A Modeling Analysis of Changing Global Land Use as affected by Changing Demands for Wood Products

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To my husband
and my father

Summary

The 21st century has brought new challenges for forest management at a time when globalization in world trade is increasing and global climate change is becoming increasingly apparent. In addition to various goods and services like food, feed, timber or biofuels being provided to humans, forest ecosystems are a large store of terrestrial carbon and account for a major part of the carbon exchange between the atmosphere and the land surface. Depending on the stage of the ecosystems and/or management regimes, forests can be either sinks, or sources of carbon. At the global scale, rapid economic development and a growing world population have raised much concern over the use of natural resources, especially forest resources. The challenging question is how can the *global demands* for forest commodities be satisfied in an increasingly *globalised economy, and where could they potentially be produced*? For this purpose, wood demand estimates need to be integrated in a framework, which is able to adequately handle the competition for land between major land-use options such as residential land or agricultural land.

This thesis is organised in accordance with the requirements to integrate the simulation of forest changes based on wood extraction in an existing framework for global land-use modelling called LandSHIFT. Accordingly, the following neuralgic points for research have been identified: (1) a review of existing global-scale economic forest sector models (2) simulation of global wood production under selected scenarios (3) simulation of global vegetation carbon yields and (4) the implementation of a land-use allocation procedure to simulate the impact of wood extraction on forest land-cover.

Modelling the spatial dynamics of forests on the global scale requires two important inputs: (1) simulated long-term wood demand data to determine future roundwood harvests in each country and (2) the changes in the spatial distribution of woody biomass stocks to determine how much of the resource is available to satisfy the simulated wood demands.

First, three global timber market models are reviewed and compared in order to select a suitable economic model to generate wood demand scenario data for the forest sector in LandSHIFT. The comparison indicates that the ‘Global Forest Products Model’ (GFPM) is most suitable for obtaining projections on future roundwood harvests for further study with the LandSHIFT forest sector. Accordingly, the GFPM is adapted and applied to simulate wood demands for the global forestry sector conditional on selected scenarios from the Millennium Ecosystem Assessment and the Global Environmental Outlook until 2050. Secondly, the Lund-Potsdam-Jena (LPJ) dynamic global vegetation model is utilized to simulate the change in potential vegetation carbon stocks for the forested locations in LandSHIFT. The LPJ data is used in collaboration with spatially explicit forest inventory data on aboveground biomass to allocate the demands for raw forest products and identify locations of deforestation.

Using the previous results as an input, a methodology to simulate the spatial dynamics of forests based on wood extraction is developed within the LandSHIFT framework. The land-use allocation procedure specified in the module translates the country level demands for forest products into woody biomass requirements for forest areas, and allocates these on a five arc minute grid. In a first version, the model assumes only actual climate conditions through the entire study period and does not explicitly address forest age structure. Although the module is in a very preliminary stage of development, it already captures the effects of important drivers of land-use change like cropland and urban expansion. As a first plausibility test, the module performance is tested under three forest management scenarios. The module succeeds in responding to changing inputs in an expected and consistent manner. The entire methodology is applied in an exemplary scenario analysis for India. A couple of future research priorities need to be addressed, particularly the incorporation of plantation establishments; issue of age structure dynamics; as well as the implementation of a new technology change factor in the GFPM which can allow the specification of substituting raw wood products (especially fuelwood) by other non-wood products.

Zusammenfassung

Das 21ste Jahrhundert ist geprägt durch eine zunehmende Globalisierung des Welthandels und durch die immer deutlicher werdenden Auswirkungen des Klimawandels. Daraus ergeben sich auch für das Forstmanagement neue Herausforderungen. Zusätzlich zu ihrer Funktion in der Bereitstellung von Nahrung, Futter, Biobrennstoffen usw. hat das Ökosystem Wald eine zentrale Bedeutung als Kohlenstoffspeicher und für den Austausch von Kohlendioxid zwischen Erdoberfläche und Atmosphäre. In Abhängigkeit vom Zustand des Ökosystems und seines Managements können Wälder sowohl Kohlenstoffquellen als auch -senken darstellen. Die rasante weltweite ökonomische Entwicklung sowie der dramatische Anstieg der Weltbevölkerung geben zunehmend Anlass zur Besorgnis um die nachhaltige Nutzung von natürlichen Ressourcen im Allgemeinen und der Ressource Wald/Holz im Besonderen. Eine große Herausforderung ist dabei die Frage wie der steigende Bedarf der globalen Weltwirtschaft an Forstprodukten befriedigt werden kann und wo diese Produktion stattfinden wird. Zu diesem Zweck müssen Annahmen über die künftige Holznachfrage im Wettbewerbskontext zu anderen Landnutzungen wie etwa Landwirtschaft und Urbanisierung gesehen werden.

Die Struktur dieser Arbeit orientiert sich an der Aufgabenstellung, die Simulation der Veränderung von Waldflächen durch Holzentnahme in ein bestehendes Framework zur Modellierung globaler Landnutzung (LandSHIFT) zu integrieren. Die Arbeit umfasst vier Forschungsschwerpunkte:

(1) Eine Literaturanalyse über existierende globale ökonomische Forstmodelle,
(2) Simulation der globalen Holzproduktion für ausgewählte Szenarien,
(3) Simulation des globalen „Kohlenstoffertrags“ von Wäldern,
(4) Die Implementierung eines Algorithmus zur Simulation des Einflusses der Holznutzung auf die räumliche Verteilung der Waldbedeckung.

Die Modellierung der räumlichen Dynamik der Waldfläche im globalen Maßstab erfordert zwei wichtige Komponenten:

1. Simulation von Langzeitdaten über die Holznachfrage, um auf Staatenebene Vorhersagen über den zukünftigen Holzbedarf und Holzernte machen zu können,
2. Angaben über Veränderungen der räumlichen Verteilung von Holzbiomasse, um zu bestimmen wie viel von dieser Ressource an welchem Ort zur Deckung des simulierten Bedarfs zur Verfügung steht.

Zunächst erfolgte die Auswahl eines geeigneten Models zur Erzeugung von Daten über den zukünftigen Holzbedarf in LandSHIFT. Hierzu wurden drei ökonomische Modelle die globale Holzmärkte abbilden miteinander verglichen. Auf Basis dieser Analyse wurde das ‘Global Forest Products Model’ (GFPM) zur Berechnung von Projektionen des zukünftigen Holzbedarfs für den Forstsektor in LandSHIFT ausgewählt.

Entsprechend wurde GFPM adaptiert und angewendet, um den globalen Holzbedarf für ausgewählte Szenarien aus dem „Millennium Ecosystem Assessment“ und dem „Global Enviromental Outlook 4“ bis 2050 zu simulieren.

Zweitens wurde das globale dynamische Vegetationsmodell LPJ (Lund-Potsdam-Jena Modell) dazu genutzt, um Veränderungen im Kohlenstoffvorrat von Wäldern in LandSHIFT abzubilden. Die LPJ Simulationsergebnisse wurden zusammen mit regionalisierten Waldinventurdaten zur oberirdischen Biomasse kombiniert, um den forstliche Produktion räumlich zuzuordnen und von Entwaldung betroffene Gebiete zu lokalisieren.

Weiterhin wurde eine Methode zur Simulation der räumlichen Dynamik der Forstnutzung innerhalb von LandSHIFT entwickelt, welche die oben genannten Informationen als Eingabegrößen nutzt. Der neu entwickelte Allokationsalgorithmus des Forstmoduls übersetzt zunächst den Bedarf nach Forstprodukten auf Länderebene in die benötigte Menge an Holzbiomasse und berechnet dann auf Ebene von Rasterzellen (Auflösung 5 Bogenminuten) die Holzentnahme für verschiedne Managementoptionen. Die aktuelle Implementierung betrachtet dabei weder die Alterstruktur von Wäldern noch mögliche Auswirkungen des Klimawandels auf das Waldwachstum. Obwohl sich das Modell in einem noch frühen Entwicklungsstadium befindet, erfasst es bereits wichtige Wechselwirkungen zwischen der Forstnutzung und anderen Landnutzungsaktivitäten wie etwa Landwirtschaft und Siedlungsentwicklung. In einem ersten Test wurde die Funktionsweise des neuen Moduls für drei Arten des Forstmanagements getestet. Das Modul lieferte in diesen Tests plausible auf konsistente Ergebnisse. Die neu entwickelte Methode wurde dann exemplarisch für eine Szenarienanalyse für Indien angewendet. Abschließend identifiziert die Arbeit eine Reihe zukünftiger Forschungsfragen zu dem bearbeiteten Themenkomplex. Diese umfassen (1) die Berücksichtigung von Plantagenwirtschaft, (2) die Modellierung der Alterstruktur gemanagter Wälder sowie (3) die Einbeziehung der Entwicklung neuer Technologien und der damit verbundenen Substitution von des Rohstoffs Holz (insbesondere Feuerholz) durch andere Nicht-Holz Produkte.

Contents

1 GENERAL INTRODUCTION……………………………………………………………1

CHAPTER 1

General Introduction

"Deforestation" by **Mikhail Zlatkovsky**, Russia.

1.1 Forests, Land-Use and Land-Cover Changes, Climate Change

From tropical rainforests, to pine woods, to the boreal forests of the northern latitudes, forests cover nearly one-third of Earth’s surface (FAO 2007). In addition to providing various goods and services like food, feed, freshwater, timber, biofuels etc., forest ecosystems are a large store of terrestrial carbon and account for a major part of the carbon exchange between the atmosphere and the land surface (WWF 2003, WRI 2007). They also play a major role in recycling atmospheric moisture and stabilizing soils (WWF 2003). To summarize, forests contribute considerably to sustain life on Earth.

Human activities like logging (commercial and/or for subsistence) and conversion of forestland for agriculture and other purposes have drastically altered the natural distribution of forests through history (Lambin and Geist, 2006). Numerous cases have been discerned and several examples have been described to illustrate the extensive modifications of forest landscapes already by ancient cultures like the Harappan civilization (Tripathi et al. 2004). Today, deforestation is one of the most commonly recognized forms of land-use change. Each year, approximately 13 million hectares are lost to deforestation (FAO 2005). Deforestation for wood and agricultural land can provide numerous economic benefits, but can have damaging impacts on the functional role forest ecosystems play in the earths system as described above. However, the occurrence and prevalence of these impacts can vary regionally, depending on the agro-ecological and socio-economic settings.

Land-use and land-cover change are intrinsically linked to global climate change. On the one hand, changes in global climate are already stressing forests through higher mean annual temperatures, altered precipitation patterns and more frequent and extreme weather events (MA 2005). At the same time, the wood produced in the forests trap and store carbon dioxide, thus playing a major role in mitigating climate change. And conversely, when destroyed or over-harvested and burned, forests can become sources of greenhouse gases, mainly carbon dioxide. At the global level, biomass burning has been shown to be a major source of greenhouse gases, contributing approximately 20% to the global budget of major gases such as carbon dioxide; and studies have identified it as almost the sole source of greenhouse gases in tropical countries (WRI 2008).

Based on the discussion above, it is clear that human causes of land-use change can have multiple and multi-directional impacts in the natural environment system. An analysis of time series of remote sensing data obtained from satellite sensors have revealed that there are short-term land-cover changes (often caused by the interaction of climatic and land-use factors) which show periods of rapid and abrupt change followed by either a quick recovery or by a non-equilibrium trajectory (Taylor et al, 2002b; Stolle and Lambin 2003). As a result of these interactive effects between land-use and climate, the role of forests as a carbon source or sink can vary from time to time. Highly variable ecosystem conditions driven by fluctuating climate conditions tend to amplify the pressures upon forest ecosystem condition and services (Geist and Lambin, 2004). Finally, these effects could lead to an increase in human vulnerability to environmental change, thereby affecting human welfare.

Understanding the significance of land-cover changes is not possible without additional information on land-use. This is because most land-cover change is nowadays driven by human use and because land-use practices themselves also have major effects on environmental processes and systems (Lambin et al. 2001). As elucidated above, it is clear that land-use/cover change dynamics are highly complex and encompass interrelated determining factors (biophysical, economic, social, cultural, political and/or institutional). Recently, the Millennium Ecosystem Assessment (MA) and the Global Environmental Outlook (GEO4), two international programs to assess the status and long-term trends in global ecosystem change, have recognized the importance of land-use and land-cover change (MA 2005, UNEP 2007). They underline not only the enormous value of the Earth’s ecosystems and the goods and services they provide, but also underscore the central role the environment has for development and human well-being. Most importantly, they emphasize the need for integrated assessment tools in order to adequately strengthen land-use/cover modeling and assessment at the global scale. The next section provides an overview of the importance of global land-change modeling and highlights some of the complexities associated with modeling forest land-cover changes at the global scale.

1.2 Forests and Global Land-Use Modeling

Over the last few decades, numerous research groups have made substantial efforts in improving the understanding and measurement of land-cover changes, in part under the auspices of the Land-Use and Cover Change (LUCC) project of the International Geosphere-Biosphere Programme (IGBP) and the International Human Dimensions Programme on Global Environmental Change (IHDP) (Lambin and Geist, 2006). Recent publications indicate that a wide range of land-use/cover change models, aiming at different scales and research questions, are now available (Veldkamp and Lambin 2001; Parker et al. 2003; Nagendra et al. 2004; Veldkamp and Verburg 2004; Verburg at al. 2004b; Verburg and Veldkamp 2005, Heistermann et al. 2006; Schaldach et al. 2009). As is illustrated by the many publications, land-use/cover change modeling has made an important contribution to land-use/cover change science in general, and will most likely continue to do so in the future.

Apart from being a learning tool in understanding the driving factors and comprehending the system dynamics, the existing land-use change models also play an important role in exploring possible future land-use dynamics. However, only a few focus on continental and/or global scale assessments (Heistermann et al., 2006). It is urgently needed that more innovative approaches for modeling land-cover change at the global scale are designed, tested and validated to better equip the many environmental and social assessments at the global scale. Global scale modeling is important for several reasons, a few of them being: (1) Land-cover change impacts are scale-dependent in that some affect the local environment (e.g. local soil degradation), while other impacts extend far beyond their origin (e.g. global carbon cycle, global climate change) (Mustard et al. 2004). (2) Specific policies and processes interlink locations and regions all over the globe: e.g., changes in international trade policies tend to shift land requirements from one world region to another (Heistermann et al., 2006).

Most current models of global land-use/cover change follow a trajectory path, starting from individual decisions taken at the micro level (local) and accounting for feedbacks to and from macro level (countries, regions, etc.) (Lambin and Geist 2006). This is because global land-use change models are often based on input datasets at the macro level, while, at the same time, the models try to simulate macro level developments by specifying mechanisms at the micro level. Examples of such models are the CLUE model (Verburg et al. 1999; Verburg and Veldkamp 2005), GEOMOD (Pontius et al. 2001), LOV (White and Engelen 2000) and LTM (Pijanowski et al. 2002a). Explicit attention needs to be given to the incorporation of interactions between agents and feedbacks in the decision-making process. Abstraction of local land-use decisions to explain regional or global processes is a major challenge for global scale land-use modeling (Geist and Lambin, 2004; Lambin and Geist, 2003).

In addition to the above-mentioned general aspects of global land-use modeling, the inclusion of spatial forestland dynamics in a global land-use model requires specific data: to begin with, simulated long-term wood demand data. Therefore, the field of long-term wood production* modeling is introduced in Section 1.3. To model the spatial dynamics of forestland, the spatial distribution of the woody biomass productivity has to be known. Biomass productivity models are an adequate tool to reflect the spatial distribution and management of stocks as well as their changes as a result of changing climate. Currently, this information in LandSHIFT is based on simulations conducted with the Lund-Potsdam-Jena Dynamic Global Vegetation Model (LPJ-DGVM; Sitch et al., 2003; Bondeau et al., 2007). Details on application and testing of the LPJ-DGVM are provided in Chapter 4. In addition, timber harvests notably depend on age structure and rotation periods, since timber can be harvested for merchandise purposes only when it reaches a certain maturity age. These data vary significantly not only between regions but also between different tree species within a particular region. The differences can be attributed to the specific ecosystems in which the trees grow and to the management strategies opted by landowners. Hence, Section 1.4 addresses the significance and particularities of forest management.

In economic forest sector models, demand is estimated in terms of wood 'production' which refers to the harvesting of raw wood from forests to be utilized in the manufacturing of wood products.

1.3 Modeling Long-Term Global Wood Production

Forests supply the raw materials for lumber, plywood, paper, packaging and other wood-based materials that are staples of modern life. Forest products trade runs the spectrum from raw wood materials, such as logs and wood chips, to highly processed products such as furniture and fine papers. Within the wood products sector, some countries specialize in the production of raw wood; others specialize in various facets of processing, while still others produce both raw wood and processed goods.

It is widely recognized that climate change will have substantial impacts upon global forest ecosystems during this century (McCarthy et al., 2001). In addition to many existing stresses, such as deforestation, pest infestations, forest fires, and invasive species, climate change is expected to increase stresses upon forested ecosystems. These stresses include potential changes in the distribution of species (Iverson and Prasad, 2001), as well as positive or negative changes in the productivity of individual species and entire ecosystems (Shugart et al., 2003). The ecological impacts of climate change could have substantial impacts on the global structure and functioning of timber markets.

How will the global wood products markets develop in the long run? This vital question underlies not only strategic decisions made by forest growers, and wood and fiber processors; but also valuable information used by institutions and researchers involved in integrated modeling and assessment of environmental issues in general. Economic forest sector models aim at providing an insight into country and/or regional forecasts of forest resources as well as the consumption, production, trade and prices of wood products.

Current global timber harvests are approximately 1.6 billion m^3 of industrial roundwood per year (FAO 2008). An assessment of timber market studies suggests that this could rise to 1.9 – 3.1 billion m^3 by 2050, depending on timber demand growth and relative price changes (Solberg et al. 1996). An alternative set of scenarios based on the global timber market model described in Sohngen et al. (1999) suggests similar results. These changes would represent an increase in annual timber harvests of 0.5% to nearly 2.0% by 2050.

In this study, the ‘Global Forest Products Model’ (GFPM), a dynamic spatial-equilibrium representation of the forest sector (Buongiorno et al., 2003), is utilized to produce information on potential production (harvest) of raw forest product commodities (industrial roundwood, fuelwood) in the future under the storylines of the Millennium Ecosystem Assessment (MA 2005) and Global Environmental Outlook-4 (UNEP 2007) scenarios. GFPM results are used to determine how much wood would be harvested in each country to meet global timber demands. These estimates are used as input in the ‘Forest’ module of the LandSHIFT model (See Section 1.6 for introduction to LandSHIFT and Chapter 5 for implementation details).

1.4 Global Forest Management

Forest ecosystems are expected to undergo dramatic changes in response to projected pressures from timber demands, land-use change resulting from factors like urbanization and expansion of croplands and pastures, and global climate change in the coming decades. Many countries have demonstrated the political will to improve the manner in which forests are currently being managed i.e., by revising forest policies and strengthening forest institutions (FAO 2007). The Seventh Biennial Issue of *State of the World’s Forests* of the global forestry sector (FAO 2007) has evaluated significant progress in sustainable forest management in regions including developed countries and having temperate climates; however, other regions - especially developing economies and those having tropical climate, continue to lose forest area. But, even in these regions that are losing forest area, a number of positive trends have been noted (FAO 2007).

In light of the above, it can be argued that the incorporation of forest mangement practices forms a significant part of land-use-land-cover change research in order to ensure that environmental and social issues are adequately evaluated. As mentioned in Section 1.1, land-use changes are the result of complex interactions between humans and biophysical driving forces (Verburg at al., 2006). Sustainable forest management activities imply various degrees of deliberate human intervention, ranging from actions aimed at safeguarding and maintaining the forest ecosystem and its functions (for example by establishing conservation areas), to favouring specific socially or economically valuable species or groups of species for the improved production of goods and services (for example by establishing plantations). The underlying determinants of this form of human interventional behavior include, but are not limited to: supply issues such as the environmental pressures to reduce timber harvesting and particularly, clear-cutting; timber management, including plantation establishment; recycling; substitution of raw timber with other non-timber products; technological change; etc. This study makes an attempt to address forest management issues by incorporating a few of the above-mentioned factors in the form of assumptions going into the timber market model GFPM (See Chapter 3).

1.5 Global Land-Use/Land-Cover Change

Land-use and land-cover change play a pivotal role in global environmental change. Changes in land-cover through human induced activities like cropping, grazing, forestry and urbanization represent the most substantial alteration through their interaction with most components of global environmental change (Ojima et al., 1994). They contribute significantly to earth-atmosphere interactions and biodiversity loss, are a major factor in sustainable development and human responses to global change, and are important to integrated modeling and assessment of environmental issues in general. Research that examines historic, current, and future land-use and land-cover change, its drivers, feedbacks to climate, and its environmental, social, economic consequences is therefore of great importance for understanding climate change (Lambin and Geist, 2006).

At the global scale, rapid economic development and a growing world population have raised much concern over the use of natural resources, especially forest resources. The challenging question is how can the *global demands* for forest commodities be satisfied in an increasingly *globalized economy, and where could they potentially be produced*? Land-use and land-cover change studies can provide valuable information for large-scale vegetation biomass and forest cover assessments that are key components of the carbon cycle. Future land-use and land-cover change goals include (1) understanding regional/global land-use changes that affect forest biomass, and (2) quantifying linkages and feedbacks between land-use and land-cover change, climate change forcings, climate change, and other related human and environmental components.

In a first version, this study aims to model the long-term land-use and land-cover changes (from 2000 to 2050) in India and to provide quantitative analysis of LUCC information in the region using the LandSHIFT modeling framework (See Section 1.6).

1.6 The LandSHIFT Modeling Framework

LandSHIFT[1] is an integrated model system currently under development at the Center for Environmental Systems Research (CESR) at the University of Kassel, Germany, that aims at simulating and analyzing spatially explicit land-use dynamics and their impacts on the environment on a global scale (Alcamo and Schaldach, 2006; Schaldach at al, 2006). It has been designed for studying changing land-use and land-cover on the global scale and its relationship to other global change processes like climate change, water cycle, biodiversity risk, etc. It is capable of carrying out a wide range of tasks including (1) identification of continental scale competition for land (2) identification of future potential “hot spots” of land-use change (3) comparison of future rates of change in different countries/regions. The framework aims at providing a tool to modelers, researchers, policy makers and agencies involved in land-use/change cover studies for medium-term analysis (20 – 50 years) of land-cover change and the resulting environmental impacts under varying scenarios. Some applications including subsets of LandSHIFT include an analysis of land-use changes in Africa until 2050 (Schaldach at al, 2006) and the development of scenarios of livestock grazing in the Middle East (Koch at al., 2008).

The guiding principle of LandSHIFT is to integrate drivers of land-use change at macro (country) level and grid variables at the micro level (5“- grid) in order to simulate changes in the spatial distribution of land-use on a global five arc minute grid. At the macro level, the driving forces describe the socio-economic and agricultural development of a country, while the grid variables (micro-level) describe the local landscape characteristics and zoning regulations (e.g. the extent of conservation areas).

