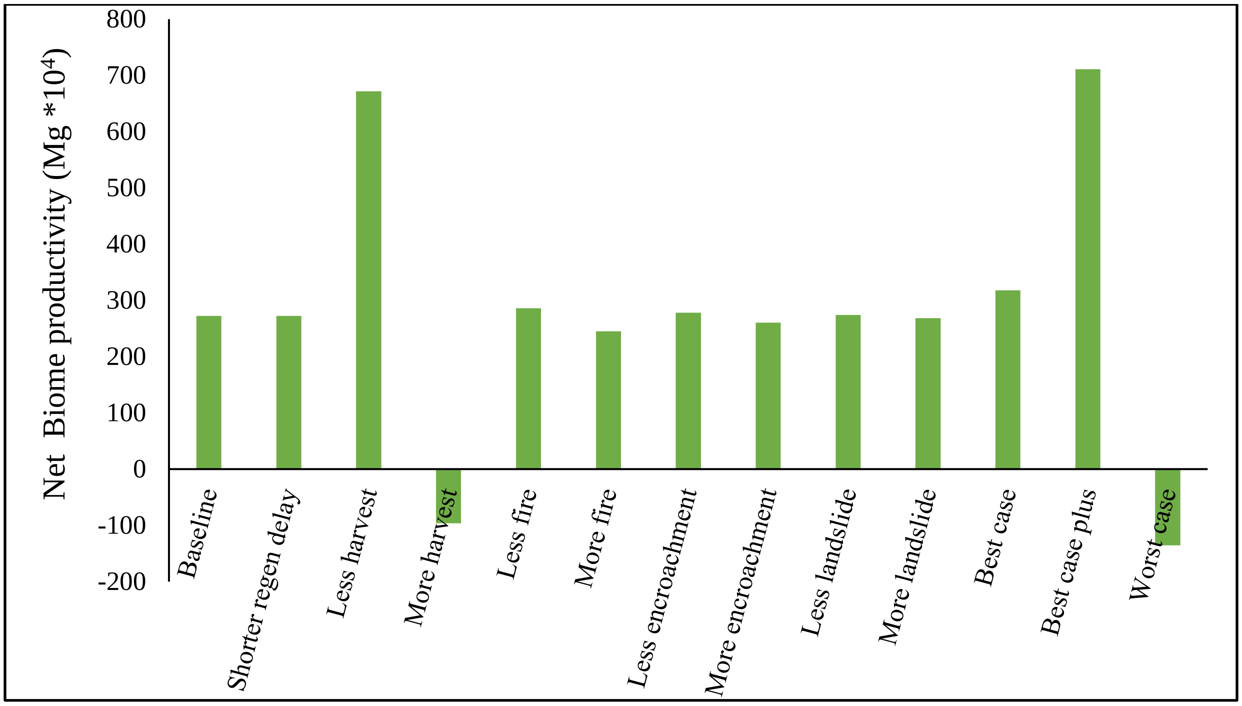


Figure 3.5: Cumulative net biome productivity under the different scenarios for 2018 to 2030 period.

The worst-case and more harvest scenarios had negative NBP, but the forests were still net sinks of the atmospheric CO_2 since carbon transferred out of the ecosystem from harvesting was removed from the atmosphere (Fig. 3.6). This is logical since carbon transferred to harvested wood products is not instantly oxidized (IPCC, 2015), especially the portion that is not fuel wood. Cumulatively (2018-2030), the best case plus scenario removed the most CO_2 (30.2 Tg), followed by the less harvest scenario with 29.0Tg. The more harvest scenario removed the least CO_2 (13.6 Tg). Some of the carbon that was transferred to harvested wood products will have been released back to the atmosphere; however, this quantity was not assessed here.

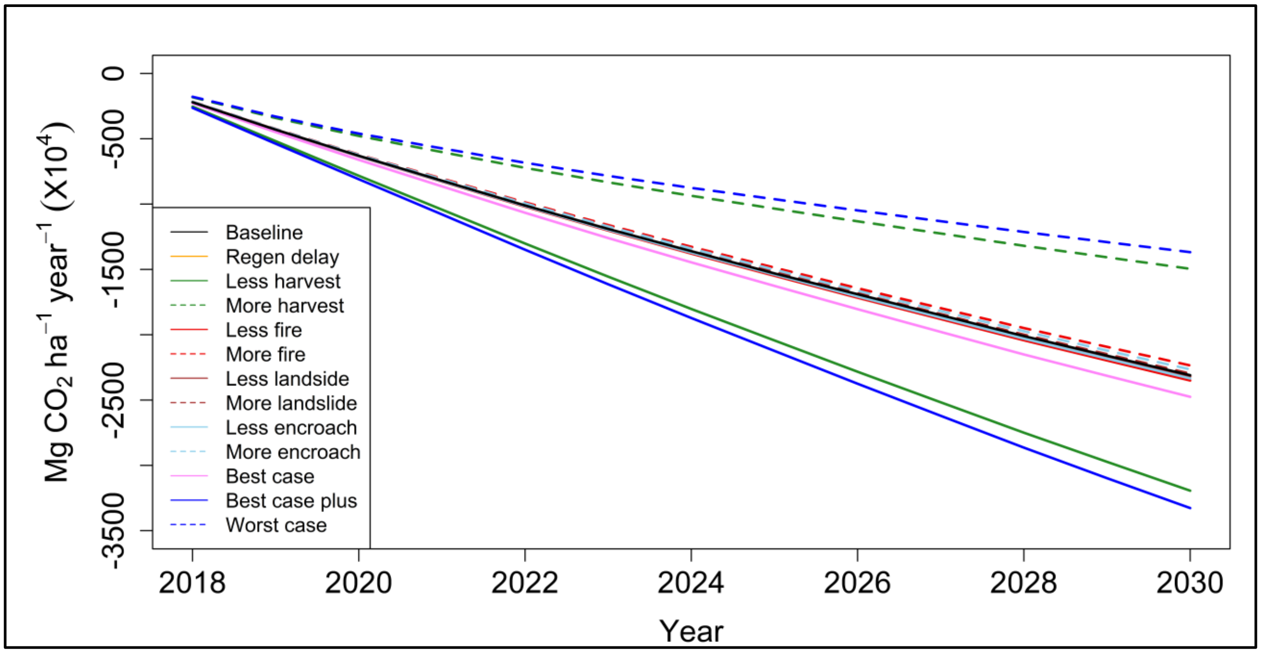


Figure 3.6: Cumulative CO_2 (Mg CO_2 ha^{-1} yr^{-1}) equivalent removal from the atmosphere by the various scenarios (Regen: regeneration; encroach: encroachment). Note that a negative value indicates removal of CO2 from the atmosphere.

The harvest levels that were applied for various scenarios removed the carbon content from the forest ecosystem and therefore decreased the carbon stock in forest; however, carbon was transferred to the HWP (Table 3.6). Cumulatively, the more harvest scenario transferred the highest amount of carbon to the HWP, followed by the worst-case scenario. Although both scenarios had the same harvest rate, the worst case had slightly less carbon transferred to HWP than the more harvest scenario. This decrease in worst case scenario might have been countered by the increased level of other disturbances (fire, encroachment, and landslide). The less harvest scenario transferred the least carbon to HWP followed by the best-case scenario. The less harvest and best-case plus scenarios had the same rate of decreased harvest; however, reducing the disturbances rates contributed towards transferring slightly more carbon to the HWP.

Table 3.6: The cumulative amount of (2018-2030) carbon (Tg) transferred to HWP for the scenarios that included different harvest rates.