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[1] **Land** **s**imulation to **h**armonize and **i**ntegrate **f**reshwater availability and the **t**errestrial environment

The central component of LandSHIFT is the LUC (Land Use Change) module, which computes changing land-use using a modified cellular automata approach (Schaldach et al., 2009). The classification of the land-use/land-cover types follows the IGBP classification (Loveland et al., 2000) which comprises arable land, urban land, grassland and a set of "natural" land cover types such as forests, shrub lands and deserts. This classification is combined with additional information on pasture and a set of major crop types (irrigated and rain-fed), based on the global map by Heistermann (2006). The major drivers of change are demand and supply side factors like demand for timber for the forest sector, food demand for agricultural sector and, supply defined by local biomass productivity. The principal goal of the module is to translate regional/national production trends for land intensive commodities (such as roundwood, field crops, etc.,) into area requirements for land-use types, and to allocate these on a grid of five arc minute resolution. The production is allocated to the most suitable cells (based on *Preference Ranking*) by changing the land-use type of as many cells as needed to fulfill the country's demand. The *Preference Ranking* of each grid cell of a particular land-use type (e.g. forest) is computed with the Multi-Criteria-Analysis (MCA) method (Eastman at al., 1995; Cromley at al; 1999). The main model output is a time series of raster maps of the changing land-use pattern of the study area in 5-year time steps. Moreover, the model generates a set of subsidiary land-related variables (like rates of deforestation), thus documenting the land-use change processes in an aggregated form.

An important feature of the LandSHIFT model is that it comprises a highly modularized structure, which permits the integration of functional model components representing different aspects of the global land-use system. While on one hand, the model supports the integrated analysis of drivers of land-use change on different scale levels, it implements a strictly modular and transparent structure which clearly distinguishes the different land-use activities such as logging, settlement and grazing. This enables the incorporation of specific knowledge on the spatial dynamics guiding the land-use processes for each individual sector. The following section presents the objectives and tasks that are oriented alongside the requirements to simulate forest dynamics in the LandSHIFT model.

1.7 Objectives, methodologies and structure of this thesis

The previous sections highlighted the following scientific issues: the significance of forests from the perspective of Land-Use and Land-Cover Change; the specific need to consider long-term simulated wood demand for such an analysis; the required input data to enable such an analysis in terms of forest management and the simulation of biomass productivity; and the need to analyze changes in the magnitude and extent of deforestation in the context of global land-use models. The guiding principle of this thesis is to integrate over these requirements by developing and providing spatial data and methodologies which are needed to simulate large-scale changes in forest areas.

This work is the first version of the incorporation and implementation of forest sector dynamics in the LandSHIFT modeling framework. The thesis does not address all the above-discussed issues. It also does not address the issues presented in this thesis in their entire complexity, but rather aims at selected interfaces relevant for this study. The data and methodologies presented here are intended to remain efficacious for themselves, but are also designed to meet the intended implementation requirements of the ‘Forest’ module in the LandSHIFT model. Accordingly, the following objectives and tasks have been identified:

a) Reviewing available global scale economic forest sector models

Over the years, many different timber market models have been developed to analyze changes in potential future demand and supply of timber products with regards to market behavior, policy changes, and other important factors like demographic trends. Not only do the models differ in theory and structure, but their outputs differ as well. The models also vary in their capacity to provide users with the flexibility and ease of scenario implementation. The main objective of this part of the thesis is to compare model theory and structure of available global scale economic forest sector models. This is done in order to select a model that is appropriately flexible to incorporate information on major economic drivers under several plausible scenarios and, that can assist in generating wood production datasets on country scale for implementation in LandSHIFT.

b) Simulating global wood production

Based on the task described above, the ‘Global Forest Products Model’ (GFPM) is selected for further study with LandSHIFT. In the specific context of this thesis, the adaptation and application of the GFPM mainly serves to provide global wood production data for major raw wood products at country level to the global modelling framework LandSHIFT. The model output enables LandSHIFT to capture the impacts of wood extraction activities on land-cover change in forest areas.

c) Modeling of spatial dynamics in forests

The final objective of this thesis goes into the research needs being expressed in Section 1.5: this is the development and implementation of an approach to simulate the large scale spatial distribution of forest areas based on wood extraction. This part of the study describes the implementation, plausibility analysis and testing of the first version of a new land-use activity called ‘FOREST’ in LandSHIFT. The main objective of this module is to quantify deforestation as result of wood extraction. The inclusion of this module in LandSHIFT adds to an increased understanding of land-use/cover changes since deforestation for timber and fuelwood might play a substantial role in altering the magnitude and spatial distribution of forest cover. It also allows for a more detailed analysis of the temporal development of land-use pattern and thus opens new directions for environmental impact assessments. In this study, the LandSHIFT model has been expanded by two new components to simulate the spatial and temporal dynamics of forest management: (1) a module to calculate cell level biomass productivity of forests (2) a forest management activity (FOREST) as new part of the land-use change (LUC) module. The general methodology is based on the implementation of the cropland/urban modules of LandSHIFT as presented in Schaldach et al. [2006]. This implies the application of Multi-Criteria-Analysis in order to assess the suitability of land to locate suitable cells for forest management (Section 4.2.3.2). The methodology also investigates the effects of varying forest management scenarios on the spatial distribution of forest patterns (Section 4.3.2). As a starting point, spatially explicit forest inventory data on aboveground biomass from Kindermann et al (2008) is used to represent the initial condition of biomass stocks in each forest grid cell. In order to make long-term assessments of biomass available for wood extraction, the study attempts to make the data available from Kindermann et al (2008) dynamic. In a first approach, this data is integrated with data on change in vegetation carbon stocks in future time periods from LPJ-DGVM in order to calculate the annual change in forest stocks in the future (Sections 4.2 and 4.6). The entire methodology is applied in an exemplary scenario analysis for India. The study attempts to integrate and expand the capabilities of LandSHIFT with scenario data from the global forest economy model GFPM and the global vegetation model LPJ-DGVM.

According to the objectives and the methodological requirements presented above, the core chapters of the thesis are structured in three parts.

Part I of this thesis (Chapters 2 and 3) describes the basis of the selection and adaptation of the Global Forest Products Model (GFPM) and offers an evaluation of the simulation results. Chapter 2 reviews the current state-of-the-art in global scale economic forest sector modeling. Major deficits and potentials of existing global scale timber market models are identified by contrasting only those aspects that are relevant for implementation in this study. Chapter 3 documents the set-up and the application of the GFPM to simulate potential production of raw forest product commodities (industrial roundwood, fuelwood) in the future under several plausible scenarios. It also provides a comparison of the simulation results from the GFPM against existing wood demand scenarios.

Part II (Chapter 4) presents the model description, plausibility testing and simulation for a first version of the FOREST module in LandSHIFT. The chapter also offers a detailed description of the implementation and testing of the dynamic global vegetation model LPJ that is utilized to simulate the productivity patterns of potential vegetation carbon for use in LandSHIFT.

Part III (Chapter 5) summarizes and discusses the main conclusions resulting from Chapters 2-4 and identifies priorities for future research.

1.8 References

Alcamo, J., and R. Schaldach, 2006. LandShift: Global Modeling to Assess Land Use Change, in: Tochtermann (2006). EnviroInfo 2006. Managing Environmental Knowledge. Proceedings of the 20th International Conference “Informatics for Environmental Protection. 223-230.

Bondeau, A., Smith, P.C., Zaehle, S., Schaphoff, S., Lucht, W. et al., 2007. Modelling the role of agriculture for the 20th century global terrestrial carbon balance. Global Change Biology 13, 679-706.

Buongiorno, J., S. Zhu, D. Zhang, J.A. Turner, and J. Tomberlin. 2003. The Global Forest Products Model: Structure, Estimation and Applications. San Diego, CA: Academic Press.

Cromley, R.G., Hanink, D.M., 1999. Coupling land use allocation models with raster GIS. Journal of Geographical Systems 1, 137-153

Eastman, J. R., J. Weigen, P. Kyem, and J. Toledano, 1995. Raster Procedures for Multiobjective Land-Use Planning, Photogrammetric Engineering and Remote Sensing, 61, 539-547.

FAOStat: FAO 2008. Food and Agriculture Organization, United Nations, Rome

FAO (Food and Agriculture Organization of the United Nations). 2007. Seventh Biennial Issue of the State of the World's Forests.

FAO (Food and Agriculture Organization of the United Nations). FRA 2005. Global Forest Resources Assessment.

Geist, H.J. & Lambin, E.F., 2004. Dynamic causal patterns of desertification. BioScience, 54(9), 817-29.

Heistermann, M., Müller, C. Ronneberger, K., 2006. Land in Sight? Achievements, Deficits and Potentials of Continental to Global Scale Land Use Modeling. Agriculture Ecosystems and Environment 114, 141-158.

Iverson, L. R. and A. M. Prasad. 2001. Potential changes in tree species richness and forest community types following climate change. Ecosystems 3:200-215.

Kindermann , G.E. , McCallum , I. , Fritz , S. and Obersteiner , M., 2008. A global forest growing stock, biomass and carbon map based on FAO statistics. Silva Fennica, 42**,** 387 – 396 .

Koch, J., Schaldach, R., Köchy, M., 2008. Modeling the impacts of grazing land management on land-use change for the Jordan River region. Global and Planetary Change 64, 177-187.

Lambin, E.F. and Geist, H. (eds), 2006. Land-use and land-cover change: local processes and global impacts. Springer: Berlin, Heidelberg, GE, 204 pp.

Lambin, E. F., and H. J. Geist, 2003. Regional differences in tropical deforestation, Environment, *45*(6), 2-36.

Lambin E.F., Turner II B.L., Geist H., Agbola S., Angelsen A., Bruce J.W., Coomes O., Dirzo R., Fischer G., Folke C., George P.S., Homewood K., Imbernon J., Leemans R., Li X., Moran E.F. Mortimore M., Ramakrishnan P.S., Richards J.F., Skånes H., Steffen W., Stone G.D., Svedin U., Veldkamp A., Vogel C., Xu J., 2001. The Causes of Land-Use and –Cover Change: Moving beyond the Myths. Global Environmental Change. Vol. 11, pp.261-269.

Loveland, T.R., Reed, B.C., Brown, J.F., Ohlen, D.O., Zhu, J, Yang, L., and Merchant, J.W., 2000. Development of a Global Land Cover Characteristics Database and IGBP DISCover from 1-km AVHRR Data: International Journal of Remote Sensing 21(6/7), 1303-1330.

McCarthy J.J., Canziani O.F., Leary N.A., Dokken D.J. and White K.S., 2001. Climate Change 2001: Impacts, Adaptation and Vulnerability. Contribution of WG2 to the third assessment report of the Intergovernmental Panel on Climate Change (IPCC). Cambridge University Press, Cambridge New York

MA (Millennium Ecosystem Assessment) 2005. Ecosystems and Human well-being: Synthesis. Island Press, Washington D.C., 137 pp.

Mustard, J. & T. Fisher, 2004. Land Use and Hydrology. In Gutman, G., Janetos, A., Justice, C., Moran, E., Mustard, J., Rindfuss, R., Skole, D., Turner, B.L. & Cochrane, M (Eds.), Land Change Science: Observing Monitoring and Understanding Trajectories of Change on the Earth's Surface (pp. 257-276)., Kluwer Academic Publishers, Dordrecht, The Netherlands.

Nagendra, H., D. Munroe, and J. Southworth., 2004. From pattern to process: landscape fragmentation and the analysis of land use/land cover change. Agriculture, Ecosystems and Environment 101 (2–3):111–115

Ojima D. S., Galván N. and Turner B. L. II., 1994. The Global Impact of Land-use Change. Bioscience, Vol. 44, No. 5, pp. 300-304.

Parker, D.C., Manson, S.M., Janssen, M.A., Hoffmann, M.J., Deadman, P., 2003. Multi-agent Systems for the Simulation of Land-use and Land-cover Change: A Review, Annals of the Association of American Geographers 93(2), 314-337.

Pijanowski, B. C., D. G. Brown, G. Manik, and B. Shellito, 2002. Using neural nets and GIS to forecast land use changes: A Land Transfor-mation Model. Computers, Environment and Urban Systems 6.

Pontius Jr, R G, J Cornell and C Hall. 2001. Modeling the spatial pattern of land-use change with Geomod2: application and validation for Costa Rica. Agriculture, Ecosystems & Environment 85(1-3) p.191-203.

Schaldach, R., Alcamo, J., Koch, J., Kölking, C., Lapola, D., Priess, J., 2009. LandSHIFT: Modeling land use change on the continental and global scale Part I. Model development. Environmental Modelling and Software (submitted).

Schaldach, R., J. Alcamo, and M. Heistermann, 2006. The multiple-scale land use change model LandShift: a scenario analysis of land use change and environmental consequences in Africa, in A. Voinov, et al. (Eds.): *Proceedings of the iEMSs Third Biennial Meeting: "Summit on Environmental Modelling and Software"*, International Environmental Modelling and Software Society, Burlington, USA.

Shugart H., R. Sedjo and B. Sohngen, 2003. "Forests and Global Change: Potential Impacts on U.S. Forest Resources" Prepared for the Pew Center for Climate Change. February 2003, pp. 52.

Sitch, S., Smith, B., Prentice, I.C. et al., 2003. Evaluation of ecosystem dynamics, plant geography and terrestrial carbon cycling in the LPJ dynamic global vegetation model. Global Change Biology 9, 161-185.

Sohngen, B., R. Mendelsohn, R. Sedjo, 1999. "Forest Management, Conservation, and Global Timber Markets**".** American Journal of Agricultural Economics. 81(1): 1-13

Solberg, B, D. Brooks, H. Pajuoja, T.J. Peck, P. A. Wardle, 1996, *Long-Term Trends and Prospects in World Supply and Demand for Wood and Implications for Sustainable Forest Management.* Research Report 6. European Forest Institute (EFI): Joensuu, Finland.

Stolle F. and Lambin E.F., 2003. Inter-provincial and inter-annnual differences in the causes of forest fires in Sumatra, Indonesia. Environmental Conservation, vol. 30, no. 4, pp. 357-387.

Taylor C., E.F. Lambin, N. Stephenne, R. Harding and R. Essery, 2002b. The influence of land-use change on climate in the Sahel. Journal of Climate, vol. 15, nr. 24, pp. 3615-3629.

Tripathi, J. K.; Bock, Barbara; Rajamani, V.; Eisenhauer, A., 2004. "Is River Ghaggar, Saraswati? Geochemical constraints". Current Science 87 (8): 1141–1145.

United Nations Environment Programme (UNEP), 2007. Global Environment Outlook GEO4: environment for development. UN-UNEP, Valletta, Malta, 572 p.

Veldkamp, A., and P. H. Verburg, 2004 "Modelling land use change and environmental impact: Introduction to the special issue." Journal of Environmental Management. 72(1-2): 1-3.

Veldkamp A. and Lambin E.F., 2001. Predicting land-use change. Editorial. Agriculture, Ecosystems & Environment, vol. 85, nr.1-3, pp.1-6.

Verburg, P. H., K. Kok, G. Pontius, and A. Veldkamp, 2006. Modeling Land-Use and Land-Cover Change, in E. F. Lambin and H. Geist (Eds.): Land-Use and Land-Cover Change: Local Processes and Global Impacts, 117-136, Springer, Berlin, Heidelberg, New York.

Verburg, P. H., and A. Veldkamp, 2005. "Spatial Modeling to explore land use dynamics." International Journal of Geographical Information Science. 19(2): 99-102.

Verburg, P.H., Schota, P., Dijsta, M., Veldkamp, A., 2004b. Land use change modelling: current practice and research priorities GeoJournal 61, 309-324.

Verburg PH, Veldkamp A, de Koning GHJ, Kok K, Bouma J., 1999. A spatial explicit allocation procedure for modelling the pattern of land use change based upon actual land use. Ecological Modelling 116**:** 45-61.

White, R., and G. Engelen, 2000. High-resolution integrated modeling of spatial dynamics of urban and regional systems. Computers, Environment, and Urban Systems 24: 383–400.

World Resources Institute (WRI). www.wri.org

World Wildlife Fund (WWF). www.worldwildlife.org

CHAPTER 2

A Review of Global Scale Economic Forest Sector Models

Summary

This chapter compares and contrasts three global timber market models. The models have been applied to predict harvests, price, inventory and market welfare impacts under different exogenous forces that impact timber markets. The goal of this assessment is to select a suitable economic model to produce information on potential production of raw forest product commodities in the future under several plausible scenarios for the forest sector in LandSHIFT. The framework and theory for each model type relevant to this study is presented and discussed. The comparison indicates that the ‘Global Forest Products Model’ is most suitable for obtaining projections on future raw wood harvests for further study with the LandSHIFT forest sector.

Keywords: timber markets; forest sector models; scenario implementation; flexibility

2.1 Introduction

Globally, the forest sector has to deal with increasing demand for forest products, with dynamic globalization in world trade of wood products, and with conversion of forests to other land-uses like agriculture or grassland (Achard et al., 2004, Lambin and Geist, 2006, Rudel et al, 2004). Furthermore, technological advancements in forest management, change in local and/or regional forest policies (e.g. for forest protection), global environment management and trade decisions made in the political arena like establishment of new plantations, have their respective consequences on the enhancement or degradation of the forest regime (Sedjo et al, 2006). In addition, forest ecosystems are a large store of terrestrial carbon and account for a major part of the carbon exchange between the atmosphere and the land surface (Lambin and Geist, 2006). All these factors have raised much concern over the future of forest resources. Moreover, any change in one or a combination of the above stated factors would, directly or indirectly, influence future production (supply) of raw wood products (industrial roundwood, fuelwood). This in turn, will affect any land-use allocation and competition for land between forest and other land-use types (Verburg et al, 1999).

As described in Chapter 1 (Section 1.6), LandSHIFT is an integrated model system that aims at simulating and analyzing spatially explicit land-use dynamics and their impacts on the environment on a global scale (Alcamo and Schaldach, 2006). It has been designed for studying changing land-use and land-cover on the global scale and its relationship to other global change processes. A preliminary application of the model deals with scenario analysis of land-use changes in Africa until 2050, conducted as part of the United Nations Environmental Programme Global Environmental Outlook (UNEP 2007) assessment (Schaldach et al, 2006). The central component of LandSHIFT is the LUC (Land Use Change) module, which computes changing land-use using a modified cellular automata approach (Alcamo and Schaldach, 2006). The major drivers of the model are demand and supply side factors like food demand for agricultural sector, etc. The principal goal of the model is to translate regional/national production trends for land intensive commodities (such as settlements, field crops, rangelands, etc.,) into area requirements for land-use types, and to allocate these on a grid of five arc minutes resolution. Section 1.7 in Chapter 1 mentioned that the main objective of this study is to incorporate and implement forest sector dynamics based on wood extraction in the LandSHIFT modelling framework. This chapter describes the first step to contribute to such an integrated assessment; that is to select a suitable economic model to produce information on potential production of raw forest product commodities (industrial roundwood, fuelwood) in the future under the Millennium Ecosystem Assessment (MA 2005) and Global Environmental Outlook (GEO4) scenarios for the forest sector in LandSHIFT.

Over the last few decades, several timber market models have been developed to analyze changes in potential future demand and supply of timber products with regards to market behavior, policy changes, and other important factors like demographic trends. The models are quite distinct in the economic theories that they are built upon, as well as in the scope of their analysis. For the purpose of this study, three economic models are reviewed. These are (1) The CINTRAFOR Global Trade Model (CGTM; Cardellichio et al., 1989) (2) The Global Forest Products Model (GFPM; Buongiorno et al., 2003) and (3) The Timber Supply Model (TSM96; Sedjo and Lyon, 1996). The models differ in theory and structure, ranging from spatial equilibrium models to dynamic optimization models. Given these differences, this chapter compares the above-mentioned models to provide insight in selecting a model that is appropriately flexible to incorporate information on major economic drivers like GDP, trade and technology under the MA and GEO4 scenarios and, that can enable in generating wood production datasets on country scale (since LandSHIFT works on country scale).

Section 2.2 briefly describes the three global scale timber market models mentioned above. Section 2.3 characterizes the major model distinctions in terms of regional classification, incorporation of market behavior, implementation of trade flows, assessment of technology change, and flexibility in scenario implementation. Section 2.4 discusses the major deficits and potentials of each model. The chapter finally concludes with the presentation of the model selected for further study with LandSHIFT.

2.2 Three Timber Market Models

The three timber models reviewed in this chapter are (1) The CINTRAFOR Global Trade Model (2) The Global Forest Products Model and (3) The Timber Supply Model (TSM96). The CGTM and the GFPM are spatial partial equilibrium models that consider in about the same detail the supply and the demand sides of the forestry sector. Their main characteristic is the endogenous determination of demand, supply, bilateral trade flows, and prices, conditional on exogenous economic activity outside the forest sector. The TSM96 is a timber supply model, which mainly concentrates on the issue of global timber supply. Its main characteristic is to study the transition of the world's timber supply from natural forests to plantations.

2.2.1 CINTRAFOR Global Trade Model

The CINTRAFOR Global Trade Model (CGTM) is a spatial partial-equilibrium model designed to assess the global trade of forest products (Cardellichio et al., 1989). It provides a broad coverage of forest products and markets and their many interlinkages. The CGTM has been applied to a wide variety of forest sector issues, including, the economic impacts of climatic change on the global forest sector (Perez-Garcia et al., 1997, 2002a, 2002b), the impacts of U.S. carbon mitigation strategies on U.S. and global carbon accounts (Perez-Garcia 1995), and the impacts of timber supply shortages on land-use allocation (Perez-Garcia 1995). This brief summary of work with the CGTM illustrates the flexibility of the model to provide input into a variety of assessment processes involving the global forest sector.

The CGTM is an integrated model since it describes all aspects of forest products production: forest growth, wood supply, processing capacity and final demand. The CGTM projects production, consumption, prices and trade for 10 forest products in 43 log-producing regions and 33 product-consuming regions. Products considered in the model range from wood pulp to hardwood and softwood sawlogs. Log markets defined for important timber producing regions include Chile, New Zealand, the US Pacific Northwest, other US regions, Coastal British Columbia (BC), Interior BC, Eastern Canadian provinces as a region, European regions, the former Soviet Union and others.

The supply and demand regions are linked by over 400 trade flows. Dynamic elements in the CGTM include interperiod changes in forest inventory, and changes in production capacity. The CGTM summarizes changes in the forest sector using regional economic welfare measures. A detailed description of the CGTM is presented in Cardellichio et al. (1989).

2.2.2 Global Forest Products Model

The Global Forest Products Model (GFPM) is a dynamic spatial partial-equilibrium model of the forest sector to predict production, consumption, trade, and prices of major forest products at the global level. The forest sector includes timber production and harvesting, manufacturing in various industries, and transportation of products from forest to industries and to markets. The model describes how world forests and their industries interact through international trade. It was developed as part of Food and Agriculture Organization's (FAO) on-going work on forestry sector outlook studies. The GFPM has been previously applied for several studies like ‘Effects of Asian Economic Crisis’ (Buongiorno et al., 2003), ‘Effects of Tariff Liberalization’ (Zhu et al., 2001), ‘Impact of US Paper Recycling Policies’ (Zhu at al., 2002) etc.

The GFPM uses historical information and exogenous assumptions in a market equilibrium model to produce forecasts of global forest products market developments. The model is calibrated using 2006 as its base year and allows for the projection of consumption, production, capacity, prices and trade in forest products for 180 countries and territories and 14 different forest products categories. Base year production, consumption, trade and prices by country and commodity are from ForesSTAT-FAO (2006). The model provides a flexible mechanism that enables users to obtain the above-mentioned forecasts on country scale in yearly (or at desired interval) time steps under various plausible scenarios.