Year	Baseline	Less harvest	More harvest	Best-case plus	Worst-case
2018	0.24	0.13	0.39	0.13	0.39
2019	0.48	0.26	0.78	0.26	0.78
2020	0.72	0.39	1.16	0.39	1.16
2021	0.97	0.53	1.55	0.53	1.55
2022	1.22	0.67	1.94	0.67	1.93
2023	1.47	0.80	2.32	0.81	2.31
2024	1.72	0.94	2.70	0.95	2.70
2025	1.97	1.08	3.09	1.09	3.07
2026	2.22	1.22	3.47	1.23	3.45
2027	2.47	1.37	3.84	1.37	3.82
2028	2.73	1.51	4.22	1.52	4.20
2029	2.99	1.66	4.60	1.67	4.57
2030	3.24	1.81	4.97	1.82	4.94

3.4 Discussion

Terai forests were a carbon sink during the simulation period for all the scenarios in this study, despite the worst-case and more harvest scenarios having negative NBP because the sum of NPB plus the cumulative harvest was a positive value. However, net system productivity could be negative (a net source) if the proportion of HWP that goes to fuel wood is high. Encroachment and illegal harvesting are the predominant disturbances in Terai (FRA/DFRS, 2014b, Kanel et al., 2012). If these disturbances continue unchecked, there is a good chance that the forests of Terai could act as a carbon source in the future. Tropical forests have a large potential for climate change mitigation. The mitigation potential of forests can be enhanced, not only through programs like REDD+ to avoid deforestation, but also through investments in management such as reforestation and afforestation (Lasco, 2008) and through programs that enhance carbon retention in wood products such as use wood for timber and houses rather than fuel wood.

The various scenarios considered in this study included both reducing deforestation and increasing investments in activities such as prompt reforestation, landslide prevention methods, and fire reduction. Assessing alternative scenarios provides the critical information needed to evaluate and implement investments for effectively enhancing and conserving carbon stocks. The less harvest scenario had the highest carbon stocks because more growing stock was left in the forest as a basis for continuing growth of the forest. Reduction of harvest levels could be practical if fuel wood consumption was reduced due to the availability of more efficient alternatives at sufficiently low prices (Kanel et al., 2012). However, if the harvest level becomes too low, forest growth will, at some point, begin to decline because and perhaps reduce to a point where the forest stock is in a state of dynamic equilibrium. Generally, the volume yield curve shape is sigmoidal, and it defines three growth stages: youth when there is a steady increase of both CAI (current annual increment) and MAI (mean annual increment), maturity which shows a slowing CAI but an increasing MAI and senescence which defines decreasing CAI and MAI and the curve levels off at asymptote (LeMay & Marshall, 1990). This signifies that a tree growth is relatively very small as it reaches asymptote and the carbon sequestration for photosynthesis is very little too.

Reducing the area burnt reduced carbon emissions because fires release a similar amount of carbon as deforestation (Nepstad et al., 1999). Decreasing the regeneration delay contributed to timely regeneration; however, due to the relatively small amount of area disturbed each year, the reduction in regeneration delay had only a small impact on the overall carbon dynamics. Investments in landslide preventive measures can reduce the frequency and extent of this disturbance type. Halting forest encroachment would stop deforestation, contributing towards REDD+. Thus, the heavy investment (best case plus) scenario resulted in the highest removals of carbon.

The best-case plus was closely followed by the less harvest. This was because harvesting affected considerably more forest area than any of the other disturbances. Reducing the harvest level transferred less carbon stock to harvested wood products and consequently more carbon remained in the forest. This result agreed with finding of Smyth et al. (2014) that decreasing harvest provided the greatest carbon stock benefits over the short term.

Not surprisingly, carbon stocks were lower in the worst-case and more harvest scenarios. The total ecosystem and biomass carbon stocks decreased over time for these two scenarios, but the simulations showed that the forest was still a sink since the amount of carbon transferred in harvested wood were not accounted as instantaneous oxidation. The disturbance rates simulated in this study were relatively low, so the forest remained a sink. However, what can be inferred from the worst-case scenario is that if disturbance levels continued to increase, then the forests of Terai could become a carbon source. The more encroachment scenario had lower carbon stocks than the baseline scenario due to more deforestation. Nepal's Department of Forest's "National Forest Development and Management Programme" is aimed at halting and reclaiming encroached forest land; however, it has not been fully successful (Bhusal et al., 2019). Reforming and enforcing policies on forest land encroachment is necessary.

The more fire scenario emitted more carbon than the baseline scenario, the opposite of the less fire scenario. Fire has impacts on carbon stocks and fluxes depending on intensity and severity. Increased investment in fire suppression and community awareness can be a good approach to increasing carbon stocks, particularly for shade-tolerant and fire-sensitive regeneration (Hurtt et al., 2002; Malcolm et al., 2009; Houghton et al., 2012).

Carbon stocks in Terai's forests can be impacted by changing the magnitude of disturbances. While there are uncertainties in my estimates, the results demonstrate that mitigation options can be simulated and their impacts on carbon assessed. The relative magnitude of the changes among the scenarios should be more accurate than the overall carbon values projected due to common assumptions among the scenarios. These changes can be used as a guide to determine which sorts of investments might have the largest impacts on carbon stocks.

There is a high value associated with carbon sequestration. Recently (2021), Nepal signed an agreement with the FCPF that it would provide revenue for the CO_2 reduced from deforestation and forest degradation in the Terai Arc Landscape through 2025[14]. Looking at the carbon stocks difference between the best-case scenario and the baseline, the Terai forests could produce some revenue if the best-case scenario were to be implemented. A number of forestry projects world-wide have been financed based on the expected sequestration effect, indicating that the cost of sequestration is relatively low in comparison with many engineering solutions to CO_2 emission

[14] https://www.worldbank.org/en/news/press-release/2021/02/26/nepal-and-world-bank-sign-innovative-financing-agreement-on-forests-and-climate-change-for-building-back. (Accessed April 20, 2021).

reductions (De Jong et al., 2000; Forest Carbon Partnership Facility, 2020; Forest Carbon Initiative British Columbia, 2020[15]).

3.5 Conclusion

There were differences in carbon stocks and fluxes amongst alternative scenarios, although the deviations were relatively small because the scenario differences were small. The best-case plus scenario, which included the highest investments and fuel wood substitution, resulted in the most carbon sequestration. Investments to suppress fire, reduce landslides and enacting and enforcing stronger legislation to stop forest encroachment can increase the carbon balance in the ecosystem. The worst-case scenario, which included possible impacts of population pressure and climate change, had the strongest negative impacts on carbon stocks and fluxes. If these problems are not alleviated, then there is a good chance that the forests of Terai will become a carbon source at some point in the future.

[15] https://www2.gov.bc.ca/gov/content/environment/natural-resource-stewardship/natural-resources-climate-change/natural-resources-climate-change-mitigation/forest-carbon-initiative. (Accessed October 23, 2021).

Chapter 4: Carbon Stored in Harvested Wood Products for Terai, Nepal

4.1 Introduction

Sustainable forest management strategies to regenerate forests quickly post-harvest, reduce annual harvest levels, and/or establish new forests can be used to meet the net zero GHGs target by 2050 (UNFCCC, 2015) by sequestering carbon. The potential impact of some of these strategies on forests of Terai were explored in Chapter 3. However, sequestering carbon in forests is not the only way that woody biomass can contribute to mitigating climate change. Using bio-based and high carbon storage capacity materials like timber products creates a carbon pool by storing carbon and simultaneously reducing CO_2 emissions from production of carbon intensive materials such as masonry, concrete, steel, etc. (Sathre & O'Connor, 2010; Werner et al., 2010; Lempiere et al., 2013; Winkel, 2017; Churkina et al., 2020). The average substitution effect of wood products as a replacement for non-wood products is 1.2 kg carbon per kg wood product; however the substitution factor is variable depending on the type of products and non-wood products substituted (Leskinen et al., 2018). As well, solid wood products can continue to provide carbon storage post-harvest for long time periods, with the amount of stored carbon and the retention period depending on the tree species, the wood properties (Lamlom & Savidge, 2003), and the type of the commodity produced.