The general principle of the GFPM is that global markets optimize the allocation of resources in the short run (within one year). Resource allocation in the long run is partly governed by market forces, as in trade, and also by political forces such as the wood supply shifts determined by forest policy, the wastepaper recovery rates influenced by environmental policy, the trade tariffs that change the cost of imports, and the techniques of production determined by exogenous technological progress. A detailed description of the GFPM can be found in Buongiorno et al. (2003).

2.2.3 Timber Supply Model

The Timber Supply Model (TSM96) is a dynamic timber market model, which uses an economic market supply/demand approach to project an intertemporal time path of the world's price and output level of industrial wood. The TSM96 maximizes the sum of consumer and producer surpluses over the entire projection horizon. This approach is based on rational expectations theory, which basically assumes that the expectations made by economic agents on an average are not systematically biased and, that the agents use all relevant information in forming expectations of economic variables, thus correctly anticipating future conditions. It is because the TSM96 rests on the above mentioned theory that it is often referred to as an optimal control model.

The main purpose of the TSM96 is to function as a tool to assess the condition and the adequacy of the long-term world timber supply. Since it concentrates on the supply side of the forest sector, it was mainly developed to study the transition of the world’s timber supply from ‘old growth’ (natural forests) to ‘second growth’ (regeneration) and to ‘plantation grown wood’. The modeling approach uses control theory to determine the economically optimal transition. The use of control theory in the TSM96 means that the wood supply is described in terms of a set of “initial conditions”, “laws of motion” and “control variables”. Such a concept produces forward-looking behavior, where decisions made today must be consistent with those made tomorrow. The implementation of this concept is rooted in the theory of renewable and non-renewable resources (Hotelling 1931; Solow 1974). The model has been used for policy analysis in applications like (a) Carbon Sequestration in Global Forests Under Different Carbon Price Regimes (Sohngen, B. and R, A. Sedjo. 2006); (b) The Role of Forest Plantation in the World’s Future Timber Supply (Sedjo et al. 2001) etc.

The model provides data on long-term industrial wood supply for eight regions, one of which has been termed as ‘Unresponsive’ to price, implying that in this region, the level of wood supply is independent of market conditions. The seven ‘Responsive’ regions are subdivided into 22 timber land classes. Each land class is distinguished and described in terms of its quality, location, accessibilty, growth and yield functions, existing inventories and their age distribution, silvivicultural response to investment inputs, and timber land management costs (including establishment, growth, transportation and harvest). Apart from projecting the transition from ‘old growth’ to ‘plantation grown wood’ in terms of optimal harvest and regeneration effort, the TSM96 also provides projection data on timber prices and trade flows within and among supply regions. A detailed description of the TSM96 is presented in Sedjo and Lyon (1996).

2.3 Comparing Model Theory and Structure

This section considers some differences between the three timber market models described above. While similar in some respects, the models are quite distinct in the economic theory upon which they rely, and all of them are different in the scope of their analysis. Scope includes issues such as how many regions or how many market levels to consider. In addition to structural differences, the models are also at odds in their incorporation of market behavior, implementation of trade flows, assessment of factors like technology change and change in trade tariffs. They also differ in their capacity to provide users with the flexibility and ease of scenario implementation.

It should be noted that although the literature on these three timber market models is quite vast and is very deeply rooted in economics, this chapter discusses only the model features that are considered relevant for this study. The model features compared in this section are selected based two factors: (1) their relevance in representing information on economic drivers from the MA and GEO4 scenarios and (2) their relevance in producing model output for further study with the forest sector in LandSHIFT. Table 2.1 provides a brief summary of the comparison of the model features.

Table 2.1: Comparison of three global timber market models

	CGTM	**GFPM**	**TSM96**
Regions	43 timber supply regions and 33 product demand regions	180 countries and territories as listed in FAO + one 'World' region	8 (7 responsive and "Rest of the World" unresponsive)
Markets	Multiple Market levels	Multiple Market levels	Delivered logs only
Trade Flows	Bilateral	Bilateral	Does not account for bilateral trade
Technology	Wood-saving	Wood-saving	Investments in regeneration and Wood –saving
Scenario Implementation	Flexible	Flexible	Pre-defined scenarios

2.3.1 Regional Classification

The regional classification in the three timber market models is as follows.

CGTM:

Number of timber supply regions = 43
Number of product demand regions = 33

GFPM:

Number of demand regions for forest product commodities = 181
Number of supply regions for forest product commodities = 181

These regions correspond to the 180 countries and territories used in the model and the world region.

TSM96:

The TSM96 subdivides the world into eight industrial wood supply regions. Seven of these are called "Responsive regions". The rest of the world is lumped together as the eighth region and is called the "Nonresponsive Region". The seven responsive regions of

TSM96 are further subdivided into 22 timber land classes, each of which corresponds to a unique geographical area.

The specific regions are:

Responsive Regions:
- Emerging region (1 land class)
- US Pacific Northwest (4 land classes)
- Canada, west (2 land classes)
- Canada, east (4 land classes)
- US South (8 land classes)
- Nordic Region (2 land classes)
- Asia-Pacific (1 land class)

Nonresponsive region: Rest of the world.

NB: The Emerging Region is a composite consisting of a number of regions that are producing industrial wood from intensively managed exotic species tree plantations. These include countries such as Brazil, Chile, Indonesia, New Zealand, South Africa and Spain. Although the species, growth rates and rotations vary somewhat across regions, all these plantations have relatively rapid growth and short rotations.

As described above, the models incorporate different regions, and have a different global scope. GFPM is by far the most comprehensive, as it attempts to model consumption and production on country scale. The CGTM is also quite compendious, as it attempts to model most major producing and consuming regions. The TSM96 incorporates multiple regions, including emerging plantation regions, but models a large part of the globe as a “non-responsive” region. The non-responsive regions include the Former Soviet Union and China.

2.3.2 Incorporation of Market Behavior

The CGTM and the GFPM include multiple market levels, where all market levels are solved simultaneously. TSM96 on the other hand, solves only for delivered log market.

2.3.3 Implementation of Trade Flows

The CGTM models trading between 40 regions of the globe. Bilateral trade flows can occur in both end product and log markets.

The GFPM models trade flows in 180 countries and territories in the world, referred to as regions in the model. All countries and territories import to and export from the ‚World' region.

The TSM96 does not model bilateral trade like the CGTM or the GFPM.

2.3.4 Incorporation of Technology Change

In both CGTM and GFPM, technological change is manifested in the form of wood-saving technology. Technological improvement is seen as a reduction in the wood requirement of various intermediate and final products using raw wood source. Hence, technology change is implemented in terms of input/output coefficients for products and how they change over time.

In the TSM96, technological progress is incorporated via investments in forest regeneration in the supply side of the model. Technology change in tree growth is measured in terms of the genetic improvement that is imparted to improve the yield of the growing stock introduced through artificial regeneration. Since naturally regenerated forests do not incorporate genetic improvement, technology change is implemented only for artificially regenerated forests (plantations). Additionally, technological change can also enter TSM96 via the demand side in the form of wood-saving technology i.e by reducing the rate of increased demand for raw wood resource.

2.3.5 Scenario Implementation

The CGTM incorporates exogenous change data on cost shifts and capacity expansion rates, which can be adjusted to reflect policy changes influencing these two factors.

In the GFPM, exogenous change data can be specified for demand, supply, manufacturing costs, technology change and ad-valorem tax import rates in order to evaluate the effects of alternative scenarios on industrial roundwood harvests.

The TSM96 offers timber harvest projections for six pre-defined scenarios. These are:

1. Decreasing Demand
2. High Demand (based on FAO forecasts)
3. Very High Demand
4. Integrated Supply Constraints with Base Case Demand
5. Integrated Supply Constraints with Low Demand
6. Very High Demand with High Plantation Establishment

2.4 Deficits and Potentials

The three models discussed in the above sections have both similarities and differences. In the discussion that follows, the five aspects described in Section 2.3 are analysed. This comparison provides an insight into the objective criteria for understanding which model will be best suited to obtain wood production data for further implementation in LandSHIFT.

The first distinction is the regional classification that each of these models incorporate. While the CGTM and TSM96 offer forecasts on regional level only, GFPM is by far the most comprehensive, as it attempts to model consumption, production, prices and trade for 180 countries and 14 forest products as listed by the FAO. Output on country scale is very desirable for LandSHIFT as it works with country level input data.

Secondly, the CGTM and the GFPM have been developed with multiple market layers, that is, they describe the vertical market for forest products (timber supply to end products), and simultaneously solve for equilibrium between demand and supply at each market level. Modelling multiple market levels enables for the capturing of important interactions between the market levels (as discussed in Haynes 1977). Hence, for example, if due to an increase in wood saving technology, the utilization rate of solidwood producing sawnwood decreases; models like the CGTM and the GFPM are fully capable of representing the rate of upward shift in demand, whereas a model like the TSM96 cannot do so.

A particular attraction of the CGTM and the GFPM is the relatively detailed treatment of bilateral trade flows in the model, which enables the user to assess the potential trade effects of alternative policies at regional or country level. However, it can be argued that the dynamics of trade are not well represented by the CGTM based on the way that historical trade relations are captured in the model, i.e. through the use of „inertial limits“ on period-to –period shifts in trade flows. This kind of approximation is not beneficial for obtaining long-term wood demand projections under varying scenarios; especially if the scenarios provide a distinctive outlook on trade liberalization (or barrier enforcement). On the contrary, the GFPM takes supply and demand curves for each country, fixes these such that the model roughly replicates global production, consumption and trade in the previous year for which actual data is available, and then shifts these curves out for every country and each year of the forecast. As part of this process, the model identifies the trade flows and price changes necessary to clear all markets within each year of the forecast using a linear programming algorithm.

While multi-market levels provide forecasts on end-products, they require a substantial understanding of implementing technological change. Due to their complex framework, both CGTM and GFPM provide a wide range of different end products for which the input/output coefficients can be changed. TSM96, on the other hand, in its implementation of technology from the supply side, includes only one aspect of investments in regeneration to be adjusted over time. Also from the demand side, it is only the rate at which the demand for raw wood resource decreases over time that needs to be assumed. While the implementation of technological change is not a difficult task in either of these models (although it is more tedious in CGTM and especially more in GFPM), there is no clear evidence that multi-market models produce more accurate forecasts as a result of a more complex implementation of technology change than compared to single market level models.

Finally, even though all three models offer scenario analysis in one form or another, it is only the CGTM and the GFPM that offer the user a mechanism to alter exogenous data to reflect the impact of alternative scenarios on raw wood harvests. Even between these two models, the GFPM offers a wider range of exogenous data that can be modified by the user to depict different scenarios. Although there is no guarantee that more specification leads to better results, it certainly offers more flexibility and enables a more thorough representation of the scenario under study.

2.5 Conclusions

This chapter attempts to clarify differences between the three timber market models by comparing certain aspects of the model's theory and structure relevant to this study. All three models predict long-term trends and harvest behaviour. Given the differences between these models as discussed in Sections 2.3 and 2.4, the 'Global Forest Products Model' is found to be most suitable for further study with LandSHIFT for the following main reasons:

1. The model provides a consistent framework for implementing alternative scenarios and policy options.
2. It provides harvest forecasts at country level. Downscaling regional data to country scale is not required with this model.
3. It is flexible with providing projections till 2100 if desired.
4. It works with the FAO country and forest product categories.
5. It provides separate output for raw wood and end products.
6. It provides a user-friendly method to implement exogenous change data on GDP, GDP per capita, technology and trade for scenario analysis.
7. It offers the flexibility to modify input base year data if necessary.

Although the GFPM is best suited for further study with LandSHIFT, it should be kept in mind that model predictions are no better than their input assumptions. The scenarios of population and income growth, as well as assumptions on changes in technology and trade influence the model predictions to a considerable extent. They also account for a substantial part of the differences observed in the projected harvests as outlined and discussed in the next chapter.

2.6 References

Achard, F., Eva, H.D, Mayaux, P., Stibig, H.-J., Belward, A. 2004. Improved estimates of net carbon emissions from land cover change in the tropics for the 1990s. Global Biogeochemical Cycles. 18 (2) GB2008 10.1029/2003GB002142

Alcamo, J., and R. Schaldach, 2006. LandShift: Global Modeling to Assess Land Use Change, in: Tochtermann (2006). EnviroInfo 2006. Managing Environmental Knowledge. Proceedings of the 20th International Conference "Informatics for Environmental Protection. 223-230.

Buongiorno, J., S. Zhu, D. Zhang, J.A. Turner, and J. Tomberlin. 2003. The Global Forest Products Model: Structure, Estimation and Applications. San Diego, CA: Academic Press.

Cardellichio, Peter A., Chang Yeo Youn, Darius M. Adams, Rin Won Joo, and John T. Chmelik. 1989. A Preliminary Analysis of Timber and Timber Products Production, Consumption, Trade and Prices in the Pacific Rim Until 1989. CINTRAFOR Working Paper, No. 22. Seattle: University of Washington, College of Forest Resources.

ForesSTAT: FAO 2006. Food and Agriculture Organization, United Nations, Rome.

Haynes, R.W. 1977. A Derived Demand Approach to Estimating the Link Between Stumpage and Lumber Markets. For. Sci. 23: 281-288.

Hotelling, H. 1931. The Economics of Exhaustible Resources. J. Pol. Econ. 39:137-175.

Lambin, E.F. and Geist, H. (eds) 2006 Land-use and land-cover change: local processes and global impacts. Springer: Berlin, Heidelberg, GE, 204 pp.

MA – Millennium Ecosystem Assessment 2005. (URL: www.millenniumassessment.org)

Perez-Garcia, John., Linda A. Joyce, and A. David McGuire. 2002a. Temporal Uncertainties of Integrated Ecological/Economic Assessments at the Global and Regional Scales. *Forest Ecology and Management* 162(2002) 105-115

Perez-Garcia, John M., Linda A. Joyce, A David McGuire, and Xiangming Xiao. 2002b. Impacts of climate change on the global forest sector. *Climatic Change* 54: 439-461

Perez-Garcia, John M., Linda Joyce, Clark S. Binkley and A.D. McGuire. 1997. Economic impacts of climate change on the global forest sector. Critical Reviews in Environmental Technology 27: S123-S138. Also as a chapter in: Sedjo, Roger A, R. Niel Sampson and Joe Wisniewski (eds), Economics of Carbon Sequestration in Forestry. CRC Press LLC, Boca Raton, Fl.

Perez-Garcia, John M. 1995. Global Forest Land Use Consequences of North American Timber Land Withdrawals. Journal of Forestry 93(7):35-38.

Rudel, Thomas K., O.T. Coomes, E. Moran, F. Achard, A. Angelsen, J. Xu, and E. Lambin. 2004. “Forest Transitions: towards a global understanding of land use change.” Global Environmental Change 15 (2005) 23-31.

Schaldach, R., J. Alcamo, and M. Heistermann, 2006. The multiple-scale land use change model LandShift: a scenario analysis of land use change and environmental consequences in Africa, in A. Voinov, et al. (Eds.): Proceedings of the iEMSs Third Biennial Meeting: “Summit on Environmental Modelling and Software”, International Environmental Modelling and Software Society, Burlington, USA.

Sedjo, R.A., and David Bael. 2006. Toward Globalization of the Forest Products Industry: Some Trends. Washington: Resources for the Future. DP 06-35.

Sedjo, R.A. 2001. The Role of Forest Plantation in the World’s Future Timber Supply. Forest Chronicle, vol. 77, no. 2, pps: 221-226.

Sedjo, R.A., and K.S. Lyon. 1996. “Timber Supply Model 96: A Global Timber Supply Model with a Pulpwood Component.” Discussion Paper 96-15. Washington: Resources for the Future.

Sohngen, B. and R.A. Sedjo. 2006. Carbon Sequestration in Global Forests Under Different Carbon Price Regimes. The Energy Journal, Special issue, Multi-Greenhouse Gas Mitigation and Climate Policy. pps. 109 -162, December.

Solow, R. M. 1974. The Economics of Resources or the Resources of Economics. American Economic Review, 64, pp. 1-14.

United Nations Environment Programme (UNEP) 2007. Global Environment Outlook GEO4: environment for development. UN-UNEP, Valletta, Malta, 572 p.

Verburg, P.H., G.H.J. de Koning, K. Kok, A. Veldkamp, and J. Bouma. 1999. A spatial explicit allocation procedure for modeling the pattern of land use change based upon actual land use. Ecological Modelling 116 (1999) 45-61.

Zhu, S., and J. Buongiorno. 2002. “International Impact of National Environmental Policies: The case of Paper Recycling in the United States.” International Forestry Review 4(2): 133-142.

Zhu, S., J. Buongiorno, and D. Brooks. 2001. “Effects of Accelerated Tariff Liberalization on the Forest Products Sector: A Global Modeling Approach.” Forest Policy and Economics 2(1): 57-78.

CHAPTER 3

Simulation of global Wood Production

Summary

The Global Forest Products Model is used to simulate wood production data for the global forestry sector, conditional on selected scenarios from the Millennium Ecosystem Assessment (MA), and from the Global Environment Outlook (GEO4) for the period 2006 - 2050. The average global production of total industrial roundwood increases by approximately 50% across the MA scenarios and by around 100% across the GEO4 scenarios during this period. The chapter presents both global and selected regional analysis. Across both MA and GEO4, the results indicate that, for example, the Russian Federation will emerge as a strong economic market for industrial roundwood in the future. Additionally, some Asian countries like Japan and South Korea will remain as active importers. Brazil and Canada will be major exporters of wood and, both regions will experience immense amounts of logging.

Keywords: forest sector, wood demand, net trade, scenario, Millennium Ecosystem Assessment (MA), Global Environment Outlook (GEO4), Global Forest Products Model (GFPM)

3.1 Introduction

One main purpose of the Global Forest Products Model (GFPM) is to predict roundwood harvests under different scenarios (Buongiorno et al. 2003). The model shows how the raw wood supply (timber harvest) is likely to change in response to changing economic environments such as changes in economic growth, trade tariffs and/or technology (Buongiorno et al. 2003). The GFPM has been previously applied for several studies like ‘Effects of Asian Economic Crisis’ (Buongiorno et al., 2003), ‘Effects of Tariff Liberalization’ (Zhu et al., 2001), ‘Impact of US Paper Recycling Policies’ (Zhu at al., 2002) etc.

The objective of this study is the adaptation and the application of the ‘Global Forest Products Model’ to obtain an estimation of wood production data. Estimates are made based on the storylines of the ‘Techno Garden’ and ‘Order from Strength’ scenarios in the Millennium Ecosystem Assessment (MA), and on the ‘Sustainability First’ and ‘Markets First’ scenarios under Global Environment Outlook (GEO4) until year 2050. These estimates represent the amount of wood to be harvested in each country to meet global wood demand. The GFPM results are used as input in the ‘Forest’ module in LandSHIFT (Chapter 4).

Section 3.2 provides an overview of the storylines of two Millennium Ecosystem Assessment scenarios (‘TechnoGarden’ and ‘Order from Strength’), and, of two Global Environment Outlook scenarios (‘Sustainability First’ and ‘Markets First’). It also briefly introduces the Global Forest Products Model and describes the model implementation. Section 3.3 presents the results of the impact of both MA and GEO4 scenarios on total industrial roundwood production in their six respective regions, as well as in selected countries/regions contrasting in fraction of forest cover, economic status and climate. Section 3.4 offers some concluding remarks. Section 3.5 offers a comparison of GFPM wood demand forecasts with other existing wood demand scenarios.

3.2 Materials and Methods

3.2.1 Millennium Ecosystem Assessment Scenarios (MA)

The MA scenarios were designed to study four possible and internally consistent global futures of ecosystems, ecosystem services and human well-being under a broad range of assumptions on key demographic, economic, social, cultural and climatic driving forces (MA 2005). This study considers only the 'Order from Strength' and 'TechnoGarden' scenarios because of their strongly contrasting underlying assumptions. These two scenarios differ with respect to most of the direct and indirect drivers of change affecting ecosystems that are part of the MA framework. The key indirect driving forces of the MA scenarios include population, income, technological development, and changes in human behavior (people's attitudes towards international cooperation and towards environmental policies).

3.2.1.1 TechnoGarden Scenario

The TechnoGarden scenario depicts a globally connected world. In this scenario, the countries opt for very strong technological improvement in all economic sectors in order to deliver needed goods and services, at the same time keeping ecosystems well maintained. Hence the technology development is overall more geared towards an efficient ecosystem management. The scenario generally assumes a moderate pace of change in both human fertility and mortality rates based on moderate economic growth assumptions. This relationship is assumed to be similar across the world regions. The global economic growth is much higher than in the 'Order from Strength' (OS) scenario, due to a combination of trade liberalization, economic cooperation, and rapid spread of new technologies. As low-income countries grow much faster than other countries, the income gap between the rich and the poor regions is closing to a considerable extent. Technological development is relatively high in this scenario throughout the entire period. Assumptions made on technological advancement in this scenario are very optimistic and can be interpreted as maxima. Finally, this scenario assumes that environmental policies, such as improved recycling of paper products, are implemented to a larger degree than in the OS scenario.

3.2.1.2 Order from Strength Scenario

The Order from Strength scenario represents a regionalized and fragmented world in which the rich countries confine themselves to their boundaries in order to avoid poverty and other threats like illegal immigration from poorer countries. As a result, the attitude towards ecosystem management becomes more locally focused and overall degradation of ecosystems is seen due to lack of international environmental policies. The scenario generally assumes high human fertility and mortality rates. This relationship however differs across regions. While the developing countries experience high human fertility and mortality trends; a reverse trend of low human fertility and mortality is seen in many of the industrialized countries, especially in Western Europe. This is because this scenario assumes to have divergent fertility trends coupled with low migration across the industrialized countries. The global economic growth in this scenario is very low because of the low level of international trade and limited exchange of technology. The income gap between the rich and the poor regions widens between 2000 and 2025. Finally, this scenario assumes a more negative attitude towards implementation of environmental policies, such as the recycling of paper products.

3.2.2 Global Environment Outlook Scenarios (GEO4)

The underlying theme of the GEO-4 report (UNEP 2007) is environment for development. It highlights the critical issues of sustainable development and the choices available to policymakers across the range of environmental, social and economic challenges – both known and emerging. In assessing the state and trends of the global as well as emerging issues, the report also addresses issues related to human well-being and the valuation of environmental goods-and-services, building upon the work of the Millennium Ecosystems Assessment (MA). GEO-4 assesses the current state of the global atmosphere, land, water and biodiversity, describes the changes since 1987 (climate change, collapse of fisheries, biodiversity loss, and emergence of diseases and pests, etc.,), and identifies priorities for action. It analyses the implications of various actions, approaches and societal choices at both regional and global levels for the future of the environment and human well-being under four scenarios – Markets First, Policy First, Security First and Sustainability First. This study considers only the ‘Markets First’ and ‘Sustainability First’ scenarios because of lack of availability of climate data for the other two. These two scenarios differ with respect to most of the direct and indirect drivers of change affecting ecosystems that are part of the Global Environment Outlook framework. The key indirect driving forces of the GEO4 scenarios are much the same as in the MA scenarios and include population, income, technological development, and changes in human behavior (people’s attitudes towards international cooperation and towards environmental policies).