Conversely, burning fuel wood for heat and cooking instantaneously releases carbon to the atmosphere (IPCC, 2014). For Nepal, more than 75 percent of the total energy used is derived from fuel wood and this is the primary source of carbon emissions (Baral et al., 2019). Current and increasing demands for fuel wood may lead to unsustainable harvesting, consequently resulting in deforestation and forest degradation (Ghilardi et al., 2007; DeFries & Pandey, 2010). Alternatively, reductions in fuel wood consumption rates could result in reductions to harvest rates and higher retention of carbon stock, and/or shifts of more of the harvested wood to manufactured wood products that can retain carbon stocks for longer periods of time.

Recognition of carbon stored in HWP and realization of relevant climate change mitigation strategies associated with HWP is a growing area of research (Kayo et al., 2015). With the use of wood substitutes, up to 31% of global CO_2 emissions could be avoided, and such wood use could reduce up to 19% of global fossil fuel usage **(**Oliver et al., 2014). The global mitigation potential of the HWP carbon pool showed a net sink of 355 Mt of CO_2e in 2015 and it is projected to increase to 441 Mt of CO_2e by 2030 (Johnston & Radeloff, 2019). There have been several other studies that have estimated the potential size of this sink, both regionally and globally (e.g., Dias et al., 2007; Stockmann et al., 2012; Smyth et al., 2014; Kayo et al., 2015; Pilli et al., 2015; Pingoud et al., 2018; Smyth et al., 2018). However, the HWP pool may also act as a source of CO_2 as old HWPs half-life is reached (Johnston & Radeloff, 2019).

The Intergovernmental Panel on Climate Change (IPCC, 1996; 2006) highlighted several methods for estimating and reporting carbon exchanges as a result of forest harvesting. First, instantaneous oxidation of HWP can be assumed, where all GHGs are considered emitted as soon as wood products are harvested. This estimation approach is commonly accepted and was used in Chapters 2 and 3. However, this approach overestimates GHG emissions since harvesting transfers carbon from standing trees to HWP, potentially resulting in a long-term delay of GHG emissions along with a slower release as HWPs decay (IPCC, 2006). A second possibility is a stock-change approach, where the carbon transferred from a forest to HWP counts as a loss for the producing country and a carbon gain to the HWP pool in the consuming countries. A third option uses a production approach where net changes to the forest and HWP carbon stocks are attributed to the producing country. A fourth option, the atmospheric-flow approach, uses net emissions or removals of carbon to/from the atmosphere associated with HWP. Finally, the simple decay approach can be used, which treats the transfer of carbon from forest to HWP and transfer and emissions are then reported from HWP. The producing country is the one that has to report all emissions regardless of where in the world they occur. The production approach was recommended by the IPCC in the Revised Supplementary Methods and Good Practice Guidance (IPCC, 2014) document under the Land Use, Land Use Change, and Forestry (LULUCF) program of the Kyoto Protocol (UNFCCC, 2011). Countries vary in their choices of the accounting approach used (Sato & Nojiri, 2019).

The forestry sector contributes about 15% of Nepal's gross domestic product; however, Nepal has not yet fully achieved the potential benefits from the forestry sector in terms of timber and value-added products, nor from using forests for climate change mitigation (Subedi et al., 2014). The domestic demand for wood products is high, contributing to an increasing dependence on imports (Subedi et al., 2014; Khatri et al., 2015). Further, the high consumption of forest products, mainly fuel wood and timber for subsistence and commercial purposes, is one of the main drivers of deforestation and forest degradation in Nepal (MoFSC, 2013).

The tropical forests of Terai contain the most valuable tree species for sawn wood products including *Shorea robusta*, *Dalbergia sissoo*, *Acacia catechu*, *Tectona grandis*, and *Terminalia alata*, with higher biomass productivity than elsewhere in the country due to better edaphic and climatic conditions (FRA/DFRS, 2014c). As a result, a substantial amount of timber and fuel wood is transported to urban centers from Terai (MoFSC, 2013). However, the forests of Terai are increasingly vulnerable to population growth, infrastructure development, and illegal harvesting for commerce and trade (FRA/DFRS, 2014c). Realizing the importance of forest products from Terai, the Government of Nepal started the commercialization of forest management through a program called the "Scientific Forest Management Initiative" in 2014. Under this initiative, intensive silvicultural operations in collaborative and community forests were implemented in eight districts in Terai. This initiative mainly addresses unsatisfactory timber production, passive forest management, and forest degradation (Bhattarai et al., 2017).

The scenarios I examined in Chapter 3 for the Terai forests included three harvest levels (1.5% area per year - baseline; 0.75% area per year; and 2.25% area per year) but did not model the carbon in the HWP. Longer-lived wood products (i.e., sawn wood) can retain carbon considerably longer than fuel wood, which is assumed to release its carbon at the time of harvest. In this chapter, I examined the impact of changes to the commodity proportions within the HWP from Terai forests on carbon stocks. I did this through simulating 15 scenarios comprised of the three harvest levels I considered in Chapter 3 crossed with five proportions of fuel wood to sawn wood products (i.e., historic ratio of 0.94 fuel wood: 0.06 sawn wood; 0.75:0.25; 0.50:0.50; 0.25:0.75; and 0.00:1.00). The carbon potential for each scenario was determined using CBM-CFS3 to track the forest carbon levels and the Carbon Budget Modeling Framework for Harvested Wood Products (CBM-FHWP; Smyth et al., 2018) to track the carbon levels in the HWP. In this analysis, I addressed the following questions:

1. What are the impacts on carbon stocks associated with increasing the proportion of sawn wood in the HWP?
2. Can shifting the commodity proportions offset the carbon loss associated with a higher harvest level?

I expected that increasing the proportion of sawn wood in the HWP would increase carbon stocks and that this increase would be able to offset carbon storage losses associated with a higher harvest level to some extent.

4.2 Methods

4.2.1 Study Area

Terai is an expansion of the lowlands in the southernmost part of Nepal with about 2 million ha of land and has 0.4 million ha of sub-tropical forest (FRA/DFRS, 2014b). Forests in Terai have high commercial and subsistence importance (Webb and Sah, 2003), containing valuable species with desirable wood properties (Table 4.1). More details on Terai's forests are given in Chapter 2.

Table 4.1: Dominant tree species in Terai with their wood properties and usage (Jackson, 1994).

Species	Wood Properties	Usage
Shorea robusta	Strong, durable, somewhat flexible	Construction, doors, window frames, planking carts, carvings, leaf plates
Terminalia alata	Heavy, strong, and considerably durable	Door and window frames, carts and plows, rice plunders, plywood and furniture, parquet, and poles for construction
Acacia catechu	Heartwood is hard and heavy	Cutch for tanning and dyeing; excellent fuel wood
Dalbergia sissoo	Strong and elastic	Furniture, cartwheels, and hand tool handles; excellent fuel wood
Tectona grandis	Durable and relatively easy to work texture	Veneers, boats, furniture; excellent fuel wood

Terai has been experiencing increasing pressure for wood products due to increasing population pressures, leading to deforestation and forest degradation. Given that Terai has the most valuable timber in Nepal and is experiencing increasing wood products demand, most forest management intervention projects are currently being conducted in this region, including REDD+ in Terai Arc Landscape (12 districts) and the Scientific Forest Management Initiative (eight districts). For these reasons, Terai was chosen for this research examining the impacts on carbon stocks of alternative harvest levels and HWP mixtures from these harvests.