3.2.2.1 Sustainability First Scenario

Sustainability First is a world in which a new development paradigm emerges in response to the challenge of sustainability, supported by new values and institutions. This scenario gives equal importance to both environmental and socio-economic policies, as well as accountability for all decisions in their arena. It also emphasizes on transparency and legitimacy across actors at all levels – local, national, regional and international, and across all sectors, including government, private and civil. It strongly supports the development of effective public-private sector partnerships, not only in the context of projects, but also in the area of governance, ensuring that stakeholders who are involved in the entire process also have the opportunity to offer their input to policy making and implementation. Technological innovation mainly concentrates on sustainable use of ecosystem services and on increased environmental protection. Freer trade is emphasized, but on fair trade principles. Even though economic growth is not very high in this scenario, the nature and level of cooperation at all levels allows for a broad acceptance for what needs to be done. This involves the allowing of all elements of global society to achieve basic needs and achieve personal goals without compromising the environment further or threatening the viability of future populations.

3.2.2.2 Markets First Scenario

The Markets First scenario depicts a liberalized and market-oriented society, almost universal. The chief characteristic of this scenario is the immense amount of trust and reliance that the world puts into the globalization and openness of markets; not only for economic improvement, but also for social and environmental benefits. The entire process revolves around a mixture of several factors: increased role of the industrial lobby accompanied by the slowly diminishing role of governments, continued movement towards trade liberalization, and the commoditization of goods obtained from nature. The world achieves much in terms of modernization and economic growth, presenting new opportunities for a significant proportion of the global population. Yet, this scenario faces the fundamental questions on the sustainability and desirability of this pattern of development. Formal environmental protection is very slow as it competes against efforts to improve the economy and expand trade. Environmental standards continue to decline and pressures on natural resources remain severe, raising again the levels of economic uncertainty and conflict. Social stresses threaten socio-economic sustainability as persistent poverty and growing inequality, exacerbated by environmental degradation, undermine social cohesion, spur migration and weaken international security. Compared to the ‘Sustainability First’ scenario, this scenario lacks a fundamental change in human behavior and in society’s demands on the environment.

3.2.3 The Global Forest Products Model

The Global Forest Products Model is a spatial, dynamic partial-equilibrium model designed to simulate trends in the forest sector under varying scenarios on country level. The model calculates production, consumption, trade, and prices for 180 countries and 14 forest products as defined by the Food and Agricultural Organization (FAO 2000) based on the theory of spatial equilibrium in competitive markets. The GFPM solves the equilibrium by maximizing the value of the products, minus the cost of production, subject to material balance and capacity constraints in each country and in each year. A more detailed description, including the mathematical formulation of the GFPM is presented in Buongiorno et al. (2003).

In each projection year, for each country and commodity, supply (domestic production plus imports) equals demand (final consumption, plus input in other processes, plus exports). Final demand is price responsive, while demand for wood or intermediate products derives from the demand for final products through input-output coefficients that describe technologies in each country. The supply of raw wood and non-wood fibers in each country is also price responsive. The supply of recycled paper is constrained by the waste paper supply, which itself depends on the paper consumption and the recycling rate. Each country exports to and imports from the world market. Projected prices are such that they clear markets; at those prices, demand equals supply in each country.

From one year to the next, demand changes in each country because of exogenous changes in income. The wood supply shifts exogenously due to changes in forest stock and forest area. The amount of recycled fiber used for making paper and paperboard changes exogenously with technology and recycling policy. Capacity increases or decreases endogenously according to new investments that depend on past production and the profitability of production in different countries, as revealed by the shadow price of capacity. Exogenous tariff changes affect the cost of ad valorem imports. Trade changes with inertia tied to past trade and the income of importing countries.

The general principle of the model is that global markets tend to optimize resource allocation in the short run (within one year). Long-run resource allocation under varying scenarios can be obtained by specifying exogenous changes in economic growth*, technology, trade tariffs on imports, and by forest resource changes affecting wood supply.

The base year (currently 2006) is the year in which the scenarios begin. All input data relating to different modules of the model like demand, supply, forest resources, manufacture, production capacity, recycling supply, transportation cost, tax and exogenous change data are read from a database. The exogenous data are organized by period. They only need to be specified for periods when an exogenous change is desired. If the exogenous change data are not specified for a period, the previous period’s exogenous changes apply. The model then computes a new equilibrium under the new demand and supply conditions, new technology, and new tariffs. In this study, the model recalculates equilibria 10 times (for the period 2006 – 2050 at 5-year intervals).

** The GFPM incorporates changes in demographic trends in the GDP growth rates, which are among the most important exogenous parameters of GFPM.*

This study implements the following exogenous variables in the GFPM in order to obtain wood production forecasts based on the MA and GEO4 scenarios.

- Annual rate of growth of Gross Domestic Product (GDP).
- Annual rate of GDP growth per capita.
- Annual rate of technology change.
- Annual rate of change in import tariffs (ad valorem).
- Annual rate of change in forest area.

Assumptions on economic growth influence the future outlook of wood supply from forests by affecting the direct drivers of forest stock changes like wood use, and indirect drivers such as technology. A higher economic growth is generally associated with higher technology development, thereby reducing the pressure on forests for wood supply. The rate of technological change represents the efficiency with which wood products are produced or used. A more efficient technology in processing wood products could, for instance, reduce the demand for raw wood extracted from the forests. Import tariffs influence the shift in forest area requirements to satisfy wood demand. An increase in trade tariffs could, for example, cause countries to import lesser quantities of wood than usual, thereby putting more pressure on their own forests for wood supply. Finally, a change in the rate of growth/decline of forest area also affects the wood supply.

For this study, exogenous change data on economic growth under the MA and GEO4 scenarios is directly taken from the respective scenarios. The data on annual rate of change in forest area is taken from the GEO4 Outlook Study (UNEP 2007). The same data has been assumed to be relevant for the MA scenarios since the scenario assumptions in MA and GEO4 are sufficiently similar. Accordingly, for the ‘TechnoGarden’ scenario, the rate of change in forest area is as described in the ‘Sustainability First’ scenario and for the ‘Order from Strength’ scenario, the rate of change in forest area is as described in the ‘Markets First’ scenario in GEO4. Exogenous changes in technology and import tariff rates are assumed based on the scenario storylines. A comprehensive description of the evaluation of these data is provided below.

3.2.3.1 Evaluation of Technology Change

In the GFPM, technological change is manifested in the form of wood-saving technology. The concept is implemented in two separate phases and follows the material flow as shown in Figure 3.1 after Buongiorno et al, 2003. In the first phase, input-output (IO) coefficients that indicate a decrease in the amount of industrial roundwood per unit of sawnwood, plywood, particleboard, fiberboard, mechanical pulp and chemical pulp are estimated. Data on base year (year 2006) IO coefficients and data on estimates of lower bounds of the IO coefficients are available from the GFPM and are used to obtain the IO coefficient change factor for each scenario. For each product within each country, the estimated lower bound value of the IO coefficient has first been subtracted from the available base year IO coefficient value. The remainder has then been divided by the number of years for which the values need to be generated (44 years in this study) Thus, the increase in technological efficiency assumes a steady linear trend until it reaches the assumed lower bound value in the year 2050 for both MA and GEO4 scenarios. Since according to the scenario descriptions, both TG and SusF scenarios describe a high regard for sustainable technological development, the same technology change calculations have been taken for these two scenarios. Similarly, technology change for both OS and MF scenarios have been calculated in the same manner since both these scenarios suggest little regard for sustainable technology progress.

Below is an example for calculation of change in IO coefficient of the amount of industrial roundwood per unit of sawnwood in Canada under the TG scenario.
Base year IO coefficient value = 1.64555;
Lower Bound =1.00
Change in IO coefficient per year till 2050 = -((1.64555 – 1.00)/44) = -0.01467

In the second phase, IO coefficient factors indicating an increase in wastepaper recovery (corresponding to a decrease in the amount of pulp utilization) are estimated for the production of newsprint, printing and writing paper, and other paper and paperboard.

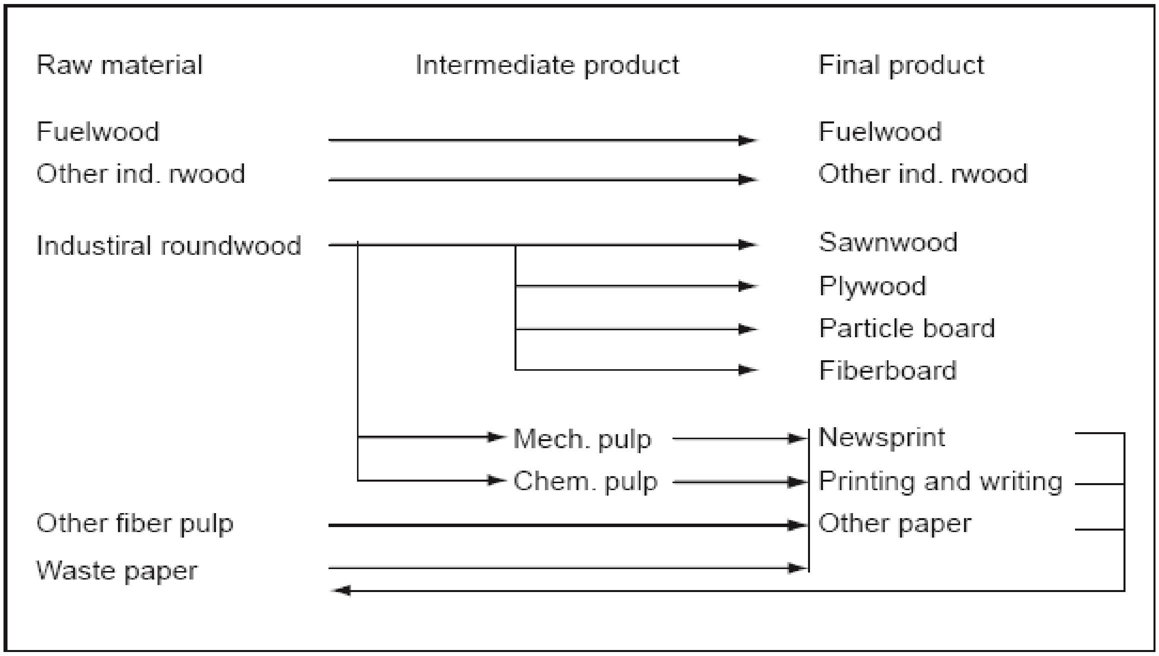

Figure 3.1: Product transformations in the Global Forest Products Model (Chapter 4, Figure 4.1, Buongiorno et al, 2003)

<u>Estimating IO coefficients for TG and SusF Scenarios:</u>

Table 3.1 lists the industrial roundwood IO coefficient bounds that have been used to calculate the change coefficients to produce each intermediate product (sawnwood, plywood, particleboard, fiberboard, mechanical pulp and chemical pulp) in all countries. The bounds are indicators of the minimum amount of industrial roundwood required in tons per unit production of each of the intermediate products. Since both TG and SusF are very optimistic with respect to technological development, it has been assumed that in these scenarios the amount of industrial roundwood used in manufacturing the above-mentioned intermediate products would gradually decrease between 2006 and 2050 until the manufacturing technology reaches a stage where it cannot be further improved. For printing and writing paper, newsprint and other paper and paperboard, the utilization of wastepaper during their production is assumed to increase gradually in accordance with the increase in the recycle paper use (as explained below), with a corresponding decrease in the amount of wood pulp used between 2006 and 2050. The resulting increase in wastepaper utilization rate is as follows: Africa (0.2% per annum); North and Central America, South America, and Europe (0.35% to 5% per annum); Asia and Oceania (0.7%

per annum); Former USSR (0.1 to 0.2% per annum). For each of the three output products (Printing Writing Paper, Newsprint and Other Paper and Paperboard), the average change values have been selected such that for each country, in each year throughout the projection period, the sum of the IO coefficient values of all three products is approximately equal to 1. This constraint has been applied to adhere to the basic requirement in paper production of having at least 1 ton of fiber input for every 1 ton of paper output. In some cases, the sum of the IO coefficient values may be slightly less than 1. This can be attributed to the fact that for some commodities, additives like clay are utilized in board and paper production.

Estimating IO coefficients for OS and MF Scenarios:

In these scenarios, technology development is assumed to be slow, as compared to the TG and SusF scenarios, due to less regard for ecosystem management. Hence, high improvement in technology is not anticipated. Accordingly, it has been assumed that the rate of growth of technology is only half of the technological growth rate in the TG (and SusF) scenario for all products in all countries.

Table 3.1: Industrial Roundwood IO coefficient lower bounds considered in TG scenario

Sawnwood*	Plywood**	Particle** Board	Fiberboard**	Mechanical** Pulp	Chemical Pulp**
1.00	0.83	0.66	0.75	0.86	1.25

** In practice, there are always losses of at least 10-15% of industrial roundwood when Sawnwood is produced. Hence, the assumption that the countries finally attain a technological efficiency standard where no waste is produced is not feasible in the real production world. However, in the GFPM, there are 46 countries for which the base year IO coefficient values for conversion of Industrial Roundwood to Sawnwood have already been set to a value of 1.00. This was done in order to reconcile the data on industrial roundwood consumption with the data on production of sawnwood, panels, etc. Hence, in this study, a lower bound value of 1.00 is only a theoretical indicator of a scenario in which maximum possible efficiency is achieved and cannot be improved further.*

*** In case of Plywood, Particleboard, Fiberboard and Mechanical Pulp, the lower bound values are lower than 1.00 because the manufacturing process of these products also involves other additives than industrial roundwood.*

Calculation of Recycle Paper Use for implementation of technology change in wastepaper utilization:

Quantifying wastepaper recovery rates in the TG and SusF scenarios:

Both TG and SusF scenarios envisage an ideal world in which high levels of recycling would be possible and every country would meet goals and targets for wastepaper recovery. In this study, the targets for wastepaper recovery have been set based on the "optimal scenario" of Mabee and Pande (1997). According to this scenario, the estimated potential best wastepaper recovery rates until 2010 are as follows: Africa, 50 percent; North America, 50 percent; Latin America, 50 percent; Asia, 75 percent; Oceania, 75 percent; Europe, 90 percent; and Former USSR, 40 percent. Although their study considers a projection period only until 2010, the target figures are indicative of recycling maximum achievable in long term also. For instance, Europe being a compact, highly developed area with traditionally high levels of recycling, has been given a target of 90% wastepaper recovery. It is highly unlikely that greater levels of wastepaper recovery could be achieved in the real world. Hence, it will not be completely incorrect to assume that the optimal scenario targets set for wastepaper recovery in Mabee and Pande (1997) will be feasible for a projection period until 2050. However, intensive-recyclable paper recovery is in general associated with greater utilization of recycled paper (Berglund 2003). Also, according to Ince (1994), a higher rate of utilization of recycled paper results in lower paper quality, because the fiber becomes weaker and more contaminated each time it is reused. Hence a plausible upper limit on the wastepaper recovery rate is 75% (Ince 1994). Based on the above studies, the assumed wastepaper recovery rates with respect to the TG and SusF scenarios in the GFPM are such that the world recovery rate would rise from 39% in 2006 to around 62% by 2050. Accordingly, the following target levels have been set for wastepaper recovery in each region in GFPM: Africa, 50 percent; North and Central America, 75 percent; South America, 50 percent; Asia, 75 percent; Oceania, 75 percent; Europe, 75 percent; and Former USSR, 40 percent. The recovery rates are also consistent with the Kuznets curve hypothesis, which predicts that for richer countries there will be a strong positive correlation between per capita income and the extent to which environmental protection measures, including waste management policies, are adopted (Berglund 2003).

Quantifying wastepaper recovery rates in OS and MF scenarios:

Both OS and MF scenarios assume technology advancement for more ideological than for environmental reasons, and people see the environment as secondary to their other challenges. Therefore, it is assumed that a significant increase will occur in wastepaper recovery and utilization in the OS and MF scenarios, although lesser in magnitude as compared to the TG and SusF scenarios. Hence, it has been assumed that the world wastepaper recovery rate would experience only a half of the increase in world wastepaper recovery that has been assumed in the TG (and SusF) scenario and rise from 39% in 2006 to around 45% by 2050. Accordingly, the following target levels have been set for wastepaper recovery in each region in GFPM: Africa, 35 percent; North and Central America, 50 percent; South America, 40 percent; Asia, 45 percent; Oceania, 50 percent; Europe, 65 percent; and Former USSR, 30 percent.

3.2.3.2 Evaluation of Import Tariff Rates

MA Scenarios

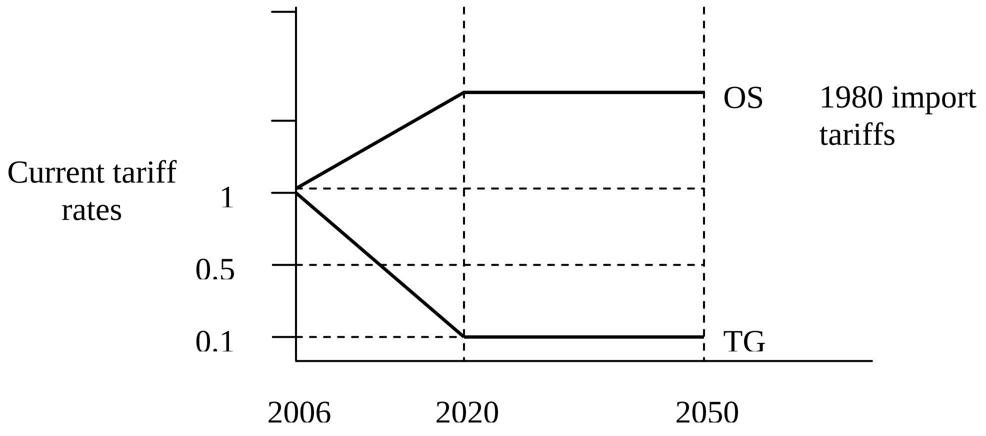

Figure 3.2: Estimation of import trade tariffs in TG and OS scenarios

Quantifying Import Tariff Rates for TG Scenario:

Since this scenario depicts a globally connected world and predicts accelerated liberalization in trade, it has been assumed that the current import tariff rates will gradually decrease to ten percent of their present values until 2020 and then remain at that level until 2050 (Figure 3.2).

Quantifying Import Tariff Rates for OS Scenario:

Since this scenario represents a regionalized and fragmented world emphasizing primarily on regional markets, it has been assumed that the import tariff rates will initially increase until 2020 and then remain constant at that level until 2050 (Figure 3.2). The 1980 import tariff rates (Buongiorno, Personal Communication) are chosen as the target that the current tariff rates will reach in 2020 since these rates originate from a more regionalized world, and thus well represent the assumptions in the OS scenario.

GEO4 Scenarios

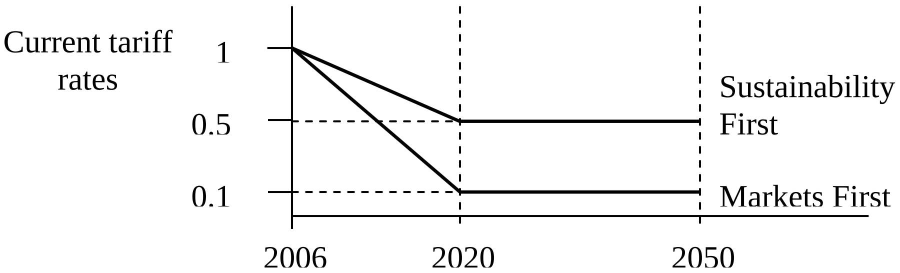

Figure 3.3: Estimation of import trade tariffs in SusF and MF scenarios.

Quantifying Import Tariff Rates for SusF Scenario:

This scenario indicates a significant increase in trade liberalization. However, it also emphasizes on strong embodiment of fair trade principles and recognition of valuing ecosystem services. Hence, it has been assumed that the current import tariff rates will gradually decrease to half of their present values by 2020 and then remain so until 2050 (Figure 3.3).

Quantifying Import Tariff Rates for MF Scenario:

This scenario depicts increased liberalization in trade. However, no global free trade zone is achieved. Hence, it has been assumed that the current import tariff rates will gradually decrease to ten percent of their present values by 2020 and then remain so until 2050 (Figure 3.3).

3.3 Results and Discussion

3.3.1 Global Analysis

3.3.1.1 Production under MA scenarios

Results

Global production of industrial roundwood increases by approximately 50% between 2006 and 2050 across the TG and OS scenarios. Detailed results on production and net trade of industrial roundwood in the six MA regions - (1) Asia (2) FSU, Former Soviet Union (3) LAM, Latin America (4) MENA, Middle East and North Africa (5) OECD90 and (6) SSA, Sub-Saharan Africa - as outlined in the Millennium Ecosystem Assessment (MA) scenarios are outlined and discussed below.

TG scenario

Globally, the production of industrial roundwood increases almost 17% between 2006 and 2050, from 1.7 billion m^3 to nearly 2.1 billion m^3. The simulations indicate a continuous increase in the production of industrial roundwood in all regions until 2050, except in OECD90, where it starts decreasing 2030 onwards (Figure 3.4a). Figure 3.4b shows the net trade of industrial roundwood in the six MA regions. The results indicate that the FSU will emerge as a major exporter of raw or processed industrial roundwood among the six MA regions. Imports into Asia increase from 2006 to 2030, and then remain on the decrease until 2050. Imports into the OECD90 countries are constant between 2006 and 2020, and then increase continuously until 2050. Also, imports into the OECD90 are higher than into Asia. The MENA and SSA regions import small quantities of industrial roundwood while the LAM is involved to a small extent in industrial roundwood exports over the entire projection period.

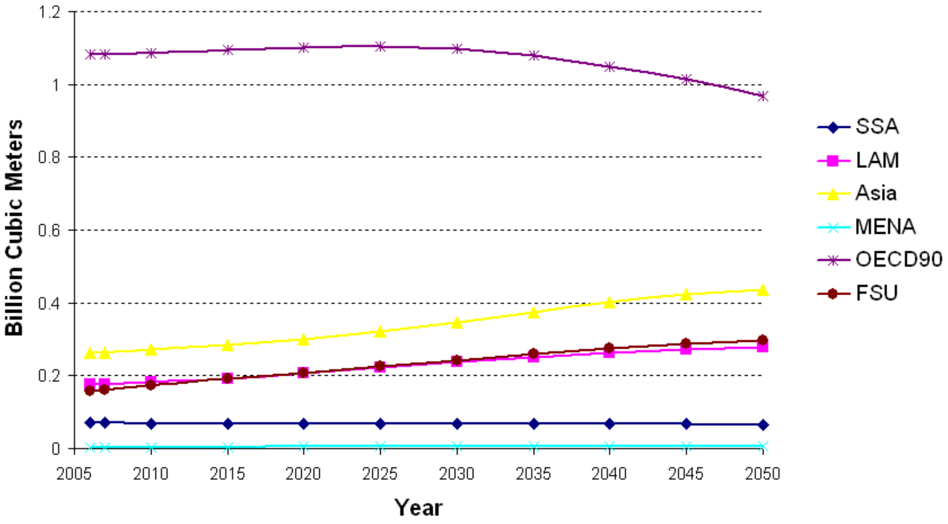

Figure 3.4a: Production of Total Industrial Roundwood in TG Scenario

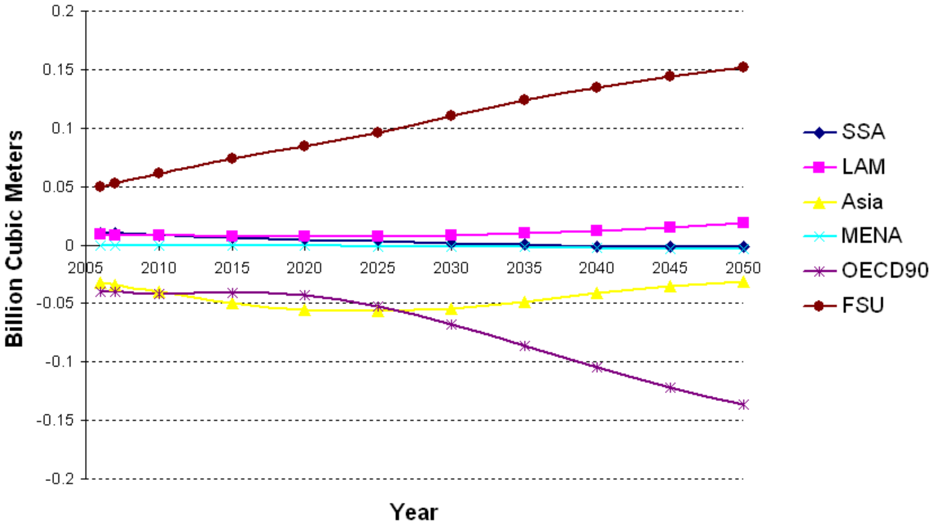

Figure 3.4b: Net trade of Total Industrial Roundwood in TG Scenario

OS scenario

The global production of industrial roundwood increases almost 80% between 2006 and 2050, from 1.7 billion m^3 to nearly 3.2 billion m^3. On a global perspective, the simulations indicate a continuous increase in the production of industrial roundwood in all regions (Figure 3.5a). Also, in each region, production in this scenario is higher than in the TG scenario.

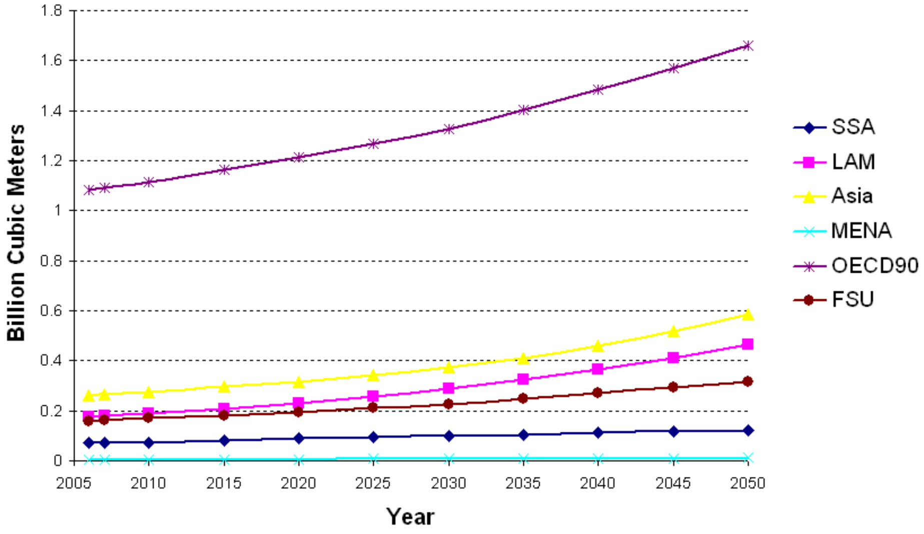

Figure 3.5a: Production of Total Industrial Roundwood in OS Scenario

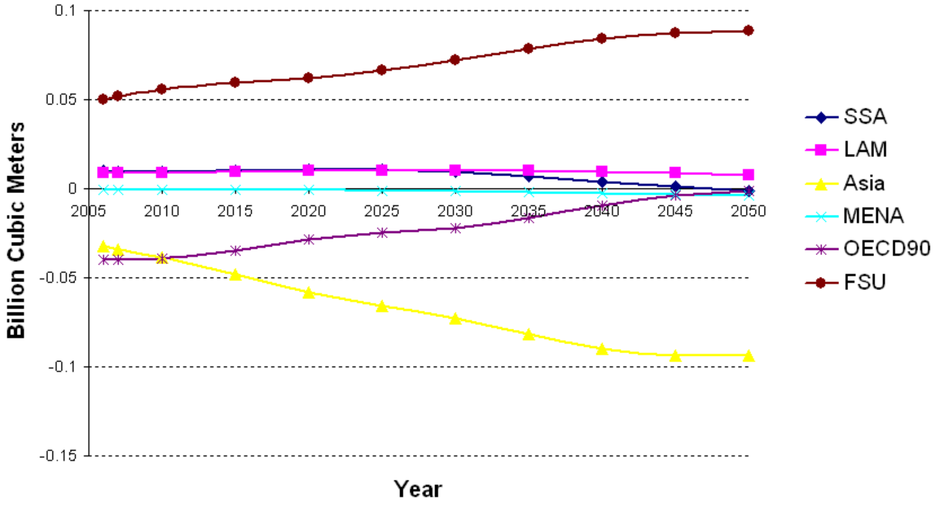

Figure 3.5b: Net trade of Total Industrial Roundwood in OS Scenario

Figure 3.5b shows the net trade of industrial roundwood in the six MA regions. Like in TG, the FSU emerges as a major exporter of raw or processed industrial roundwood among the six MA regions. However, the export quantity of industrial roundwood from FSU is much less in this scenario as compared to in the TG. Also, imports into OECD90 are much less than in the TG. Unlike in TG, Asia imports more industrial roundwood than the OECD90 over the entire projection period. In the LAM region, export quantities are very low during the entire period. As in the case of TG, the MENA region imports small quantities of industrial roundwood over the entire period. However, in this scenario, the SSA region is involved in exporting small quantities of industrial roundwood till 2050.

Discussion

Global production of industrial roundwood is 55% higher in the OS scenario than in the TG scenario by 2050. In general, lower economic growth and less technology development are responsible for higher production (extraction of raw wood) in the OS. High technology advancement in TG enables the countries to produce more wood products with fewer raw materials, thus putting less pressure on their forest resources. However, low tariff rates in the TG scenario also enable exports from developing regions, and the FSU, which lead to a decrease in forest resources in these regions in the long run.

TG Scenario

The TG scenario (Figure 3.4a) shows a continuous increase in the production of industrial roundwood in all six regions, except in OECD90 where it decreases 2030 onwards. This decrease in production is not related to a decrease in the demand for industrial roundwood. It only indicates that the countries in this region will be able to satisfy increasing industrial roundwood demands while keeping raw roundwood removals low due to high progress in technology, implementation of effective paper recycling and increasing involvement in imports of raw or processed industrial roundwood. Even though production is highest in OECD90, Figure 3.4b indicates that FSU will emerge as a major exporter of raw or processed industrial roundwood among all six MA regions. There is already a steady increase in the number of wood processing industries interested in logging in this region (http://www.borealforest.org). Many countries in Asia, especially South Korea, import large quantities of tropical hardwood. However, as these supplies get more limited, FSU represents a potential supplier to these regions. Current economic problems and need for foreign currency might force the region to engage in higher wood technology progress, thus being able to play the role of a major wood exporter as well as to protect the cultural and environmental interests of its country and people (http://ces.iisc.ernet.in). Asia and OECD90 are active importers in this scenario with imports in to the OECD90 region being at a higher level than into Asia (The major importers in OECD90 are Japan, Finland, Sweden and Italy. China, Korea and India are the major importers in Asia.) While low economical growth is mainly responsible for higher imports into Asia during the entire study period, a very high economical growth in the OECD90 is mainly responsible for higher imports into the region in order to maintain forest resources. Figure 3.4b shows that industrial roundwood exports from the LAM remain at a constant level throughout the projection period. Despite technology progress, heavy increase in population (leading to low per capita GDP) in the region as assumed in the MA scenario is mainly responsible for the LAM inability to participate to a greater extent in industrial roundwood exports. Furthermore, as indicated in Figure 3.4b, the MENA and SSA regions are hardly involved in industrial roundwood trade. This trend can be attributed to constantly improving technology in these regions, which enables them to satisfy their own industrial roundwood demands while maintaining their forest ecosystems to some extent.

OS Scenario

The OS scenario shows a continuous increase in the production of industrial roundwood in all six MA regions (Figure 3.5a). Also, in all regions, production in the OS is higher than in the TG scenario. Higher production in the OS can be attributed to lower per capita GDP, slower development of technology and less consideration for forest conserving activities like paper recycling, leading to greater exploitation of forest resources. However, trade quantities in this scenario are much lower than in the TG since this scenario depicts a regional world with trade barriers, thereby tending to reduce trade among regions. Like in the TG, Figure 3.5b indicates that FSU will emerge as a major exporter of raw or processed industrial roundwood, while Asia (mainly China, Korea and India) and OECD90 (mainly Japan, Sweden, Finland and Italy) remain as major importers. However, unlike in the TG, the OECD90 imports much less compared to Asia. This difference occurs for two reasons. First, population growth in Asia is assumed to be higher than in OECD90 in the OS. Second, OECD90 owing to its economy is very capable of equipping itself for wood requirements without depending on imports. On the other hand, Asia, with a less developed economy and experiencing an assumed heavier increase in population, still needs to import raw/processed industrial roundwood. Another reason that adds to the phenomenon is that slow development in technology and increasing pressure on forest ecosystems additionally force the region to import more industrial roundwood. The LAM is involved only to a small extent in industrial roundwood exports. As in the case of the TG, MENA and SSA are hardly involved in imports or exports of industrial roundwood. They manage to satisfy their regional wood demands based on their internal production.

3.3.1.2 Production under GEO4 scenarios

Results

The global production of industrial roundwood increases by approximately 100% between 2006 and 2050 across the SusF and MF scenarios. Detailed results on production and net trade of industrial roundwood in the six GEO4 regions - (1) Africa (2) Latin America and the Caribbean (3) North America (4) Asia and the Pacific (5) Europe and (6) West Asia - as outlined in the Global Environment Outlook (GEO4) scenarios are outlined and discussed below.

SusF Scenario

Globally, the total production of industrial roundwood increases almost 40% between 2006 and 2050, from 1.7 billion m^3 to nearly 2.4 billion m^3. The simulations indicate a continuous increase in the production of industrial roundwood in all regions until 2050, except in North America, where it continuously decreases over the entire projection period; and in West Asia, where it remains almost constant throughout (Figure 3.6a). Figure 3.6b shows the net trade of industrial roundwood in the six GEO4 regions. The curves indicate that ‘West Asia’ and ‘Asia and the Pacific’ regions are the only two

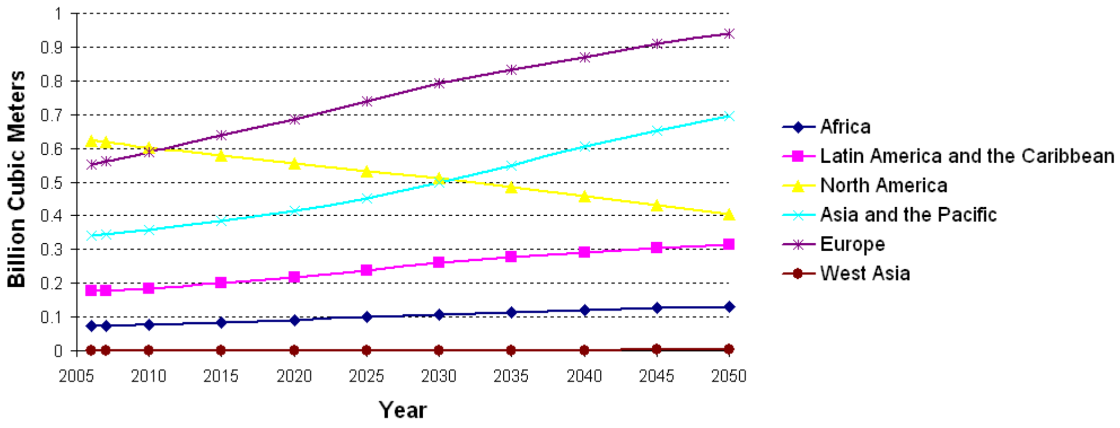

Figure 3.6a: Production of Total Industrial Roundwood in SusF Scenario

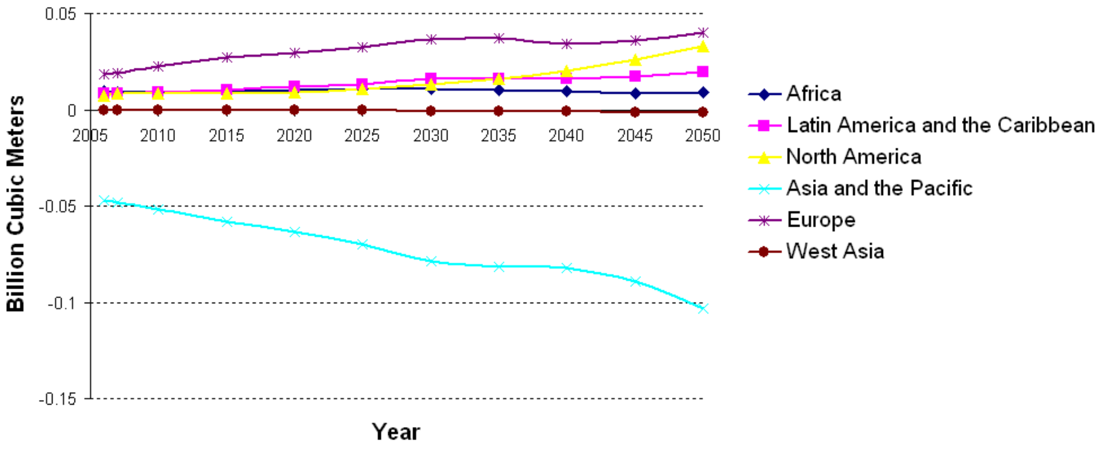

Figure 3.6b: Net trade of Total Industrial Roundwood in SusF Scenario

importers of industrial roundwood among the six GEO4 regions. Europe is the major exporter of industrial roundwood. North America, Latin America and Caribbean, and Africa are also significant industrial roundwood exporters over the entire projection period.

MF Scenario

The global production of industrial roundwood increases almost 150% between 2006 and 2050, from 1.7 billion m^3 to nearly 4.5 billion m^3. The simulations indicate a continuous increase in the production of industrial roundwood in all regions (Figure 3.7a). Also, in each region, production in this scenario is higher than in the SusF. Figure 3.7b shows the net trade of industrial roundwood in the six GEO4 regions. Like in the SusF scenario, Europe emerges as a major exporter of industrial roundwood among the six GEO4 regions. The ‘Asia and the Pacific’ region emerges as a major importer. However, the export quantities of industrial roundwood from Europe and Latin America and Caribbean regions as well as the import quantities of industrial roundwood into the Asia and the Pacific region are much higher in MF than in the SusF over the entire projection period. Europe exports almost three times more than in the SusF. Imports into the Asia and the Pacific region are almost twice as much as in the SusF. However, export quantities from North America are almost the same in both MF and SusF scenarios. Also, unlike in SusF, exports from Africa decrease continuously over the entire projection period and the region starts importing industrial roundwood in small quantities from 2040 onwards. Finally, West Asia is involved in industrial roundwood imports to a small extent and these import quantities are almost the same in both MF and SusF scenarios.

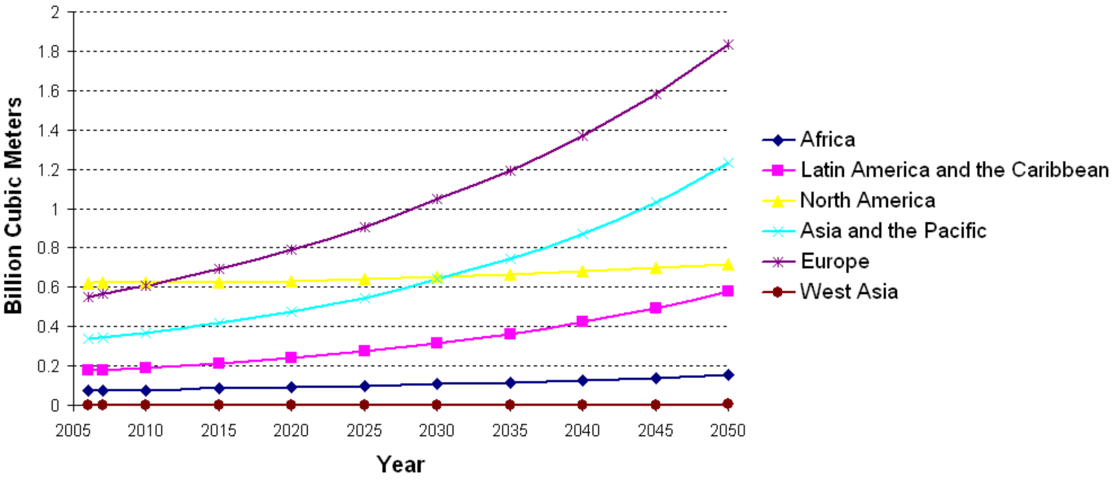

Figure 3.7a: Production of Total Industrial Roundwood in MF Scenario

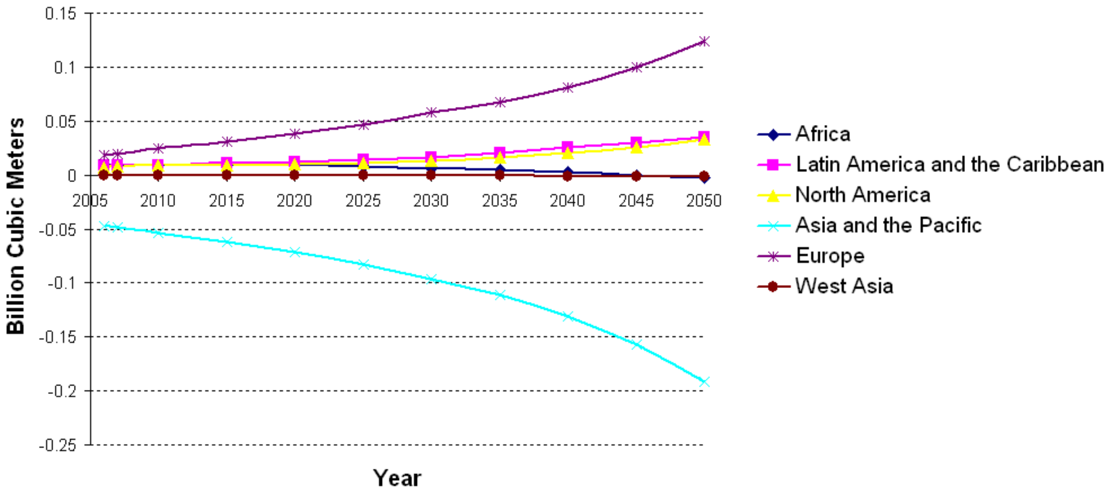

Figure 3.7b: Net trade of Total Industrial Roundwood in MF Scenario

Discussion

Global production of industrial roundwood is almost 100% higher in the MF scenario than in the SusF scenario by 2050. In general, higher population and less technology development are responsible for higher production (extraction of raw wood) in MF. Lesser population than in MF and higher technology advancement are the major factors responsible for lower production in the SusF scenario. However, low tariff rates in the MF scenario are responsible for promoting exports from developing regions, especially the Russian Federation, which might lead to a decrease in forest resources in these regions in the long run.

SusF Scenario

The SusF scenario (Figure 3.6a) shows a continuous increase in the production of industrial roundwood in all six regions, except in North America, where the production decreases continuously between 2006 and 2050. This decrease in production is not necessarily related to a decrease in the demand for industrial roundwood. It only indicates that Canada and USA will be able to satisfy increasing industrial roundwood demands while keeping raw roundwood removals low due to high progress in technology, implementation of effective paper recycling and increasing involvement in imports of raw or processed industrial roundwood. Among all six regions, production is highest in Europe. According to the regional classification in GEO4, Russian Federation is a part of the Europe region. Also, the results indicate that it will export very high amounts of industrial roundwood among all the countries in Europe. Even in the TG scenario in MA (Figure 3.4b), the FSU region emerges as a major exporter, with exports from Russia being the highest. The discussion for Russia emerging as a major exporter in the SusF scenario can be attributed to the same lines of thought as discussed in the TG scenario above. Asia and the Pacific is the only active importer in this scenario with the majority wood being imported by China and Japan. However, the results indicate that China will see a continuous increase in imports whereas Japan will experience a continuous decrease in its imports. Japan already has a long history of tropical timber exports. The main sources of tropical timber imported into Japan were Malaysia, Indonesia and Papua New Guinea (ITTO Annual Review 1999). Since Japan's tropical log imports declined in the 1990's, the world's number one importer of tropical logs is now China. The net trade projections for China and Japan are very representative of the current trends seen in these two countries. According to the GEO4 assumptions, decrease in GDP per capita in China is mainly responsible for higher imports. On the other hand, continuously increasing GDP per capita between 2005 and 2050 in Japan is mainly responsible for reduced imports into the region. North America (mainly Canada), Latin America and Caribbean (mainly Brazil and Chile), are also significant industrial roundwood exporters over the entire projection period in this scenario. High wood technology growth in these countries is the main factor that will enable these countries to continue being major exporters to their regions. Africa (mainly South Africa) is also involved in exports to some extent.

MF Scenario

The MF scenario (Figure 3.7a) shows a continuous increase in the production of industrial roundwood in all six GEO4 regions. Also, in all regions, production in MF is higher than in the SusF scenario. Higher production in this scenario can be attributed to higher population growth, slower development of technology and less consideration for forest conserving activities like paper recycling, leading to greater exploitation of forest resources. However, trade quantities in this scenario are much higher than in the SusF since this scenario depicts a liberalized world with decelerating trade barriers and encouraging active trade among regions. Figure 3.7b indicates that Europe, mainly Russian Federation, will emerge as a major exporter of raw or processed industrial roundwood like in SusF. Also, Asia and the Pacific (mainly China and Japan) is the only importer in this scenario as well. Higher increase in population than in the SusF, slower development in technology, and much reduced trade import tariffs are mainly responsible for higher imports into the Asia region in this scenario. As in the case of SusF, North America (mainly Canada), Latin America and Caribbean (mainly Brazil and Chile), are significant industrial roundwood exporters over the entire projection period. Africa (mainly South Africa) is also involved in exports to some extent.

3.3.2 Regional Analysis

Exemplarily, regional results are presented for Brazil and Canada, because these regions strongly contrast in forest cover, economic status and climate. In both scenarios, these countries also play an important role in the net trade of Industrial Roundwood. According to the projections, Brazil is one country within the LAM region in MA as well as within the ‘Latin America and the Caribbean’ region in GEO4 that is actively involved in Industrial Roundwood exports. In the MA, within the OECD90, while most of the countries are mainly shown to be importers of Industrial Roundwood, Canada is shown to emerge as a major exporter. Also, in the GEO4, Canada is the major exporter in the North America region.

3.3.2.1 Brazil

MA Scenarios

Industrial roundwood production increases continuously between 2006 and 2050. Table 3.2a shows the production of industrial roundwood in Brazil from 2006 – 2050 under the TG and OS scenarios. In TG, the production of industrial roundwood increases by approximately 66% until 2050. The OS scenario shows a production increase of 180% during the projection period. The relative difference between the estimated production of industrial roundwood in the OS and TG scenarios increases continuously during the entire projection period (Table 3.2a). Production in TG is almost 68% less than in the OS by 2050. This difference can be attributed to modest population growth, increased economic growth in terms of GDP and GDP per capita as well as to greater improvement in technology in the TG scenario. Hence, increased production activity is possible while keeping raw wood extraction low. On the contrary, higher population growth, lower income and less progress in technology as described in the OS scenario are responsible for increased raw wood removals in the country.