4.2.2 HWP Carbon Dynamics Under Alternative Forest Sector Activities

As in Chapters 2 and 3, CBM-CFS3 was used to track forest carbon levels through time under various harvesting levels while retaining historic levels of other natural and human disturbances. After harvesting, the carbon transferred out of the forest ecosystem as HWPs was tracked using CBM-FHWP (Smyth et al., 2018) throughout the lifetime of the HWPs. For this, the IPCC production approach was used for estimation of HWP carbon balances, where the carbon in HWPs is assigned to the harvest location regardless of where in the world the products ultimately reside (IPCC, 2013). Also, the IPCC default value for decay rates were used, specifically that sawn wood and other industrial roundwood were assumed to have a 35-year half-life (IPCC, 2013). This modelling framework has also been used in harvested wood products analysis in a similar regional-scale analysis in Mexico (Olguin et al., 2018), and in the United States (Dugan et al., 2018 and 2021).

As noted in Chapter 3, harvest levels might drop because of policies to retain carbon stocks and other changes in land use policies. Alternatively, harvest levels might increase from increasing population demands for HWPs, as well as substitution of fuel wood for higher GHG emissions products. At the same time, substituting other fuel sources for fuel wood would result in a higher proportion of harvested wood available for solid wood products. Specifically, I selected sawn wood to represented solid wood products in this analysis since it is a common product in Nepal and data were available on the historical split between fuel wood and sawn wood (94% and 6% of the harvest, respectively[16]). I then simulated the same three harvest rates as in Chapter 3: 1) baseline historical harvest rate (1.5% of the forest area each year); 2) lower harvest (0.75% of the forest area each year); and 3) higher harvest (2.25% of the forest area each year). The lower harvest level was used to simulate increased retention of carbon stored in forests, while the highest rate simulated greater transfer of forest carbon to HWP. Finally, I simulated five fuel wood to sawn wood ratios for each harvest rate: 1) the historic ratio of 0.94:0.06; 2) 0.75:0.25; 3) 0.50:0.50; 0.25:

[16] http://www.fao.org/faostat/en/. (Accessed December 10, 2019).

0.75; and 4) 0.00:1.00 (Table 4.2). Since CO_2 is released to the atmosphere at the time of burning, instantaneous loss of carbon was assumed for fuel wood (i.e., no fuel wood storage). For sawn wood, carbon is released over time. I used the IPCC half-life default value of 35 years and a decay rate of 0.0198 (Decay rate (k)= Ln (2)/half-life) for sawn wood, assuming no wood treatments were used (IPCC, 2013) and assuming 100% emissions.

4.3 Results

4.3.1 Carbon Transferred to Harvested Wood Products

Total ecosystem carbon levels changed by harvest level, with the highest values for the lowest harvest level (Scenarios 6 through 10, Table 4.3). Within a harvest level, as the percentage of fuel wood in the HWP decreased from 94% to 0% in favor of sawn wood, the cumulative carbon that was in sawn wood over the period from 2018 to 2030 increased (Figure 4.1). Also, the maximum level of carbon stored in sawn wood resulted from the highest harvest rate and 100% sawn wood (4.96 10000×Mg of carbon - Scenario 15). The total amount of carbon stored (sum of total ecosystem carbon and HWP carbon) was highest for the lowest harvest rate and 100% sawn wood products (106.76 10000×Mg of carbon - Scenario 10; Figure 4.2). However, for the highest harvest rate, an improvement over the baseline was achieved if all the harvest was used for sawn wood (Scenario 15).

For all scenarios, fuel wood was assumed to be consumed at the time of harvest resulting in the carbon being released to the atmosphere at that point in time, but the carbon in sawn wood was assumed to be released much more slowly over time. As a result, the lowest cumulative emissions were associated with Scenario 10 with the lowest harvest level and 100% sawn wood (Fig. 4.3). Higher CO_2 emissions were associated with higher harvest levels and higher fuel wood compositions in the HWP.

The forest remained a sink for all three harvest levels. The differences in carbon stocks compared to the baseline scenario are shown in Figure 4.4. Shifting the HWP composition to around 80% sawn wood would allow the higher harvest level to occur with no loss of carbon stocks compared to the historic harvest level and fuel wood: sawn wood proportions.

Table 4.2: Alternative Forest sector activities scenarios implemented for the 2018 to 2030 period.

Scenario	% Forest Area Harvested Yearly	% Yearly Forest Area Harvested as Fuel wood (Proportion of Harvest)	% Yearly Forest Area Harvested as Sawn Wood (Proportion of Harvest)	Description
1 (Baseline)	1.50	1.41 (0.94)	0.09 (0.06)	Historic harvest and historic fuel wood: sawn wood proportions ("Status quo")
2	1.50	1.12 (0.75)	0.38 (0.25)	Baseline harvest level with some reduction in fuel wood proportion
3	1.50	0.75 (0.50)	0.75 (0.50)	Baseline harvest level with even split between fuel wood and sawn wood
4	1.50	0.38 (0.25)	1.12 (0.75)	Baseline harvest level with a considerable reduction in fuel wood proportion
5	1.50	0.00 (0.00)	1.50 (1.00)	Baseline harvest level with no fuel wood
6	0.75	0.71 (0.94)	0.04 (0.06)	Lower harvest level with no change in the fuel wood proportion
7	0.75	0.56 (0.75)	0.19 (0.25)	Lower harvest level with some reduction in fuel wood proportion
8	0.75	0.38 (0.50)	0.38 (0.50)	Lower harvest level with even split between fuel wood and sawn wood
9	0.75	0.19 (0.25)	0.56 (0.75)	Lower harvest level with a considerable reduction in fuel wood proportion
10	0.75	0.00 (0.00)	0.75 (1.00)	Lower harvest level with no fuel wood
11	2.25	2.11 (0.94)	0.14 (0.06)	Higher harvest level with no change in the fuel wood proportion
12	2.25	1.69 (0.75)	0.56 (0.25)	Higher harvest level with some reduction in fuel wood proportion
13	2.25	1.13 (0.50)	1.13 (0.50)	Higher harvest level with even split between fuel wood and sawn wood
14	2.25	0.56 (0.25)	1.69 (0.75)	Higher harvest level with a considerable reduction in fuel wood proportion
15	2.25	0.00 (0.00)	2.25 (1.00)	Higher harvest level with no fuel wood

Table 4.3: Total ecosystem carbon and the carbon transferred to sawn wood (10000 × Mg) for different scenarios by the end of the projection (2030).