Exports of Industrial Roundwood from Brazil are continuously on the rise over the entire length of the projection across both TG and OS (Table 3.2b). However, export quantities are much less in the OS than in the TG mainly because of higher tariff rates in the OS.

Year	TG (million m^3)	OS (million m^3)	Relative Difference
2006	112.0	112.0	0.00
2010	116.8	119.1	1.96
2015	123.6	130.7	5.78
2030	157.2	180.8	15.02
2050	186.2	314.1	68.69

Table 3.2a: Production of industrial roundwood in Brazil (2006-2050). The table shows the relative difference in the estimated production of industrial roundwood in TG and OS scenarios in Brazil.

Year	TG (million m^3)	OS (million m^3)
2006	2.2	2.2
2010	2.7	2.2
2015	3.5	2.3
2030	7.4	2.5
2050	20.1	6.0

Table 3.2b: Net trade of industrial roundwood in Brazil (2006-2050). The table shows the estimated exports of industrial roundwood in TG and OS scenarios from Brazil.

GEO4 Scenarios

Industrial roundwood production increases continuously between 2006 and 2050. Table 3.3a shows the production of industrial roundwood in Brazil from 2006 – 2050 under the SusF and MF scenarios. In SusF, production of industrial roundwood increases by 55% until 2050. The MF scenario shows a production increase of 192% by 2050. The relative difference between the estimated production of industrial roundwood in the MF and SusF scenarios increases continuously during the entire projection period (Table 3.3a). Production in the SusF is almost 87% less than in the MF by 2050. Low population and very high technology growth in the SusF scenario are mainly responsible for lesser production than in the MF scenario, where, on the contrary, population is quite high (as described in the GEO4 scenarios) and technology growth is less.

Exports of Industrial Roundwood from Brazil are continuously on the rise over the entire length of the projection across both SusF and MF (Table 3.3b). However, export quantities are much less in SusF than in the MF, especially from 2030 onwards, mainly because of lower tariff rates in the MF.

Year	SusF (million m^3)	MF (million m^3)	Relative Difference
2006	112.1	112.1	0.00
2010	116.6	119.1	2.14
2015	123.6	130.0	5.20
2030	153.8	185.8	20.82
2050	174.8	328.0	87.67

Table 3.3a: Production of industrial roundwood in Brazil (2006-2050). The table shows the relative difference in the estimated production of industrial roundwood in SusF and MF scenarios in Brazil.

Year	SusF (million m^3)	MF (million m^3)
2006	2.2	2.2
2010	2.7	2.7
2015	3.5	3.5
2030	7.4	7.5
2050	13.37	20.04

Table 3.3b: Net trade of industrial roundwood in Brazil (2006-2050). The table shows the estimated exports of industrial roundwood in SusF and MF scenarios from Brazil.

3.3.2.2 Canada

MA Scenarios

The results for Industrial Roundwood production in Canada for the period 2006-2050 in both TG and OS scenarios are presented in Table 3.4 a. Industrial roundwood production under the TG scenario decreases by approximately 11% by 2050. In the OS scenario, production increases continuously by around 50% between 2006 and 2050. The production of industrial roundwood is much less in TG scenario than in OS. This is mainly because Canada is a developed country and according to the TG scenario, high GDP growth, higher involvement in paper recycling activities and high technology growth enables the country to fulfill the demands for raw forest product commodities keeping production at a low level from its available forest resources. On the other hand, high increase in population, less consideration for ecosystems management and low technology progress are responsible for increased raw wood removals in the OS scenario.

Industrial Roundwood export quantities in the OS scenario are less than in the TG scenario mainly because of higher tariff rates in the OS (Table 3.4b).

Year	TG (million m³)	OS (million m³)	Relative Difference
2006	197.7	197.7	0.00
2010	193.2	200.1	3.56
2015	190.3	206.0	8.29
2030	185.3	231.3	24.82
2050	175.2	295.2	68.51

Table 3.4a: Production of industrial roundwood in Canada (2006-2050). The table shows the relative difference in the estimated production of industrial roundwood in TG and OS scenarios in Canada.

Year	TG (million m³)	OS (million m³)
2006	1.5	1.5
2010	1.5	1.5
2015	4.3	4.3
2030	10.5	7.9
2050	32.2	23.4

Table 3.4b: Nettrade of industrial roundwood in Canada (2006-2050). The table shows the estimated exports of industrial roundwood in TG and OS scenarios from Canada.

GEO4 Scenarios

Industrial roundwood production under the SusF scenario decreases by 8% by 2050, while in the MF scenario, it increases by 61% by the end of the projection period (Table 3.5a). The production of industrial roundwood is much less in SusF than in the MF. Like in the case of Brazil, low population combined with very high technology growth in the SusF scenario is mainly responsible for lesser production than in the MF scenario.

Exports of Industrial Roundwood from Canada are continuously on the rise over the entire length of the projection across both SusF and MF (Table 3.5b). However, export quantities are slightly less in the SusF scenario than in the MF scenario, mainly because of lower tariff rates in the MF.

Year	SusF (million m³)	MF (million m³)	Relative Difference
2006	197.7	197.7	0.00
2010	194.6	201.1	3.34
2015	193.5	209.0	8.01
2030	191.7	244.6	27.60
2050	182.9	318.4	74.08

Table 3.5a: Production of industrial roundwood in Canada (2006-2050). The table shows the relative difference in the estimated production of industrial roundwood in SusF and MF scenarios in Canada.

Year	SusF (million m³)	MF (million m³)
2006	1.5	1.5
2010	1.5	1.5
2015	4.2	4.3
2030	10.6	10.7
2050	32.3	32.4

Table 3.5b: Nettrade of industrial roundwood in Canada (2006-2050). The table shows the estimated exports of industrial roundwood in SusF and MF scenarios from Canada.

Regarding regional analysis, in both Brazil and Canada, very rich forest ecosystems are located. Brazil holds about one-third of the world's remaining rainforests, including the major fraction of the Amazon rainforest (http://www.mongabay.com); while, Canada’s temperate and boreal forests account for about 10% of the world’s forest cover (http://www.globalforestwatch.org). Both regions are major exporters of wood and, both regions have experienced and are still seeing immense amounts of deforestation due to logging (FAO 2008). With the occurrence of increased logging activities and inappropriate replanting, Northwest Canada has earned itself the nickname "the Brazil of the North."(E: The Environmental Magazine, April, 1994 by Andre Carothers) That is because both Canada and Brazil have similar overall forestland masses, and have witnessed similar amounts of hectares destroyed by forestry (www.mongabay.com). Therefore, without some sort of forest management program, deforestation and environmental degradation can become a severe problem for any country, irrespective of whether that country is considered industrialized like Canada or developing like Brazil.

3.4 Conclusions and Outlook

The end of the 20th century and the beginning of the 21st century have witnessed an increasing amount of globalization in world trade of forest products. This makes it more and more necessary for any individual country or region to plan a strategy or enact a policy taking into account the effects on forestry and trade in other countries. Hence, the implementation of future scenarios in GFPM, which allows simultaneous treatment of the large number of countries and forest commodities, may contribute a very useful feature that can be employed for global land use models like LandSHIFT (Schaldach et al, 2006), which are also taking all other land-intensive sectors into account. The GFPM results obtained in this study will be used to drive forest sector dynamics in LandSHIFT, in order to simulate and analyze spatially explicit land use change and its impacts on the environment on a global scale. The simulated amounts of industrial roundwood production obtained in this study should be regarded as first estimates, obviously depending heavily on both endogenous and exogenous assumptions in the GFPM. Nevertheless this study provides consistent datasets to be used as input for an integrated assessment of the global forestry sector in LandSHIFT as discussed in detail in Chapter 4.

3.5 Supplement: Comparison of GFPM results with existing wood demand scenarios

Over the last 20 to 30 years, numerous timber market models have been developed for various purposes like analyzing policy changes, projecting market behavior, or to consider other, more specific questions related to timber markets (Buongiorno et al., 2003). A key output of all economic forest sector models is the projected demand for forest products. The previous sections presented a detailed analysis of future global and regional demands for total industrial roundwood under the MA and the GEO4 scenarios using the Global Forest Products Model (GFPM). In order to evaluate these outcomes, the global projections of total industrial roundwood production from the GFPM are compared with those from other models and organizations. This section reviews existing demand projections and comments on how the results from the GFPM relate to the forecasts obtained from other economic models and studies.

The comparison includes 26 projections including data from various sources and the results for the four (two from MA and two from GEO4) scenarios obtained with the GFPM. In a few cases, existing studies have provided multiple scenarios that consider variation in factors like projected population, economic growth rates, technology, etc. that could affect demand. Some studies provide projections until year 2010; three studies offer projections until year 2020; one study provides projections until 2035, and three studies offer long-term projections until 2050. The historical baseline data (year 2000) is taken from FAOSTAT online database (FAO Statistical Database, 2008). It should be noted that the model projections are a function of both theoretical and structural differences, as well as of the specific set of scenario assumptions (at regional and/or global levels) leading to model output. It is quite possible that these scenario assumptions may be a more important aspect of any differences than the theory. This study does not take into account these differences/assumptions in this analysis. The main focus is to compare the GFPM output on global industrial roundwood demand to other existing long-term global demand projections. Table 3.6 offers a brief overview of some existing global demand projections. Table 3.7 provides a summary of the global results simulated under the MA and the GEO4 scenarios with the GFPM.

The reference studies that offer projections until 2010 are: Brooks et al (1997), Brown et al. (1999), FAO (1999), Jaako Poyry (1995), and Nilsson (1996), non-mainstream. Three studies that provide demand projections till 2020 are Apsey & Reed (1995), International Tropical Timber Organization (ITTO 1999) and Nilsson (1996). One study (Sedjo and Lyon, 1990) provides demand estimates till 2035. Other projections that go until the year 2050 are those of Sohngen et al. (1999), Solberg et al. (1996) and Victor and Ausubel (2000).

Table 3.6: Summary of Projections from reference studies

*Reference Studies**	Demand for industrial roundwood (billion m^3)				
	2000	2010	2020	2035	2050
Apsey & Reed (1995)		--	2.2	--	--
Brooks et al (1997) scenario #1		1.8	--	--	--
Brooks et al (1997) scenario #2		1.9	--	--	--
Brown et al. (1999)		1.8	--	--	--
FAO Committee on Forestry (1999)		1.8	--	--	--
FAOStat (Historical)	1.6	--	--	--	--
ITTO (1999)		--	2.2	--	--
Jaako Poyry (1995)		1.7	--	--	--
Nilsson (1996)		--	2.4	--	--
Nilsson (1996), non-mainstream		1.8	--	--	--
Sedjo & Lyon (1990) base case		--	--	2.0	--
Sedjo & Lyon (1990) high demand		--	--	2.3	--
Sohngen et al (1999) high demand		--	--	--	2.5
Sohngen et al (1999) low access cost		--	--	--	2.2
Sohngen et al (1999) baseline		--	--	--	2.1
Sohngen et al (1999) low plantation		--	--	--	2.0
Solberg et al (1996) scenario 1		--	--	--	1.8
Solberg et al (1996) scenario 2		--	--	--	1.9
Solberg et al (1996) scenario 3		--	--	--	2.4
Solberg et al (1996) scenario 4		--	--	--	2.5
Solberg et al (1996) scenario 5		--	--	--	2.9
Solberg et al (1996) scenario 6		--	--	--	3.0
Victor and Ausubel (2000)		--	--	--	2.0

**The studies included are for total world industrial roundwood, undistinguished between dimension lumber and pulp. Non-industrial woods such as fuelwood are not included.*

Table 3.7: Summary of Projections from the GFPM

GFPM results	Demand for industrial roundwood (billion m^3)				
	2000	2010	2020	2035	2050
MA 'Techno Garden' (TG)		1.8	1.9	2.0	2.1
MA ‘Order from Strength’ (OS)		1.8	2.0	2.5	3.2
GEO4 ‘Sustainability First’ (SusF)		1.8	1.9	2.1	2.4
GEO4 ‘Markets First’ (MF)		1.8	2.2	3.1	4.5

For the entire set of projections until 2010 only, the average estimate of total industrial roundwood is 1.9 billion m^3. This figure is quite comparable to the GFPM average forecast of 1.8 billion m^3 in all four scenarios. For the year 2020, the demand forecasts from the existing studies are in the range 2.2 – 2.4 billion m^3. This corresponds to the GFPM forecast for the MF scenario, which is 2.2 billion m^3. The demand forecasts for the TG, OS and SusF scenarios are also comparable but are slightly more modest. The TSM (Sedjo and Lyon, 19960), which is a formal economic model, provides demand projections of 2.0 billion m^3 for a ‘base-case’, and of 2.3 billion m^3 for a ‘high-demand’ scenario for the year 2035. The TSM results correspond closely to the TG, OS and SusF scenarios. However, when compared to the demand forecast from the MF scenario in GEO4, the difference gets quite large.

The three case studies that offer long term total industrial roundwood demand projections until the year 2050 are those of Sohngen et al. (1999); Solberg et al. (1996) and, Victor and Ausubel (2000). Victor and Ausubel (2000) provide a range of 2.0 - 2.5 billion m^3, but again argue for the lower estimate of 2.0 billion m^3 by 2050. Sohngen et al. (1999) provides a global demand estimate of 2.0-2.5 billion m^3 by 2050. On an average, Solberg et al. (1996) also provides an estimate of 2.4 billion m^3 across the six scenarios. These figures are quite corresponding to the TG scenario estimate of 2.1 billion m^3 and to the SusF scenario estimate of 2.4 billion m^3 for the year 2050. However, the difference gets quite significant when compared to the OS scenario forecast of 3.2 billion m^3 (although it corresponds quite closely to Scenario 6 when individual scenarios are considered). The forecast of 4.5 billion m^3 for the MF scenario in GEO4 is almost double than that what most of the existing demand projections estimate and is very much beyond the average range.

In summary, variance among the projections from existing scenarios and from the GFPM increases as the projections reach farther and farther into the future. For the long term till 2050, the GFPM projections of global industrial roundwood demands in the TG and SusF scenarios are quite modest and conservative. They agree with what most of the analysts believe that demand in 2050 will be near 2 billion m^3, or roughly a one-third increase over 50 years above current levels. On the other hand, GFPM demand projections in the OS and MF scenarios are quite extreme and reflect very high future demand.

3.6 References

Apsey, Mike; Reed, Les. 1995, cited in FAO, 1997, *XI World Forestry Congress*. Volume 4, Topic 21, Part 1. Food & Agriculture Organization of the United Nations (FAO): Antalya, Turkey, 13-22 October.

Berglund, C., P. Söderholm. 2003. An Econometric Analysis of Global Wastepaper Recovery and Utilization. Environmental and Resource Economics, Vol. 26, pp. 429-546.

Boreal Forests: http://www.borealforest.org/

Brooks et al, 1997, cited in FAO, 1997, *XI World Forestry Congress*. Volume 4, Topic 21, Part 1. Food & Agriculture Organization of the United Nations (FAO): Antalya, Turkey, 13-22 October.

Brown, Christopher, Gary Bull and Adrian Whiteman, 1999, *Forest Product Market Developments*. Working Paper FAO/FPIRS/02. Food & Agriculture Organization of the United Nations (FAO): Rome.

Buongiorno, J., S. Zhu, D. Zhang, J.A. Turner, and J. Tomberlin. 2003. The Global Forest Products Model: Structure, Estimation and Applications. San Diego, CA: Academic Press.

Buongiorno, J. Personal Communication.

E – The Environmental Magazine: http://www.emagazine.com/

FAO 2008: FAOStat. Food and Agriculture Organization, United Nations, Rome.

Food and Agriculture Organization. 2001. “Global Forest Resources Assessment 2000: Main report.” FAO Forestry Paper No. 140, Food and Agriculture Organization, United Nations, Rome.

FAO Committee on Forestry, 1999, *14th Session*. Food & Agriculture Organization of the United Nations (FAO): Rome, March 1-5.

FAO, 1999, *State of the World's Forests 1999*. Food & Agriculture Organization of the United Nations: Rome.

Forestry Statistics of Canada and Brazil: www.mongabay.com

GFPM User Manual: http://www.forest.wisc.edu/facstaff/buongiorno/book/GFPM.htm

Global Forest Watch: http://www.globalforestwatch.org/

Ince, Peter J. 1994. Recycling and the Long-Range Timber Outlook. General Technical Report RM-242. Ft. Collins: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station.

ITTO – International Tropical Timber Organization. Annual Review 1999. URL: http://www.itto.int.

Jaako Poyry, 1995, cited in FAO, 1997, *XI World Forestry Congress*. Volume 4, Topic 21, Part 1. Food & Agriculture Organization of the United Nations (FAO): Antalya, Turkey, 13-22 October.

MA – Millennium Ecosystem Assessment 2005. URL: www.millenniumassessment.org.

Mabee, W. E. 1998. The importance of recovered fibers in global fiber supply. Unasylva 49(193):31-36.

Mabee, W.E., and H. Pande. 1997. Recovered and Nonwood Fiber: Effects of Alternative Fibers on Global Fiber Supply. Working Paper GFSS/WP/04. Food and Agriculture Organization of the United Nations, Rome.

Nilsson, Sten 1996, cited in FAO 1995, cited in FAO, 1997, *XI World Forestry Congress*. Volume 4, Topic 21, Part 1. Food & Agriculture Organization of the United Nations (FAO): Antalya, Turkey, 13-22 October.

Russia's First World Heritage Site: http://ces.iisc.ernet.in/

Schaldach, R., J. Alcamo, and M. Heistermann, 2006. The multiple-scale land use change model LandShift: a scenario analysis of land use change and environmental consequences in Africa, in A. Voinov, et al. (Eds.): *Proceedings of the iEMSs Third Biennial Meeting: "Summit on Environmental Modelling and Software"*, International Environmental Modelling and Software Society, Burlington, USA.

Sedjo, R.A., and K.S. Lyon. 1996. "Timber Supply Model 96: A Global Timber Supply Model with a Pulpwood Component." Discussion Paper 96-15. Washington: Resources for the Future.

Sedjo, Roger A. and Kenneth S. Lyon, 1990, *The Long-Term Adequacy of World Timber Supply*. Resources for the Future (RFF): Washington.

Sohngen, Brent, Robert Mendelsohn, and Roger Sedjo, 1999. "Forest Management, Conservation, and Global Timber Markets," American Journal of Agricultural Economics 81 (February).

Solberg, B, D. Brooks, H. Pajuoja, T.J. Peck, P. A. Wardle, 1996, *Long-Term Trends and Prospects in World Supply and Demand for Wood and Implications for Sustainable Forest Management.* Research Report 6. European Forest Institute (EFI): Joensuu, Finland.

Turner, J.A., J. Buongiorno, F.M. Maplesden, S. Zhu, S. Bates, and J. Tomberlin. 2006. World Wood Industries Outlook 2005 – 2030. Forest Research Bulletin 230.

Turner, J., and J. Buongiorno. 2001. International freight rates for forest products: Structure, past trends and forecasts. International Forestry Review 3(2):136-145.

UNEP 2007. GEO 4 scenario descriptions. (URL: www.unep.org/geo/geo4)

Victor D. G. and Jesse H. Ausubel, 2000, “Restoring the Forests,” *Foreign Affairs*, vol. 79, No. 6. (November/December), pp. 127-144.

Zhu, S., and J. Buongiorno. 2002. “International Impact of National Environmental Policies: The case of Paper Recycling in the United States.” International Forestry Review 4(2): 133-142.

Zhu, S., J. Buongiorno, and D. Brooks. 2001. “Effects of Accelerated Tariff Liberalization on the Forest Products Sector: A Global Modeling Approach.” Forest Policy and Economics 2(1): 57-78.

CHAPTER 4

Implementation of FOREST Module in LandSHIFT

Summary

Deforestation is recognized as one of the most significant components in land use/cover change and global environmental change processes. It is imperative to assess its trend and the rates at which it is occurring by accounting for various proximate and underlying drivers of land-use/land-cover change. This study concentrates on the implementation of a new land-use activity that identifies wood extraction as a *proximate driver* of land-cover change in LandSHIFT. Accordingly, a methodology to simulate the spatial dynamics of forests based on wood extraction is developed within the LandSHIFT framework. New features in the model include (1) a module to calculate cell level biomass productivity of forests (2) a forest management activity as a new addition to the land-use change (LUC) module. Simulated changes in forest areas are exogenously driven by wood demands at country scale. The spatial allocation of wood demands on a five arc minute grid is governed by a set of spatial factors such as forest stock, terrain slopes, proximity to settlements, etc. The methodology is tested and applied in an exemplary simulation experiment for India based on a Global Environmental Outlook scenario. Although the module is in a very preliminary stage of development and is based on coarse assumptions, it already captures the effects of important drivers of land-use change like cropland and urban expansion. As a first plausibility test, the module performance is tested under three forest management scenarios. The module succeeds in responding to changing inputs in an expected and consistent manner. This study is a first attempt to integrate and expand the modeling capabilities of LandSHIFT with wood scenario data from a global forest economy model and forest stock data from a global vegetation model.

Keywords: Land use change, forests, human interaction, wood extraction, India, plausibility testing, simulation experiment.

4.1 Introduction

Recently, human influence on land has become globally extensive and intensive, ranging from the extreme transformation of urban environments, to the intensive management of agricultural areas, or the careful protection of recreational areas and parks (Foley et al. 2005). Deforestation, agricultural expansion and intensification, urban expansion, and desertification are significant global environmental issues (Lepers et al. 2005). According to Foley et al. (2005), nearly 30 to 40 percent of the global land surface is being exploited for agriculture. Also, tropical deforestation continues unabated, especially in Southeast Asia (Lepers et al. 2005). Such large-scale changes in land- use/land-cover can modify regional and global climate, degrade freshwater resources, cause air pollution, fragment habitats, cause species extinction and biodiversity loss, and have various other negative impacts (Foley et al. 2005). Clearly, land-use and land-cover change is a major driver of global change. In order to anticipate and understand future land-use/land-cover changes, it is helpful to have models that incorporate the cause-effect relationships involved in these global change processes. Chapter 1 (Section 1.6) offered a brief introduction to LandSHIFT, a global scale model that can be used to develop scenarios of future land-use/land-cover changes.

Contemporary land-cover change is generated principally by human activities directed at manipulating the Earth's surface for some individual or societal need or want, such as wood, agriculture, etc. (Ojima et al. 1994; Cassman et al. 2005). Land- use is the sum of the proximate (or direct) causes of land-cover change i.e., human activities that originate from the intended manipulation of land-cover (Lambin and Geist 2006). Proximate causes involve a physical undertaking on land-cover and usually comprise a recurrent set of land-use activities such as development of infrastructure/ expansion of built-up areas, agriculture/expansion of agricultural areas, and forestry/wood extraction (Lambin and Geist 2006). So far, the land-use/change (LUC) module in LandSHIFT comprises three sub-modules, each of them representing a particular land-use activity: "settlements", "crop cultivation" and "rangeland grazing" (Schaldach at al., 2006). This study concentrates on the implementation of a new land-use activity called "forest", which identifies wood extraction as an additional '*direct driver*' of land-cover change in the

LUC module in LandSHIFT. The implementation of this land-use activity facilitates the simulation of the effects of wood extraction on the spatial dynamics of forest areas. The driving force behind "wood extraction" that might lead to deforestation* is demand for raw wood commodities (industrial roundwood, fuelwood) per country. In this study, wood demand scenarios have been generated using the Global Forest Products Model (Buongiorno et al. 2003).