Scenarios	Annual Harvest Level (%)	Sawn Wood Percentage	Total Ecosystem Carbon	Sawn Wood Carbon	Total Carbon Stocks	Difference From Baseline
1 (Baseline)	1.50	0	100.89	0.23	101.11	0.00
2	1.50	25	100.89	0.81	101.70	0.59
3	1.50	50	100.89	1.62	102.51	1.40
4	1.50	75	100.89	2.43	103.32	2.21
5	1.50	100	100.89	3.24	104.13	3.02
6	0.75	0	104.96	0.13	105.08	3.97
7	0.75	25	104.96	0.45	105.41	4.30
8	0.75	50	104.96	0.90	105.86	4.75
9	0.75	75	104.96	1.35	106.31	5.20
10	0.75	100	104.96	1.81	106.76	5.65
11	2.25	0	97.14	0.35	97.49	-3.62
12	2.25	25	97.14	1.24	98.38	-2.37
13	2.25	50	97.14	2.48	99.62	-1.49
14	2.25	75	97.14	3.73	100.87	-0.24
15	2.25	100	97.14	4.97	102.11	1.00

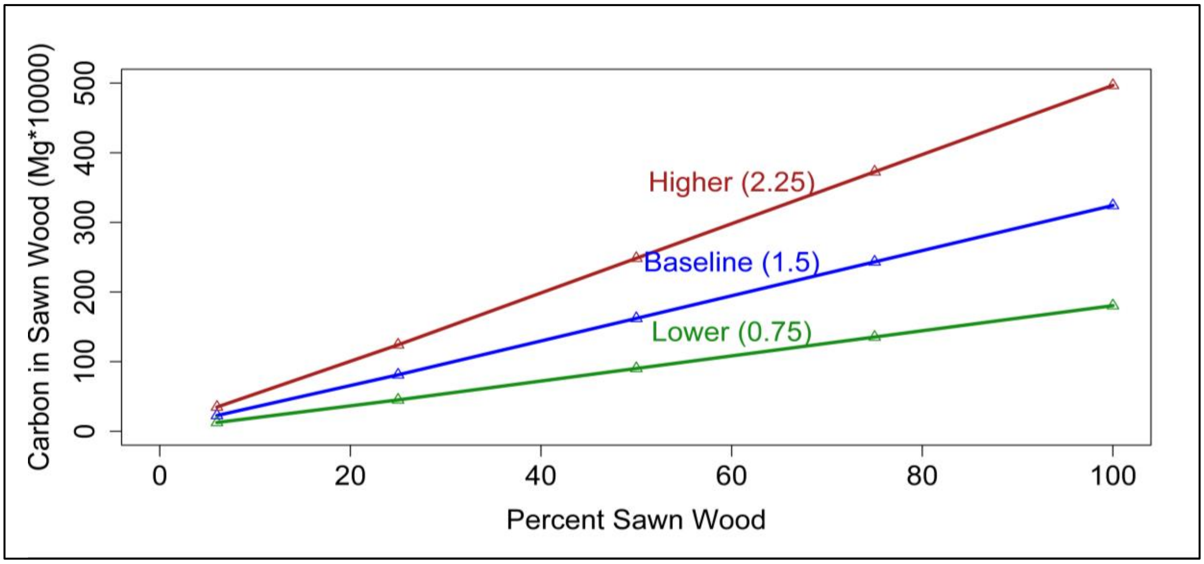


Figure 4.1: Cumulative carbon transferred to sawn wood for 2018-2030 for the three harvest levels and different percentage compositions of sawn wood in the harvested wood products.

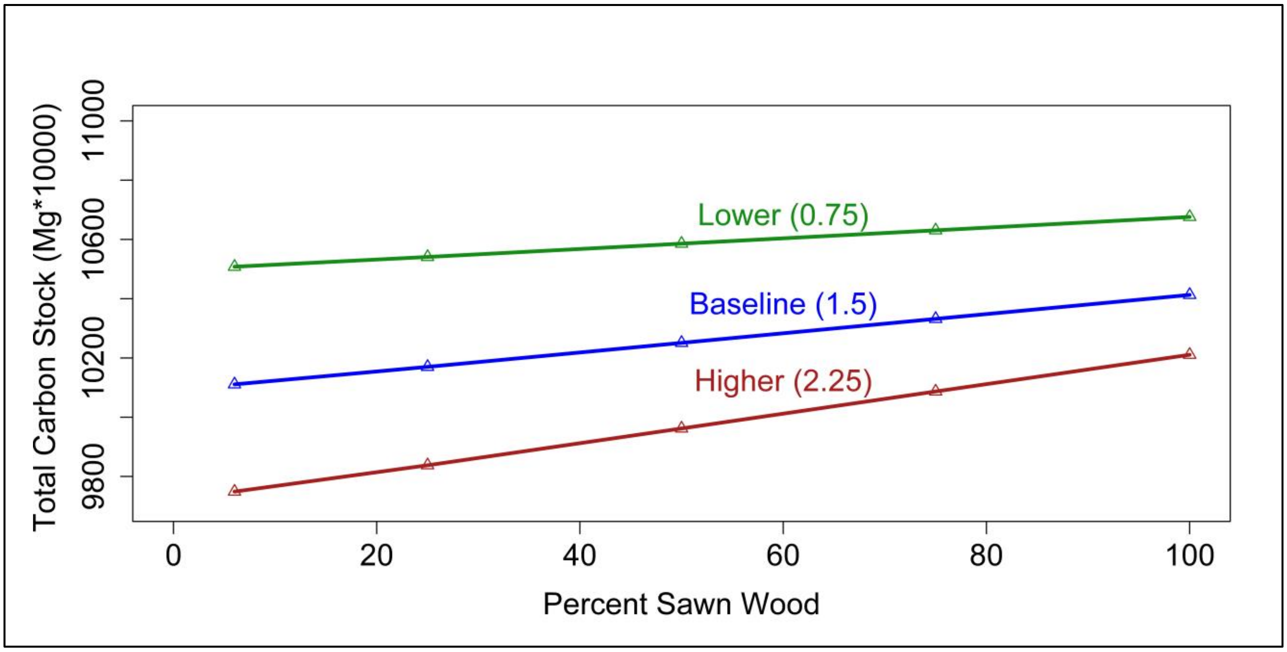


Figure 4.2: Total ecosystem carbon stocks (total ecosystem carbon + carbon transferred to sawn wood) at the end of projection period (2030) for the three harvest levels and different percentages of sawn wood.

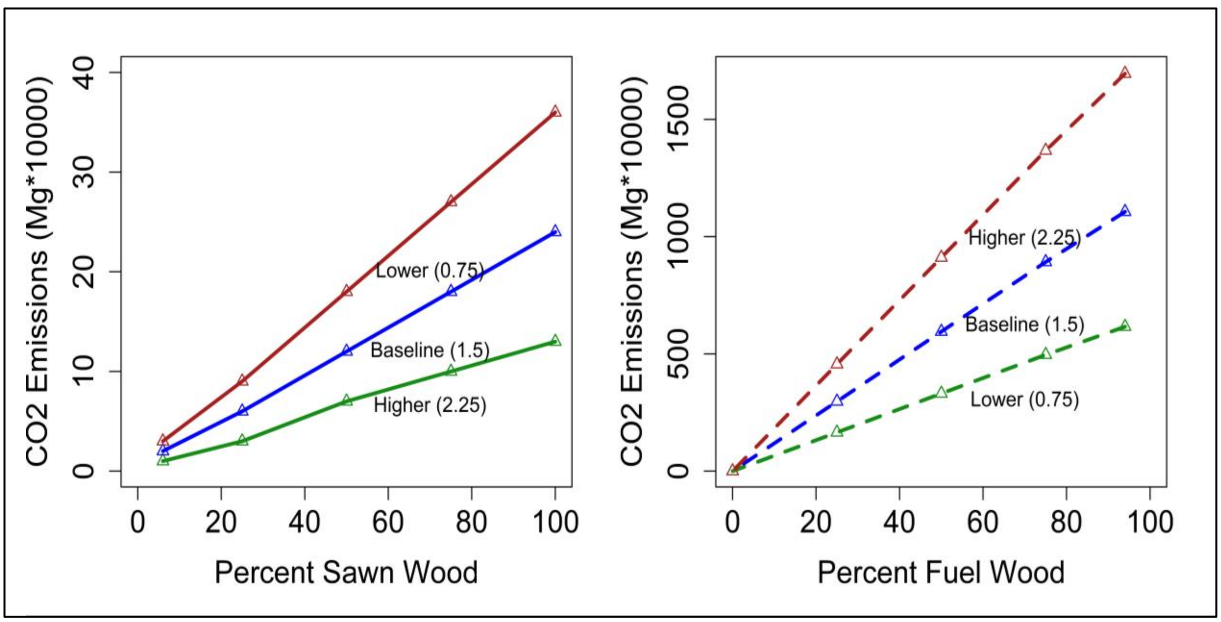


Figure 4.3: Cumulative CO_2 emissions for 2018-2030 for the three harvest levels and for different percentages of sawn wood and fuel wood. Total emissions can be determined as the sum of the values within a harvest level of the percentages in the two charts that add to 100 (e.g., 25% sawn wood + 75% fuel wood).

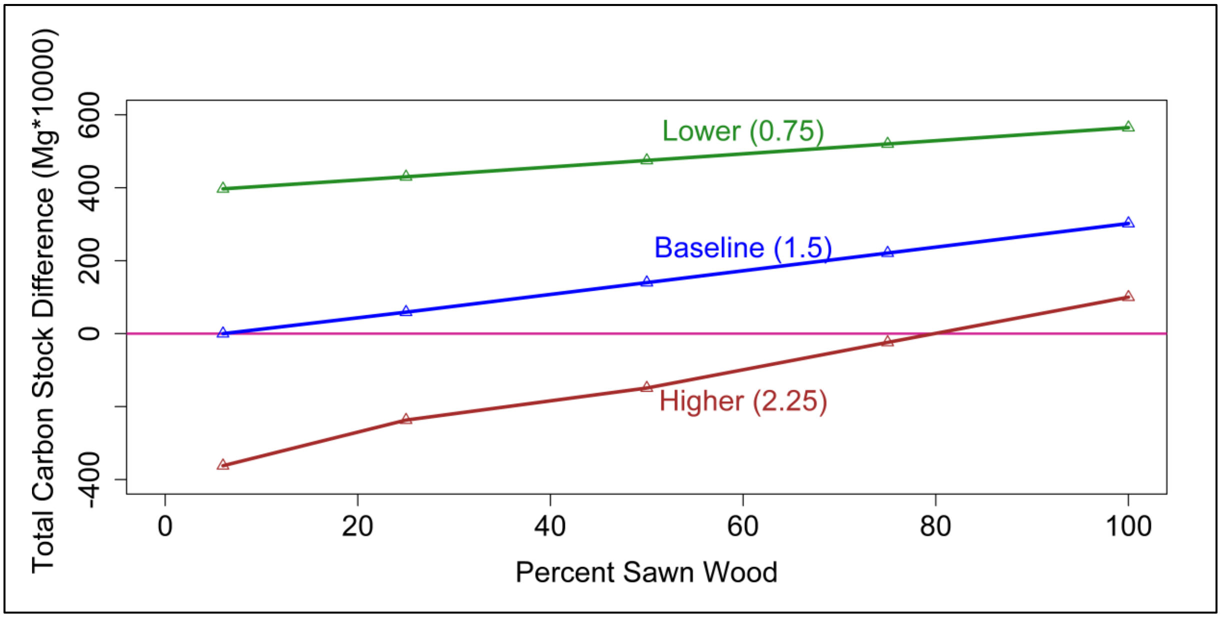


Figure 4.4: Differences in carbon stocks from the baseline scenario (1.5% annual forest area harvest with 6% sawn wood and 94% fuel wood for the harvested wood products) for the three harvest levels and different percentages of sawn wood.

4.4 Discussion

Economic and socio-economic analyses are necessary to understand the potential barriers to implementation of alternative forest management interventions (Lemprière et al., 2017; Xu et al., 2018). Although specific analyses were beyond the scope of this study, economic and social benefits would be expected to accompany the environmental gain from shifting higher proportions of the HWP from fuel wood to solid wood products in Terai. Increasing the proportion of sawn wood in the HWP increased the amount of carbon stored in those products irrespective of harvest levels, whereas the immediate burning of fuel wood contributed immediately to the emissions CO_2. As well as lower CO_2 emissions, such products should generate more value than fuel wood for the harvesting companies, which may spin off into benefits for workers (higher wages and more jobs) and to the local and national governments through increases in taxation revenues (Olguin et al., 2018; Xu et al., 2018). More sawn wood products can further contribute "value added" jobs, for example with wood furniture companies, thus contributing towards sustainable local economies. More interest in, and revenue from, sawn wood products could encourage more investment into managing the forests to improve growth rates and reduce losses to disturbances as well. For example, Scenario 10 in Chapter 3 showed a 3.4% increase in above-ground carbon biomass for the historic harvest level from such investments. Finally, some sawn wood products could be used to displace carbon emissions intensive materials. An extensive review done by Leskinen et al. (2018) showed that the average substitution effect of wood product as replacement for non-wood products was 1.2 kg carbon per kg of wood product, although it varied considerably among products.

Despite the apparent advantages, a shift to a smaller proportion of fuel wood within the HWP is only practical if there is availability of more efficient alternatives to fuel wood at sufficiently low prices (Kanel et al., 2012). Shifting from reliance on fuel wood in Nepal can be accomplished in a few ways. First, reductions in fuel wood use would occur by transitioning to improved burning cookstoves such as mud-brick and metallic improved cooking stoves (ICS), which have higher thermal efficiency and required less fuel wood consumption (Adler, 2010; Teune, et al., 2020). Second, non-renewable fuels, notably, liquefied petroleum gas (LPG) could also be substituted for fuel wood since LPG has higher thermal and combustion efficiency, resulting in much lower emissions than traditional fuel wood cooking stoves (Bruce et al., 2017). As a cleaner burning fuel, LPG can also reduce various health risks (WHO, 2016). However, LPG must be imported to Nepal, causing other GHG emissions during long transport distances. Other reductions in fuel wood consumption can be realized by using alternative renewable energy source options such as biogas from cattle manure, and vegetable wastes, water energy via improved water mills, hydroelectricity via large installations, stand-alone micro-hydro plants, or mini-grid micro-hydro plants, and solar power via solar systems (Suman, 2021). Hydroelectricity is a relatively clean energy source and offers a particularly good alternative as one of the GHG emissions reduction options for Nepal (Gunatilake et al., 2020). Nepal has excellent water resources (6,000 rivers) with a capacity of producing 42 gigawatts of hydroelectricity, considerably above present demands (peak demand was 1,320 megawatts for the 2018–2019 fiscal year)[17].

Similarly, increasing the amount of sawn wood products is only feasible if there are markets for such products and sufficient facilities for producing such products, such as small

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[17] https://www.adb.org/sites/default/files/publication/612641/hydropower-development-economic-growth-nepal.pdf. (Accessed October 06, 2021).

sawmills. Building markets and enhancing production facilities will obviously take time. However, if there is a reliable supply of suitable timber, and sufficient local and national governmental support (i.e., incentives), this should be achievable.

If the primary purpose of Terai's forests is to store carbon, then, at least in the shorter term, the harvest level should be reduced and the totality of the harvest should be used for sawn wood products (e.g., Scenario 10). However, higher carbon sequestration rates occur in forests that are actively growing rather than older forests (Pan et al., 2011; Erb et al., 2013; Pugh et al., 2019). If the harvest level becomes too low, forests will age and forest growth will, at some point, begin to decline and perhaps reduce to a point where the forest stocks are in a state of dynamic equilibrium (Binkley et al., 2002). At this point, no net carbon would be sequestered. Not enough is known specifically about the growth of Terai's forests and their natural disturbance patterns to be precise as to what ages different stand types might begin to stagnate. However, judging from the constructed yield curves for *Shorea robusta* and T*ectona grandis* (Fig. 2.4) this might begin to occur around age 120 years for those stand types.