Section 4.2 describes the methodology to implement the allocation of wood demand in LandSHIFT. Section 4.3 outlines a simulation experiment for India and presents the first model results. It also offers a brief sensitivity analysis of the module behavior under different forest management scenarios. Section 4.4 presents the discussion on this study. Section 4.5 offers some concluding remarks. Section 4.6 describes in detail the application and testing of the LPJ (Lund-Jena-Potsdam) model to generate simulation data on potential vegetation carbon to be used as input in LandSHIFT.

4.2 Forestry in LandSHIFT

The LandSHIFT model has been expanded by two new components to simulate the spatial and temporal dynamics of forest management: (1) a module to calculate cell level biomass productivity of forests (2) a forest management activity (FOREST) as a new part of the land-use change (LUC) module.

4.2.1. Additional input data and model output

Table 4.1 lists all the relevant data used for this study, categorised according to spatial scale and purpose.

As additional input, wood demand generated by the Global Forest Products Model (Chapter 3) is included at the country level. Secondly, a global forest inventory map described by Kindermann et al. (2008) is included on the 5 arc minute grid. It provides spatially disaggregated FAO forest inventory data for the year 2000 on a 0.5-degree raster. Based on this information the initial biomass stock is computed for each micro

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** LandSHIFT assumes the FAO definition of deforestation in its framework. According to FAO 2000, deforestation refers to change of land-cover with depletion of tree crown cover to less than 10%.*

level cell that is classified as 'forest' in the base land-cover map in LandSHIFT (Section 4.2.2).

As additional output, the module generates time series of 5 arc minute maps (in 5-year time steps) that include data on (1) amount of extracted biomass and (2) current forest stock for each simulation time step (Figure 4.1).

Table 4.1: Input datasets used in this study.

Spatial level	Model variable	Temporal coverage	Purpose	Comments	Source
Country	Wood Production	2000 - 2050	Scenario Driver	Production of 2 major wood types per country, from GFPM (See Chapter 3)	Prepared for this study
	Change in crop production			Change in food crop production relative to baseline based on IMPACT model	Rothman et al. (2008)
	Change in crop yields			Change in crop yields due to technology change, based on IMPACT calculations	
	Population growth			Change in human population per country relative to baseline based on IFs calculations	
	Crop production	1990 - 2000	Baseline definition	Production of major crop types per country	FAO (2006)
	Total irrigated area per crop	1991 - 1993		Specifies the area irrigated for each of the above crops; sums up to FAOStat total irrigated area per country	FAO (2006); Schaldach et al. (2009)
Grid, 30 arc minutes	Change in vegetation carbon	2000 - 2050	Carbon productivity	Change in vegetation carbon stocks relative to the baseline as influenced by soil and climate (Section 4.6)	LPJ-DGVM (Sitch et al., 2003)
Grid, 5 arc minutes	Forest inventory data	2005	Initial condition	Biomass stock of each 5 arc minute grid cell in LandSHIFT	Kindermann et al. (2008)
	Land-use/land-cover type	1991 - 1993		Map of natural land-cover types	Heistermann (2006)
	Population density	1990		Population density	Klein-Goldewijk (2005)
	Terrain slope	1995 - 2050	Preference ranking	Median slope within grid cell; includes seven slope classes	IIASA and FAO (2000)
	Road infrastructure	1995 - 2050		Line density of road infrastructure per grid cell	Heistermann (2006)
	Conservation areas	2000		Areas designated as national conservation areas	WDPA (2004)

4.2.2 Forest productivity module

The main purpose of this module is to maintain information on woody biomass stocks per forest grid cell (base land-use map) in each time step. Accordingly, the module performs the following tasks:

1. Computes woody biomass stocks per grid cell (before demand allocation)
2. Computes balance of the forest stock in each grid cell (after demand allocation)

Computing woody biomass stocks per grid cell

As a first step, the module computes woody biomass stocks per grid cell in order to allocate wood demands (*See Section 4.2.3.3 for demand allocation*). For this purpose, it uses output data on vegetation carbon from LPJ (Section 4.6) in collaboration with data on aboveground vegetation carbon from Kindermann et al. (2008) as described below.

For each time step, information on aboveground carbon from Kindermann et al. (2008) is used to represent *current carbon stocks* at the 0.5° grid. The *actual availability* of carbon stock per grid cell (referred to as *'corrected stock'* in LandSHIFT) is then calculated by adding 5-year average changes in vegetation carbon* simulated by the LPJ-DGVM to the *current carbon stock* according to Equation 4.1 as follows.

$$Y_k(t+0.5) = Y_k(t) * (1 + \text{Change}) \qquad \text{with } Y_k(0) \text{ from Kindermann et al. (2008)} \qquad \textit{Eq. 4.1}$$

$Y_k(t)$ Forest biomass stock in cell k in time step t [Mg km^{-2}]

Change Change of biomass stock as calculated by the LPJmL model [Mg km^{-2}]

The output is then geographically mapped to the 5 arc minute grid of LandSHIFT.

Next, the corrected carbon stocks are multiplied by a factor of 0.71 to convert forest aboveground carbon to *merchantable wood carbon* (Seiler & Crutzen, 1980). These merchantable wood carbon values are then converted to *woody biomass* values based on

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** The amount of vegetation carbon in each grid cell as simulated by the LPJ is an aggregation of both above- and belowground carbon of all its PFTs. Therefore, the vegetation carbon stock resulting from LPJ is first multiplied by a factor of 0.75; assuming that living belowground carbon (roots) adds up to 25% (Seiler & Crutzen, 1980).*

the assumption that carbon content in woody biomass is 50% (Intergovernmental Panel on Climate Change (IPCC) 2006). Finally, based on wood density data (IPCC 2006) for each forest land-use class in LandSHIFT, the data on woody biomass stocks on *area basis* is converted to woody biomass data on a *volume basis*. Currently LandSHIFT differentiates between five forest types (as defined in the base land-cover map), characterized by different wood densities (Table 4.2).

Table 4.2: Forest types and their respective wood densities.

Forest type	Wood density (t/m^3)
Evergreen Needleleaved	0.55
Evergreen Broadleaved	0.75
Deciduous Needleleaved	0.45
Deciduous Broadleaved	0.75
Mixed	0.65

Source: IPCC (2006). Guidelines for National Greenhouse Gas Inventories, Chapter 4.

Computing forest stock balance in each grid cell

Once the demand allocation routine is fulfilled, the module calculates the balance of the forest stock in each 5 arc minute forest cell according to the following equations:

$$Y_k(t+1) = Y_k(t+0.5) * (1 - \text{Harvest}) \qquad \textit{Eq. 4.2}$$

$Y_k(t)$	Forest biomass stock in cell k in time step t [Mg km^{-2}]
Harvest	Part of biomass stock removed by logging [Mg km^{-2}]

The term *Harvest* represents the fraction of wood to be removed from the available forest stock by logging. This term is computed by the forest management activity as described in Section 4.2.3.3.

4.2.3 Forest management activity

In this study, the land-use change (LUC) module has been enhanced by a new activity designating forest management in LandSHIFT. The task of this module is to regionalize country level demands for forest commodities to the micro level, based on preferences and constraints described in the following paragraphs.

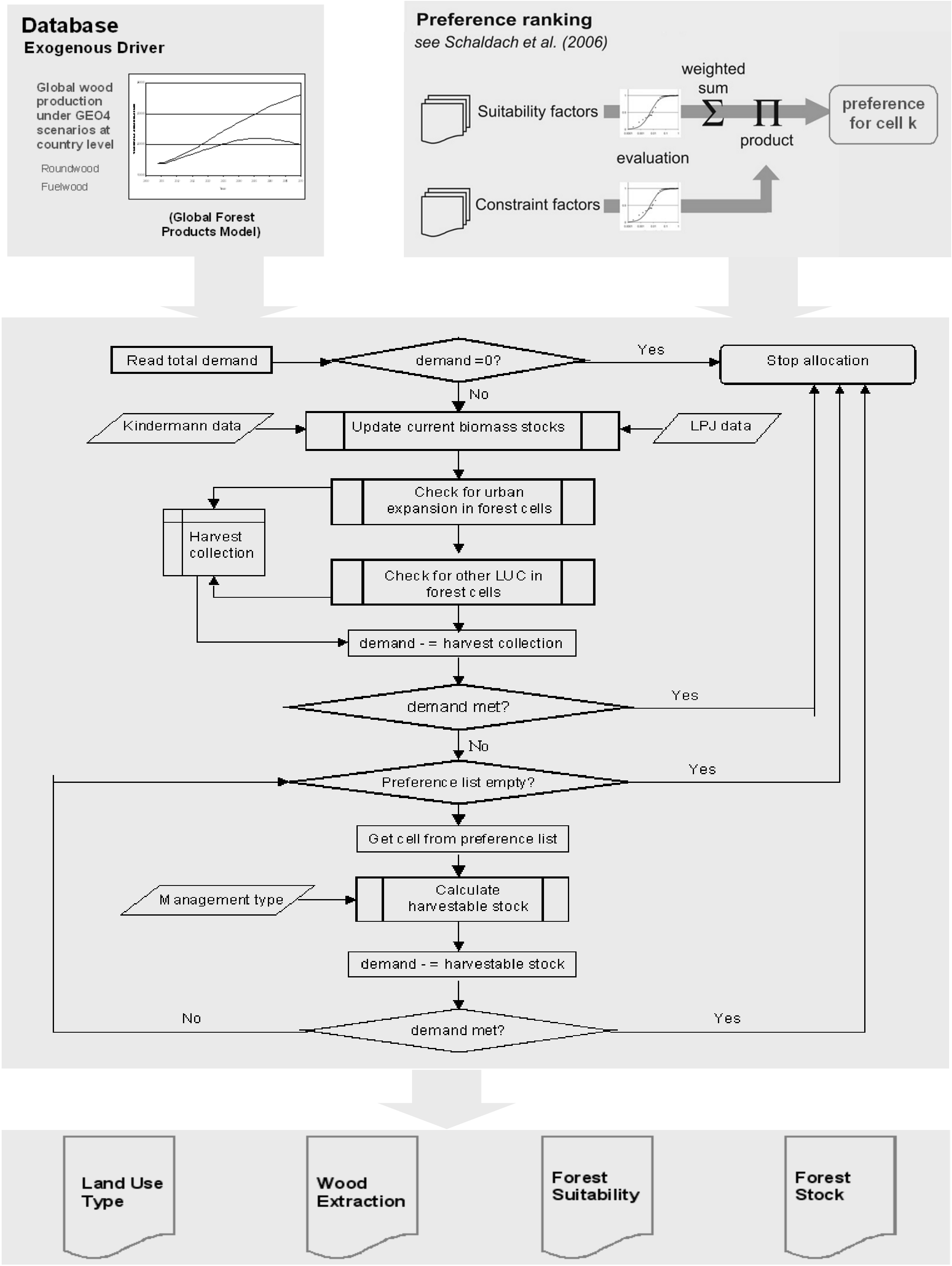


Figure 4.1: Schematic overview of the modelling procedure for a particular time step and country, including the steps driving force processing, preference ranking, and allocation.

Figure 4.1 provides an overview of the modelling procedure. Similar to the other modules in LandSHIFT (Schaldach et al., 2006), this module consists of implementation functions for wood demand calculation (4.2.3.1), preference ranking (4.2.3.2) and wood demand allocation (4.2.3.3). The following sections go through the modelling procedures in detail.

4.2.3.1 Demand Calculation

The wood demands for raw forest commodities are computed by the Global Forest Products Model (GFPM). The application of the GFPM has been described in detail in Chapter 3. Demands for fuelwood and industrial roundwood form the input to the demand allocation function. In this version of the forest management activity, there is no differentiation between the two demand pools. Hence the two demand estimates are first aggregated before being used as input in the allocation procedure (Figure 4.1).

4.2.3.2 Preference Ranking

A preference ranking is carried out on the micro-level in order to identify the most suitable cells for logging (wood extraction). The forest activity conducts a multi-criteria-analysis (MCA) in order to determine the preference value of each micro-level grid cell, based on a set of local cell properties and neighborhood relations. Then, the cells are ranked according to their values.

The *preference value* (Ψ_k) of a forest grid cell is expressed in Eq. 4.3 as:

$$\Psi_k = \underbrace{\sum_{i=1}^{n} w_i f_i(p_{i,k})}_{suitability} \times \underbrace{\prod_{j=1}^{m} g_j(c_{j,k})}_{constraints}, \quad with \sum_i w_i = 1, \; and \;\; f_i(p_{i,k}), g_j(c_{j,k}) \in [0,1] \qquad Eq.\ 4.3$$

w_i	weight of suitability factor p_i	$g_j()$	value function applied on constraint c_j
$f_i()$	value function applied on factor p_i	$c_{j,k}$	constraint j on cell k
$p_{i,k}$	suitability factor i on cell k		

The first term of Eq. 4.3 is the sum of weighted factors p_i that contribute to the cells' suitability for being managed or deforested. These factors include n landscape properties that reflect preferable local conditions. The factor weights w_i determine the importance of a single factor p_i in the analysis. The second term is appended by multiplication and represents m land-use constraints $c_{j,}$ which reflect important aspects of human decision-making. For example, land-use changes in natural conservation areas can be prohibited by setting the corresponding constraint to zero. Both p_i and c_j are standardized by value functions f_i and g_j, which have a co-domain from 0 to 1 (Geneletti, 2004). This allows considering the degree of implementation of a constraint, e.g. the degree of protection of a national park from forestry activities.

The suitability and constraint factors included in this version of the study are briefly described below. This choice is based on an estimation of the most important factors affecting wood harvests (see e.g. Geist and Lambin 2002; World Rainforest Movement (WRM) 1998; Alcamo et al., 1998; Chattopadhyay et al., 1996).

p_1 – forest stocks: Potential yields of forest stocks have been computed on a 30 arc minute resolution with the LPJ-DGVM (Section 4.6) and have been used in collaboration with inventory data on biomass stock provided by Kindermann et al. 2008 (Section 4.2.2). The resulting spatial forest stock distributions are also used in the allocation algorithm in order to assign wood production functions to each grid cell (Section 4.2.4).

p_2 – terrain slope: This dataset was derived from the GTOPO30 data [USGS, 1998] by IIASA and FAO (2000). It includes maps of median terrain slopes categorized into seven slope classes on a 5 arc minute resolution. Terrain slopes are considered an important determinant in wood harvesting because of aspects such as workability and accessibility.

p_3 – proximity to roads: The map on line density of road infrastructure per grid cell has been taken from Heistermann (2006). Forest areas closer to roads are easily accessible for wood harvesting and also provide market access.

p_4, p_5 – population density and neighborhood to agriculture: Forest areas located in close proximity to areas with high population density and neighborhood to agriculture are more attractive for wood harvesting since it provides infrastructure, market access and/or local demand for wood.

c_1 – nature conservation: This constraint assumes the availability of two equally suitable grid cells – one protected, one unprotected. It seems obvious that the protected one is less likely to be harvested than the other. On the other hand, many nature reserves around the globe are actually encroached for timber extraction (WWF, 2004). One could think of different ways to quantify how rigorously the nature protection status constrains encroachment of forest areas (e.g. by considering country level governance indicators such as published by Kaufmann et al. (2005)).

c_2 – availability of minimum vegetation carbon: This constraint is applied as an indicator to identify the locations where wood harvesting would not be ecologically or economically efficient due to low availability of forest stocks. For this study, the total vegetation carbon threshold is set to 1000 Mg/km². This threshold value has been derived from Kindermann et al. (2008) in order to exclude forest grid cells with lower productivity from demand allocation. In a later version, the threshold value will be selected based on sensitivity tests and will thus be more established.

4.2.3.3 Demand Allocation

On the basis of preference ranking the demand allocation routine fulfils the country-level demands for forest commodities by allocating forest stock from micro-level grid cells with the highest preference values. Step by step, a forest cell is taken from the preference list and its stock is allocated to fulfill the wood demands. The amount of forest stock to be harvested from the cell is determined from (1) the amount of harvestable woody biomass available in the cell (Section 4.2.2) and (2) harvest rate. The harvest rate designates the fraction of harvestable stock and is defined by the model parameter *Harvest*. This parameter allows for the implementation of different types of forest management scenarios e.g. clear-cut or sustainable. The *Harvest* value can range from 0 to 1 where 1 represents complete deforestation in a cell. Thus, for example, if clear-cut management is desired, the harvest rate can be set to a value of 1. In this case the entire stock from a selected forest cell is removed and the cell is marked as deforested (reforestation is currently not included in the model). Apparently harvest rates below the value of 1 indicate that only a fraction of the cell can be harvested. Assuming a positive rate of change in forest stocks, if the harvest rate exceeds this rate of change, it implies that the forest stock is slowly diminishing, leading to a continuous decline of the natural resource. In contrast, if the harvest rate is below this rate of change, stability or an increase in forest stock is indicated.

4.2.4 Simulation Schedule

The allocation algorithm of the forest module considers both industrial roundwood and fuelwood demands (Section 4.2.3.1). Figure 4.1 provides an overview of the procedure. As a first step, each grid cell is assigned a vector of production functions that quantifies the potential *local* production of biomass stocks in the particular simulation year (as described in Section 4.2.2). Next, the urban and cropland (including grazing) activities are executed. In case that a forest cell is converted to urban or to another land-use type, the current biomass stock of that cell is stored in a buffer called ‘Harvest collection’. This procedure is executed until all expansion of urban and/or other land-use types (cropland/grazing in this study) has taken place. The biomass stocks stored in the ‘harvest collection’ are first utilized to fulfill the wood demand. In case, the wood demand has still not been met, forest management is computed. Similar to the procedure in other modules in LandSHIFT (Schaldach et al., 2006), the demand for raw wood commodities is satisfied for every single country by selecting grid cells according to a preference ranking (Section 4.2.3.2). Subsequently, grid cells with the highest ranking are selected for demand allocation (Section 4.2.3.3). The selected grid cells then contribute to satisfy the remaining country wood demands. This routine is executed until *either* the demand in each country is met *or* the natural forest resources are exhausted.

The next section presents a simulation experiment for India in order to demonstrate a potential application of the presented methodology.

4.3 Simulation Experiment

4.3.1 Experiment Set-Up

The first application of the ‘FOREST’ module in LandSHIFT is on country scale for India based on macro-level drivers that are derived from the Global Environmental Outlook 4 of the United Nations Environmental Programme (GEO4, UNEP 2007). In the present study, scenario data from the ‘Markets First’ Scenario in GEO4 is used to investigate possible country-scale changes in forest cover patterns. This scenario describes a world of market-driven economic and technological development, implying low response capacities to ecosystem problems in many parts of the world. The scenario assumes a population growth in India from about 1 billion people in 2000 to more than 1.7 billion in 2050 (UNEP 2007).

The plausibility test and simulation experiment presented in Sections 4.3.2 and 4.3.3 require large input datasets, as specified in Table 4.1. For the simulation experiment the model is driven with assumed country-level changes between 2000 and 2050 in population, crop production, crop yields and wood demand. Population scenarios were computed by the IFs model (Hughes, 1999) and future agricultural production and crop yields by the IMPACT model (Rosegrant et al., 2008). Wood demand scenarios are computed by the Global Forest Products Model (See Chapter 3). Additionally, biomass productivity comprises woody biomass stocks for each 5 arc minute grid cell under local climate, soil and management conditions. This data is derived from changes in vegetation carbon stocks obtained from the global vegetation dynamics model LPJ-DGVM and data on aboveground vegetation carbon from Kindermann et al. 2008 (Section 4.2.2).

4.3.2 Testing Model Plausibility

Section 4.2 presented the implementation of the first version of the ‘FOREST’ module in LandSHIFT. This section explores the plausibility of the module behavior to different forest management scenarios (Table 4.3). The test identifies the number of grid cells being selected for harvest in year 2000 under three harvest management options. The reasoning behind this analysis is that the number of grid cells being selected for harvest should vary with the management scenario. If the model performs correctly, the number of grid cells selected under clear-cut management will be less than the number of grid cells selected under sustainable management, since in the latter only a fraction of the grid cell is being used to satisfy wood demands.

Table 4.3: Management scenarios

Scenario	**Harvest Management**
(a)	Clear cut[1]
(b)	Sustainable[2]
(c)	0.75 * Sustainable[2,3]

1. Clear cut management refers to harvesting the entire forest stock of a grid cell.
2. Sustainable harvest (in this study) refers to logging the amount of increase in forest stocks only, thus keeping original stocks undisturbed.
3. ‘0.75 * Sustainable’ represents a scenario in which forest stocks are increasing.

Table 4.3 lists the three scenarios. Scenario (a) assumes clear-cutting of suitable grid cells to fulfill wood demands. Hence, entire grid cells are harvested in this scenario. In scenario (b), sustainable harvests are assumed to occur in suitable grid cells. Sustainable harvesting produces a condition in which the original stocks remain stable over the study period. Scenario (c) investigates the effects of harvesting a fraction of the sustainable harvest amount, thus enabling forest stocks to increase over the study period. Figure 4.2 shows the number of grid cells selected for harvest in the year 2000 under these scenarios. Conservation areas are offered strict protection under all three management assumptions.

Figure 4.2 indicates that the selected number of grid cells is substantially higher in scenario (c) than in scenario (b). In scenario (a) where clear-cutting is assumed, only a few grid cells are subjected to harvest, and this number is considerably less than the number of grid cells selected in scenarios (b) and (c). It is logical that higher number of grid cells is selected in scenarios (b) and (c) since only a fraction of a suitable grid cell is cleared to maintain sustainability. This indicates that the ‘FOREST’ module in LandSHIFT is sensitive to changing management scenarios in a logical manner.