Studies have shown that the best forest conditions for sequestering carbon are when a forest is actively managed and maintained in a balanced state across age classes through time (Ontl et al., 2020). However, total carbon storage is only increased if the HWP are used to store much of the carbon harvested (Churkina et al., 2020; Dugan et al., 2021). Utilizing HWP other than fuel wood results in a transition of carbon from the forest carbon pool to the harvested wood products pool, rather than a direct emission from the forest carbon stocks to the atmosphere at the time of harvesting (Schlamadinger & Marland, 1996; Sathre et al., 2010; Smyth et al., 2014). Various studies have shown that the substitution for energy intensive materials by wood leads to considerably lower emissions of CO_2 (e.g., Eriksson et al., 2006; Gustavsson, 2006; Sathre et al., 2010), along with considerable reduction in the consumption of fossil-fuels in the production and transportation of energy-consuming materials (IPCC, 2013).

Reducing the portion of HWP directed to fuel wood to zero is clearly not feasible. However, I included this scenario to establish an upper limit on the gain in carbon stocks that would be possible from reducing the proportion of the HWP used for fuel. Significantly, after 80% of the HWP were shifted from fuel wood to solid wood products, more carbon was stored than for the baseline scenario, even under the higher harvest level. Fuel wood substitution is beneficial in many ways and the hydro power potentiality of Nepal could make this feasible. For example, Bhutan became carbon-negative because it uses hydroelectricity extensively[18].

4.4 Conclusions

Improved understanding of potential future carbon stock changes in the HWP pool is essential to assess effective carbon sequestration options. As expected, increasing the sawn wood proportion in the HWP pool relative to fuel wood increased the amount of carbon sequestered. Although higher harvest levels led to a reduction in the quantity of carbon sequestered in the forest relative to the current harvest level, this reduction in forest carbon stocks could be more than offset by an immediate 80% shift in the HWP mix from primarily fuel wood to sawn wood products. Of course, in application, such a shift in the HWP mix could not occur immediately, but rather would need to be phased in over a period of several years to a few decades. Although investment in alternative sources of energy for cooking/heating and development of markets for the sawn wood products are necessary for such a shift to occur, the net benefits from these investments are likely to be positive ecologically, socially, and financially. Terai's forests are comprised of economically valuable and ecologically robust tree species; however, the potential benefits from these forests are not fully realized.

[18] https://www.gvi.co.uk/blog/bhutan-carbon-negative-country-world/#:~:text=Bhutan%20absorbs%20roughly%20seven%20million,millions%20of%20tonnes%20each%20year. (Accessed online on August 08, 2022).

Chapter 5: Conclusion

5.1 Summary

An increased level of CO_2 in the atmosphere has contributed to accelerated global climate changes, notably increased temperatures (Lindsey, 2020). Human activities that increase atmospheric CO_2, such as burning fossil fuels or reducing carbon sequestration by permanent removals of forest cover (deforestation), are dominant causes of climate change (Ciais et al., 2011; IPCC, 2014). Forests form a major part the global carbon cycle, sequestering carbon from the atmosphere and storing it in biomass, soils, and HWP (IPCC, 2007). However, current climate changes are increasing the frequency, severity, or extent of natural disturbances (Williams et al., 2016; Seidl et al., 2017), which impacts on the tree physiology and affects the growth and survival of forests (Sturtevant & Fortin, 2021). As well, people are dependent on a variety of products from forests, including a wide variety of wood-based products, which necessitates intelligent management of the forests if they are to remain a sustainable source of products as well as an important carbon sink. This is particularly important in developing countries, such as Nepal, that often lack the resources necessary to manage their forests to provide a balance of uses.

My goal in this dissertation was to provide insights into how changes to forest management and policy in Nepal could enhance carbon storage, while continuing to obtain benefits through harvesting. I did this by assessing the carbon stocks and carbon dynamics of the forests and HWP in two critical physiographic regions of Nepal (Terai and Churia), under a variety of managerial and policy assumptions, from the date of the most recent inventory (2010) to 2030.

The impacts of disturbances (fire, encroachment, landslides, and harvesting) on the forest carbon stocks in Terai and Churia were assessed in Chapter 2. In order to accomplish this assessment, the Canadian carbon budget model (CBM-CFS3) was adapted to reflect the forest conditions in these regions of Nepal. Growth and yield functions for common tree species were developed from information available for these species from other countries and adjusted for site quality and density conditions in Nepal. Disturbances were identified using the Forest Resource Assessment (2014c) and annual forest loss was quantified using high-resolution global forest cover change maps (Hansen et al., 2013). Historic harvest rates were determined from FAO statistics. The following specific questions were addressed:

1. What are the differences in carbon dynamics between Terai and Churia?
2. What might be causing those differences?
3. Are there differences in carbon stocks amongst administrative units in Terai and Churia?
4. How could this information be used to improve future forest management?

Despite having similar species compositions, the two regions differed in carbon stock estimates due to variation in elevation, soil, and climate. Terai was impacted more by encroachment, while Churia was impacted more by landslides, fire, and harvesting. The forests of Terai and Churia remained a carbon sink for the forecast period under the historic disturbance levels. The modelling results can be used to suggest region-wide management options to increase carbon sequestration.

Possible management options for the forests of Terai, the most densely populated region in Nepal, were explored in more depth in Chapter 3. The ground-based inventory data were coupled with remotely sensed data to develop a finer spatial resolution for the forest attributes that was used in Chapter 2. Twelve forest management scenarios were developed to reflect possible changes to the disturbance regimes and forest policies. Carbon dynamics over the period from 2010 to 2030 were assessed using the adapted version of CBM-CFS3 and the growth and yield functions from Chapter 2. The following specific questions were addressed:

1. What are the impacts on carbon stocks and dynamics resulting from altering the level of each forest disturbance type, specifically, increasing or decreasing harvesting, forest encroachment, landslides, and forest fires relative to the historic (2010 to 2017) baseline?
2. What are the impacts on carbon stocks and dynamics resulting from investments to reduce regeneration delay, suppress fire, institute landslide preventive measures, implement policies to minimizing encroachment relative to the historic baseline and decrease the harvest rate because of fuel wood substitution (best case scenario)?
3. What are the impacts on carbon stocks and dynamics resulting from increased population pressure causing increased harvesting and encroachment, along with increased forest fires relative to the historic baseline (worst-case scenario)?

Terai's forests remained a carbon sink during the simulation period for all of the scenarios examined. The scenario that included decreasing disturbances (fire, landslides, encroachment, and harvesting) as well as decreasing the regeneration delay, resulted in the highest carbon stocks at the end of the simulation period. Conversely, the scenario that included increasing disturbance levels resulted in the lowest carbon stocks. The carbon differences among the various scenarios could be used to inform investment and policy decisions for reducing disturbance levels.

Much of the current forest harvest in Nepal is used as fuel wood, resulting in rapid release of the carbon to the atmosphere following harvest. Solid wood products can store carbon for extended periods of time following harvest. Chapter 4 was focused on exploring the impact of alternative compositions of fuel wood versus sawn wood in the HWP for three harvest levels (status quo, a 50% decrease and a 50% increase) in Terai. Fifteen scenarios were created comprised of different combinations of harvests levels and HWP mixtures. The adapted version of CBM-CFS3 was used to assess the forest carbon stocks under the three harvest levels and CBM-FHWP was used to track the carbon stored in the HWP over a simulation period from 2018 to 2030. The following specific questions were addressed:

1. What are the impacts on carbon stocks associated with increasing the proportion of sawn wood in the HWP?
2. Can shifting the commodity proportions offset the carbon loss associated with a higher harvest level?

Increasing the proportion of sawn wood relative to the fuel wood transferred more carbon to longer-lived products. Some of the decrease in the forest carbon stocks associated with higher harvest levels could be offset by increasing the proportion of sawn wood in the HWP. Specifically, the higher harvest level with at least 80% of the HWP used as sawn wood stored an equivalent amount of carbon as the status quo harvest level and HWP mixture. Approaches to achieving a shift in the HWP components and the environmental, social, and economic benefits of implementing this shift, were discussed.

5.2 Contributions

The major contribution of this research was illustrating a means of examining the effectiveness of strategies which could be implemented to increase the carbon stocks in forests and

HWP in Nepal, while maintaining or enhancing an active forest sector. The specific contributions from this dissertation were:

- Producing yield tables for the dominant tree species using published yield information from geographically similar regions and adjusting them for stand density and site quality classes. These growth and yield functions could be used for other studies (Chapter 2).
- Quantifying the most commonly occurring disturbances (i.e., encroachment, forest fires, landslides, and harvesting) for Terai and Churia and simulating their impacts on carbon stocks (Chapter 2).
- Using CBM-CFS3, a sophisticated carbon budget model based on a Tier 3 approach, to estimate forest carbon stocks in Terai and Churia. Prior estimates of carbon stocks for Nepal have been primarily estimated based using a Tier 2 approach (IPCC, 2006). My work has illustrated that forest carbon stocks in two regions of Nepal could be estimated well using modelling approaches with available forest inventory data and derived growth and yield curves. However, the allometric equations for biomass conversions and other ecological parameters for each Nepali species need to be modified for a more accurate estimation (Chapter 2 & 3).
- Producing spatially explicit forest maps for Terai for critical forests attributes such as volume (m3/ha), species composition, age (years), stand density classes (low, medium, high) and site quality classes (low, medium, high) using ground cluster plots data, Landsat imagery and other mapped information. This detailed forest inventory can be used to provide spatially explicit data at higher levels of resolution than was possible using the ground-based data alone (Chapter 3).
- Assessing the impacts of altered disturbance levels on carbon stocks and dynamics in Terai relative to the historic baseline to provide insights into which managerial or policy interventions might provide the largest impact (Chapter 3).
- Assessing the impacts of altering the HWP composition under three levels of harvest on carbon stocks and dynamics in Terai to illustrate the carbon benefits of decreasing the proportion of fuel wood in the harvest (Chapter 4).

- Adapting the ecosystem and HWP carbon models to Nepal. These can now be used for additional analyses of policy options over longer time horizons (post 2030) or expanded to all of Nepal or neighboring regions.

Together, these analyses have increased the understanding of the main drivers of forest carbon dynamics in Nepal, and the opportunities and constraints to change the forest sector GHG balance through changes in management, land use and wood product uses.

5.3 Limitations

Nepal is a developing country and lacks some of the information infrastructure often available in developed countries. Additionally, I needed to make several assumptions to apply the approaches I used. The following list describes the resultant limitations associated with the research I conducted.

- CBM-CFS3 was developed to apply to Canadian tree species, and I had to customize the model to use it in Nepal. The choices and adjustments I made were reasonable but are not likely as precise as would be the case if more comprehensive data specific to Terai and Churia were available.
- Nepal lacks growth and yield functions developed using local data. CBM-CFS3 is a yield-driven model and yield functions are required for its use. I adapted published yield curves for the major tree species from geographically similar regions. However, local yield curves would likely have been more reflective of growing conditions if they had been available.
- Yield curves were not available for all the tree species found in the study area. Stands that had dominant species for which no yield curves were available were projected using yield curves from the most common species.
- Age is an essential classifier in CBM-CFS3 that is used to estimate annual growth rates from yield curves. Since age information was not available from the inventory data available for each cluster, the yield associated with forest unit was located on the assigned yield curve to determine the age to assign to the forest unit.
- Disturbance data for forest fires, landslides, and encroachment were identified from the FRA report (FRA/DFRS, 2014a, b) and Hansen's (2013) high-resolution maps. I

could not retrieve this information from the Department of Forest Research and Survey in Nepal. It would have been informative to have compared reported disturbance amounts to those observed from remote sensing and to track the impact of disturbances on carbon stocks and changes.

- The HWP estimates were collected from FAO statistics because I could not retrieve the data from the Nepalese authorities.

5.4 Challenges to Implementation

There are challenges to implementing the alternative scenarios presented in Chapter 3. The less harvest scenario could leave higher growing stock in the forest while not meeting the demands of the population, while the more harvest scenario may not maintain the growing stock over a longer period if reforestation and regeneration are not timely or effective. Ensuring less encroachment requires solid legislation to halt the encroachment process and effective enforcement by the authorities. The best case and best case plus scenarios might not be cost-effective since they involve combinations of actions related to mitigating climate change, improving forest management, and reducing population pressure. Conducting cost-benefit analyses of the various scenarios would be a logical next step prior to implementing any major changes. However, the worst-case scenario could come about if actions are not taken, given the current situation in Terai where climate change is ongoing, and migration continues.

The possible shifts in HWP from fuel wood to sawn wood examined in Chapter 4 are difficult to attain considering the present forest management implementation plans and infrastructure, existing forest policies, and the economic situation of most of the people in Terai. I ran these commodity shifts increasing the sawn wood up to 100% to see the spectrum of change in carbon stock that could be achieved. However, in order to actually decrease fuel wood consumption, the government, local organizations, and environmental non-governmental organizations will have to play a major role in offering people affordable alternatives to wood fuel. This might not be feasible immediately but in a long run possibly. The challenge lies in finding solutions to affordably replacing fuel wood, especially in remote areas where attaining change and development is onerous. It will also be challenging to develop milling and market capacity for an increasing supply of sawn wood. It will be necessary to implement changes to the HWP mix slowly, perhaps with initial government subsidies to support sawmill development and offset alternative fuel costs, in selected locations. Ideally, this shift will prove to be economically attractive as well as beneficial environmentally and the subsidies could be phased out over time.

5.5 Recommendations for Future Work

Carbon sequestration by forests is important for climate change mitigation. Consequently, regular monitoring of forest carbon dynamics should occur on a regional or national basis to provide feedback important for assessing the effectiveness of forest management policies and activities at maintaining or enhancing forest carbon stocks. Future research in this field should prioritize the following areas.

- Document the extent of disturbances from ground observations and satellite imagery on an annual basis to better quantify the impact that the disturbances have on carbon fluxes leading to improved estimation of emissions and removals. Each disturbance type affects the forest structure and successional dynamics in a unique way, changing the amount of carbon that is stored in the vegetation and soils and released into the atmosphere. Detailed observations of drivers of change on an annual basis are essential for the reliable estimates of carbon dynamics (Kurz, 2010).
- Identify key management strategies on a regional basis that are locally relevant, and which are effective at improving carbon sequestration. The finer spatial resolution maps of Chapter 3 could be used for this purpose.
- Apply the methodology presented in this dissertation to other regions of Nepal using more complex scenarios, over longer periods, and could be assessed for better mitigation options.
- Expand the composition of HWP considered to include additional products such as panel boards and paper, if data on the quantities of these commodities produced in Nepal could be found. This would allow for a more nuanced analysis of the impact of different mixtures of HWP on carbon storage sequestration.
- Provide detailed economic analyses of the costs and benefits of different silvicultural investments, harvest levels, and HWP mixtures in Nepal to allow decision makers to make informed forest management and policy decisions.

Research and implementation of research findings should go hand in hand. The research findings of this dissertation provide insights into the impact of natural and human disturbances on forest carbon and HWP in Terai and Churia. These insights may help to maximize the benefits of forest carbon sequestration and carbon storage in addressing climate change challenges, as well as impact positively on the social and economic benefits associated with sound forest management. It is important to consider all components of the “three-legged stool” (environment, economy, and society) identified in the Brundtland (1987) report if Nepal’s forests are to be managed sustainably into the future.

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