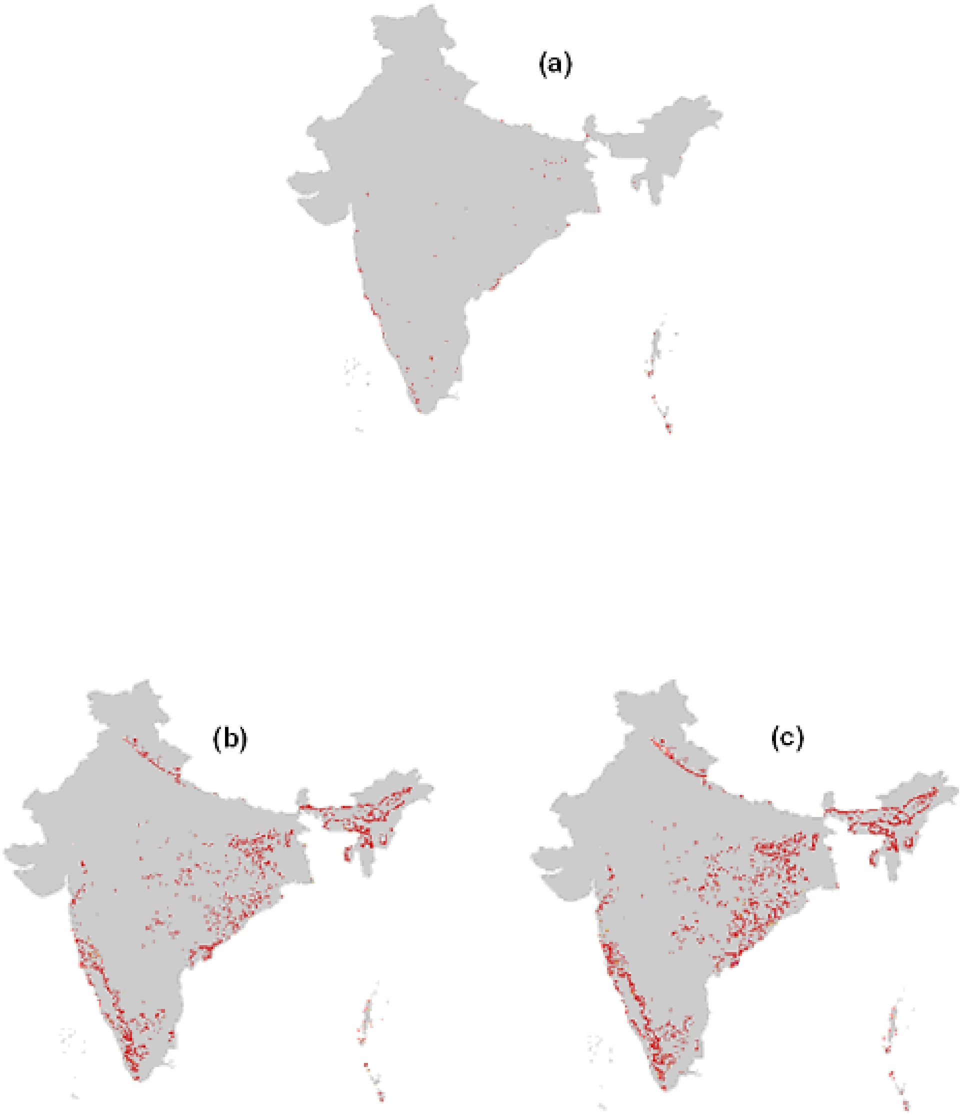


Figure 4.2: Comparison of number of grid cells being selected for harvest in three management scenarios, (a) Clear-cut (b) Sustainable and (c) 0.75 * Sustainable in the year 2000. It is logical that higher number of grid cells is selected in scenarios (b) and (c) since only a fraction of a suitable grid cell is harvested.

4.3.3 Simulation Results

The simulation experiment for India starts with relatively simple assumptions. Climate change has not been considered in this run.

Relevant suitability factors (p_i) for FOREST are local forest stock, terrain slope, accessibility (road infrastructure), population density, and neighbourhood to agriculture (Section 4.2.3.2). Higher preference is given to grid cells with:

- The fraction of forest stock within the grid cell. The more the stock, the higher the preference.
- Slope. The lesser the slope, the higher the preference.
- Proximity to roads. The shorter the distance, the higher the preference.
- Proximity to agricultural land, large cities, and other areas with high population density. The shorter the distance, the higher the preference.

In this version of the study, the value functions (f_i) and (g_j) are strictly linear and the factor weights (w_i) are assumed as equal (Section 4.2.3.2). Additionally, a constraint specifies the exclusion of nature protection area from forest management. These coarse assumptions however do not take into consideration expert knowledge regarding the importance of each suitability factor or the enforcement of the constraint factor. Hence, it is acknowledged that in this version of the study, the understanding of suitability and constraint factors as well as their interplay is incomplete and uncertain. The results are presented for clear-cut management scenario.

The simulation results are presented in Table 4.4 and Figure 4.3. For visualization purposes land-use types have been aggregated to five classes namely ‘Forest’, ‘Cropland’, ‘Urban/Builtup land’, ‘Other land use types’ and ‘Regrowth forest’. Forest types are aggregated to the class ‘Forest’. The ‘Cropland’ class includes all crop types. The ‘Urban/Builtup land’ class is an aggregate of urban and built up land. All other land-use types like wetlands, grasslands, etc, are classified as ‘Other land use types’, which are not an object of discussion in this study. The ‘Regrowth forest’ class represents grid cells that are deforested and are set aside for regrowth (and are also not utilized for conversion to any other land-use type during the study period).

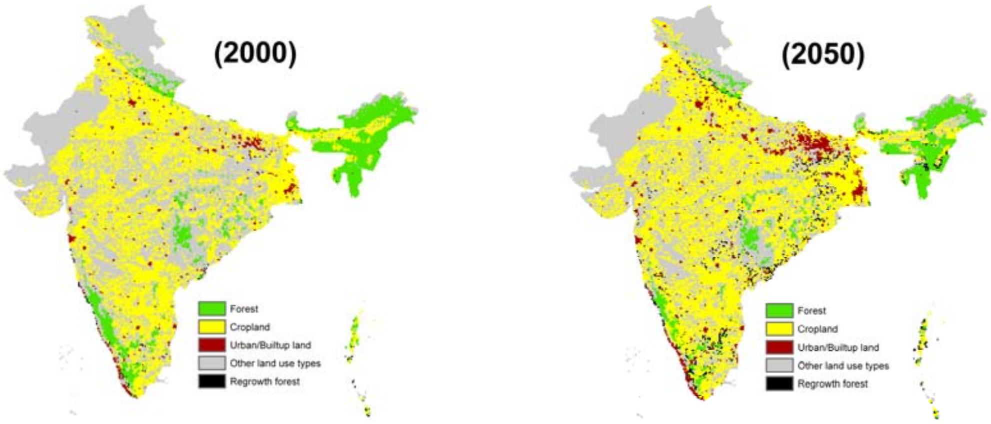


Figure 4.3: Land-use scenario under clear-cut forest management for India for the year 2000 and 2050 (Climate change is not included).

The quantitative results on the change in land-use/cover types in this simulation experiment are shown in Table 4.4. The urban/builtup land increases by almost 53% between years 2000 and 2050. This reflects the large population increase under the Markets First scenario. Cropland increases by approximately 14% during this period. Although the expansion of urban area is high in percentage terms, it is far exceeded by the expansion of cropland in absolute terms. Urban land grows by more than 100000 km^2. Cropland also grows significantly by more than 200000 km^2 because of large population and food demand. Scenario (a) in Figure 4.2 shows the number of grid cells that have been harvested for timber and fuelwood in the year 2000. These grid cells account for an area of approximately 272 km^2. As seen in Table 4.4, the area under cropland and urban use increases over the study period while deforestation for wood extraction decreases until 2020 and does not occur thereafter. At this point, it is not feasible to provide a quantitative analysis since the module is currently based on two major coarse assumptions (1) all types of natural vegetation can be converted to urban and cropland. (2) All the wood extracted from forest cells for urban and cropland expansion can be used to allocate both timber and fuelwood demands. Furthermore, the contribution of plantation establishments in providing commercial timber has not been considered in this study. Therefore, the results presented in Table 4.4 should only be seen as an indication that wood extraction is not a major cause of deforestation in natural forests in India. Expansion of cropland (including graze lands in this study) and urban / built-up land play a more significant role in this regard.

Table 4.4: Simulation results (Climate change is not included).

Land-use/cover type	Area in km^2			
	2000	2010	2020	2050
Urban	193475	226445	253814	296373
Cropland	1450000	1463850	1533490	1653540
Wood extraction	272	190	0	0
Forest	326775	303702	290124	242202

According to the results of the Global Forest Products Model (Chapter 3), demand for industrial roundwood in India increases from 21384 m^3 in year 2006 to more than 100000 m^3 in year 2050. Also, demand for fuelwood increases from around 300000 m^3 in year 2006 to more than 500000 m^3 in year 2050. Despite continuous increase in wood demand in the ‘Markets First’ scenario, deforestation for roundwood does not lead to huge amount of forest loss (Table 4.4). This result is partly in accordance with several case studies carried out to understand the underlying causes of deforestation and forest degradation in India (Joshi and Singh, 2003; Jha et al., 2000; State of Forest Report 2001 (Forest Survey of India)). The reports clearly highlight the main causes of deforestation in India, the predominant cause being agricultural expansion, and urbanization followed by consumerism (mainly fodder for cattle). Also according to an estimate made by FAO (FAO 2006), conversion of natural forests to agricultural land for crops and oil palm cultivation was mainly responsible for deforestation in India during 2000 and 2005. Section 4.4 presents the discussion on this study.

4.4 Discussion

This study is a first attempt to integrate and expand the modelling capabilities of LandSHIFT with wood scenario data from a global forest economy model and forest stock data from a global vegetation model. In Section 4.3.2, the module performance is tested under three forest management scenarios. The module is found to respond to changing inputs in an expected and consistent manner. Once the module is enhanced, it can further be tested for its sensitivity towards several other factors like suitabilities/constraints, climate change, effect on potential productivity under different vegetation carbon models, etc., The sensitivity analysis can enable LandSHIFT to explore the effects of varying combinations of driving forces on deforestation rates.

Presently, the module is based on a few coarse assumptions and does not involve climate change in its simulations. Therefore, this study does not attempt to validate the results. Although the module is in a very preliminary stage of development, it already captures important drivers of land-use change like cropland and urban expansion. However, the current version of the allocation algorithm is based on a simple assumption that all forest stocks extracted to allow these expansions are initially utilized to satisfy wood demands before additional logging is necessary. Also, the model does not differentiate between industrial roundwood and fuelwood demands in this version. This differentiation is very important because almost all types of wood species can be used for fuelwood; but in case of commercial timber only certain types of species in a certain age class are desired. Here it can be said that these are two main reasons why the model simulates zero wood extraction from 2020 onwards.

Another major issue to be considered is the supply of timber and fuelwood from plantations. About 50% of India’s commercial wood supply is provided by non-forest sources, while the rest is fulfilled by imports and supply from forest plantations (International Tropical Timber Organization, 2008). This is an indicator that wood extraction for commercial timber is not a major source of deforestation in India. Countrywide, approximately 22% of the urban population and 75% of the rural population relies on fuelwood as a source of household energy (Defries and Pandey, 2009). However, with the implementation of social forestry and other large-scale afforestation programmes like the Joint Forest Management Programme (Ministry of Environment and Forests, Government of India), the area of production of fuelwood is gradually shifting from natural forests to non-forest areas like farms, wastelands and plantation establishments (Forest Survey of India 2000). Also according to Defries and Pandey (2009), increasing fuelwood demands due to increasing households might lead to local degradation of forests but not to large-scale deforestation.

The result on wood extraction in India presented in Table 4.4 does reflect some of the points mentioned above. However, the basis of this result is not very realistic and well established in this version of the study. This module is being designed to assess land-use/cover changes in the global context. There are many countries (e.g. Brazil and Indonesia) where wood extraction is a significant proximate driver of deforestation (International Tropical Timber Organization, 2008). Therefore it is important to incorporate atleast some of the above-mentioned issues in the module in order to be able to obtain wood extraction estimates on a more established basis.

The next section provides a detailed description of the application and testing of the Lund-Potsdam-Jena Dynamic Global Vegetation Model (LPJ-DGVM).

4.5 Concluding Remarks

The study presents the first version of the ‘FOREST’ module in LandSHIFT. In a first simulation experiment for India it has been demonstrated that forest scenarios are a valuable illustration of the connection between trends in other land-use types like urban and cropland, and the future tempo of global deforestation or afforestation. Additionally, the scenario analysis implies that forest trends are driven to a significant extent by cropland and urban expansion. Wood extraction is not the only factor causing deforestation. It is emphasized that the results of this version of the module are not to be understood as a *prediction* of future land-cover change estimates, rather as a means to identify the significance of wood extraction as a *direct driver* of deforestation.

The inclusion of this module in LandSHIFT is the leap forward to an increased understanding of land-use/cover changes. This allows a more detailed analysis of the temporal development of land-use pattern and thus opens new directions for environmental impact assessments. Further research focuses on three fields of action. First is the refinement of the methodological aspect of the allocation algorithm. Here a major issue is the inclusion of age structure and plantation establishments. The second field covers questions of model testing while the third field aims at extending the ability of the module for environmental impact assessment (e.g. climate change and biodiversity). The next chapter elaborates on the outlook for future research and development in LandSHIFT in order to enhance its role in studying global change.

4.6 Supplement: Application and Testing of LPJ

4.6.1 Introduction

Land-use change profoundly affects many global change processes (Achard et al., 2004). Examples of such processes include fluxes of greenhouse gases (especially CO_2), planetary surface energy and moisture (e.g. Achard et al., 2004) as well as water and nutrient cycles (Foley et al., 2005). Therefore, in order to anticipate and understand future land-use/cover changes, the development of the ‘Forest’ module in LandSHIFT requires consistent quantification of vegetation carbon pools in order to compute future rates of change. For this purpose, the Lund-Potsdam-Jena Dynamic Global Vegetation Model (LPJ-DGVM; Sitch et al., 2003; Bondeau et al., 2007) has been utilized to obtain projections on the change in vegetation carbon stocks. One of the main purposes of the LPJ-DGVM as articulated in Sitch et al. (2003), is the simulation of the geographical distribution of vegetation carbon under changing climate. This section has two main purposes:

1. To describe the simulation of global vegetation carbon with the LPJ-DGVM
2. To test its performance for using its results in the study

4.6.2 Simulation of global vegetation carbon with LPJ-DGVM

4.6.2.1 Model Description

The dynamic global vegetation model LPJ has been used to simulate the productivity patterns of potential natural vegetation on a global 0.5° x 0.5° grid. LPJ is a process-based model, which simulates carbon and water fluxes as driven by climate and soil variables on grid scale. A grid cell is treated as a mosaic of fractional coverages of plant functional types (PFTs) and bare ground. Natural vegetation is represented in the LPJ by eight woody and two herbaceous PFTs. For each PFT, a set of parameters describes the processes of plant growth, physiology and bioclimatic constraints including competition between the PFT populations. Based on plant phenology, gross primary production is calculated as a function of insolation, climate and soil conditions, and atmospheric CO2 concentration for each PFT. After subtracting maintenance requirements, the resulting net primary production (NPP) is allocated to four different plant compartments. For the eight woody PFTs the model distinguishes between the following compartments: leaves, heartwood, sapwood and roots. The carbon content of each of these pools is calculated in monthly time steps. An assessment of the environmental suitability and the establishment of new PFTs are carried out on a yearly basis. A more detailed description of the model can be found in Sitch et al. (2003).

4.6.2.2 Data Input and Model Application

In order to simulate vegetation carbon dynamics, the LPJ is driven by monthly climatologies of mean temperature, precipitation, number of rainy days, cloud cover, and atmospheric CO_2 concentration. The data on atmospheric CO_2 concentration is obtained from assessments made for the “Markets First” scenario of Global Environmental Outlook 4 (UNEP, 2007). A typical simulation with LPJ is initialized with “bare ground” land-cover. The model then *spins up* for 1000 model years until approximate equilibrium is reached with respect to carbon pools and vegetation cover. The model is then driven using transient climate data for the period 1901 – 2050.

The monthly climatology of temperature and precipitation are taken from the CRU-TS2.1 data set (Mitchell and Jones, 2005) for the period 1901 - 2003. For the remaining study period (2004 – 2050), climate results of the IMAGE model (MNP, 2006) are combined with climate variability from the CRU-TS2.1 data set (Mitchell and Jones, 2005) for climate normal period 1961-1990. The CO2 concentration data for the period 2000-2050 are taken from the IMAGE model (MNP, 2006). Regarding input data on cloudiness and number of wet days, CRU data for the period 1961-1990 is used for the future period. For this study, the LPJ is run in the “natural vegetation only” modus, which means that the land-cover in each 0.5° grid cell consists of potential natural vegetation existing under the given climate and soil conditions only. This simulation results in a mosaic of different PFTs (including the respective vegetation carbon stocks) for each 0.5° grid cell, depending on its soil and climate.

4.6.3 Testing of the LPJ-DGVM

This section describes the testing of the output data on vegetation carbon produced by the LPJ model at both grid and country scale. Additional testing has been carried out for India, since the first simulation experiment of the forest module in LandSHIFT (as described in Section 4.3) considers forest cover changes in India only.

Test design

The main caveat for testing is the lack of standardized and internationally comparable data sets, especially on the grid level. Some available data on global biomass distribution are relatively old and provided only in the form of a general ecosystems map (Olson et al. 2001). Others are outputs of current global dynamic vegetation models that are still under development with respect to carbon allocation and need further improvement (Kucharik et al. 2006). One dataset that is available and can be considered as a consistent and reliable source of vegetation carbon is the Global Forest Resources Assessment (FRA) produced by the Food and Agricultural Organization of the United Nations (FAO 2005). The dataset contains aggregated country-level information on growing stock, biomass and carbon stock in forests for 229 countries and territories. Kindermann et al. (2008) illustrates a technique to downscale the aggregated results of the FRA2005 to a half-degree global spatial dataset. This dataset contains information on: forest growing stock; above/below-ground biomass, dead wood and total forest biomass; and above-ground, below-ground, dead wood, litter and soil carbon. Out of all these, only the map results on ‘above-ground carbon’ and ‘below-ground carbon’ are of interest for testing model performance. The LPJ has been tested with the following four exercises:

1. Comparison of gridded maps of “observed” vs. computed vegetation carbon at the global level.
2. Comparison of country-scale “observed” vs. calculated vegetation carbon at the global level.
3. Comparison of country-scale “observed” vs. calculated vegetation carbon in India.
4. Comparison of gridded maps of “observed” vs. calculated vegetation carbon in India.

The term “observed” has been put in quotes because the data sets that have been used for model testing are not based on a single set of direct observations, but on an amalgam of different data sets as in Kindermann et al (2008), or on secondary data such as national inventory information as in FRA2005.

The LPJ data has been tested for the year 2000. For country-level and regional-level comparisons, data on computed and “observed” vegetation carbon is available for year 2000. However, for the grid level comparisons, “observed” data from Kindermann et al. (2008) is for the year 2005 only. The maps of vegetation carbon produced on grid scale by Kindermann et al. (2008) represent one of the first attempts to produce a consistent global spatial database at half-degree resolution.

Another map of vegetation carbon available on grid-scale is a New IPCC Tier-1 Global Biomass Carbon Map for the year 2000 available from Ruesch et al. (2008). It is a globally consistent map depicting vegetation carbon stocks for the year 2000. It follows the widely accepted IPCC methods for estimating carbon stocks at the national level. However, the methods employed in this study are not directly linked to ground-based measures of carbon stocks and have not been validated with field data. Therefore, it is found preferable to test the LPJ model performance with data from Kindermann et al. (2008). The datasets used in this testing are listed in Table 4.5 and described as follows.

Table 4.5: Datasets for LPJ testing

Datasets used	**Values**	**C/G**	**Source**
Total vegetation carbon	gC/m^2	G	Sitch et al. (2003); Bondeau at al. (2007)
Above-ground carbon	MtC	G	Kindermann et al. (2008)
Below-ground carbon	MtC	G	Kindermann et al. (2008)
Land-cover classification	-	G	Heistermann (2006)
Country shape file	-	C	Voss, Personal Communication
Grid area	Sq. kms	G	Prepared for this study

C/G = Information available for country (C) / for grid points (G)

The LPJ model provides a global map of total vegetation carbon (above and below-ground) estimates for the year 2000 at 0.5-degree grid scale (Sitch et al., 2003; Bondeau at al., 2007). The carbon stock estimates are in gC/m^2 (grams carbon per square meter). Kindermann et al. (2008) offers two separate global spatial datasets containing above and below-ground carbon at the 0.5-degree grid scale in MtC (metric tons carbon). A global land-cover map following the International Geosphere-Biosphere Programme classification is available at the 5 arc minute grid scale (Loveland et al., 2000; Heistermann (2006)). The land cover classification consists of thirty-one categories, five of which are forest types (Table 4.2). The country shape file provides the country outlines for all countries listed in the FAOSTAT (FAO 2000). The map of the grid area was created using the 'Raster Creation' tool in ArcGIS 9.2, where each rectangular grid has a uniform cell size of 5 arc minutes (approximately 9 km x 9 km at the Equator).

All datasets mentioned above are available as ASCII maps. In order to perform calculations in ArcGIS 9.2, these maps are first converted to raster. The maps of above/below-ground carbon from Kindermann are added to obtain a map of total vegetation carbon. The grid cell units of total vegetation carbon maps from both LPJ and Kindermann are converted to gC/km^2. Both these maps are then multiplied with the map of the grid area to represent the total vegetation carbon data on 5 arc minute grid scale. The global land-cover map is then used to select grid cells containing total vegetation carbon in forest areas from both these maps. The resulting maps on total vegetation carbon in forest areas in both LPJ and Kindermann are used in the following four testing exercises.

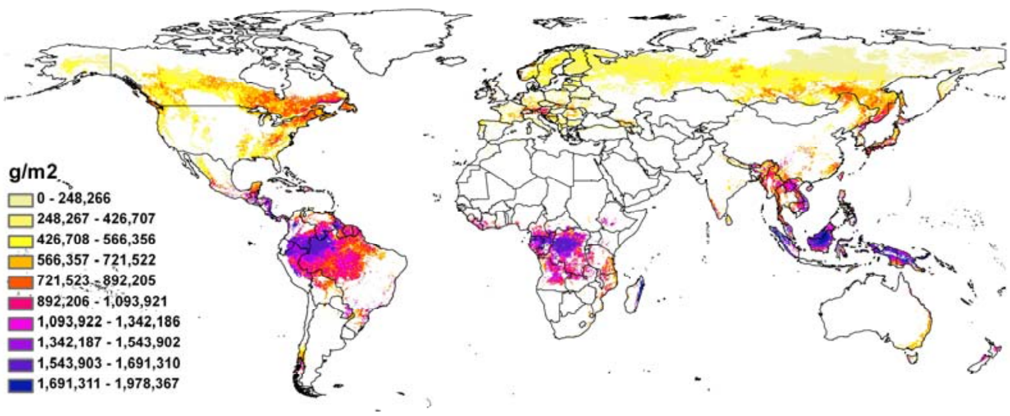
Test 1: Comparison of gridded maps of "observed" vs. computed vegetation carbon at the global level.

The estimation of forest vegetation carbon is a key steering mechanism of land-use/cover changes since it determines how much from a forest grid cell is available to be put into production to meet new demand for wood supply. Hence, it is of great interest to test the ability of the model to compute vegetation carbon at a global spatial resolution of 5 arc minutes. Section 4.6.2 explains how the total vegetation carbon estimates have been obtained from LPJ. Here two spatial methods are used to compare the consistency of the computed vegetation carbon from LPJ with estimates from Kindermann et al. (2008).

The first method is to compare the spatial pattern of the distribution of vegetation carbon in the two maps. Figure 4.4 shows the total vegetation carbon computed from LPJ and the estimated total vegetation carbon from Kindermann et al. (2008). Both the maps have a resolution of 5 arc minutes.

Figure 4.5 shows the difference in the vegetation carbon quantities in the two maps. The difference map shows that total vegetation carbon computed with the LPJ is substantially higher than the estimated total vegetation carbon from Kindermann et al. (2008). Exceptions are seen in Indonesia, Papua New Guinea and some other surrounding small islands, where estimates from LPJ in many locations are more than double of the estimates given in Kindermann et al. (2008).

One main reason why LPJ simulates high amount of vegetation carbon stocks is that it does not include age structure dynamics and forest management in its calculations. Changes in the carbon sink size are largely attributed to the dynamics of forest age distribution (Ryan et al., 1997).


1) LPJ

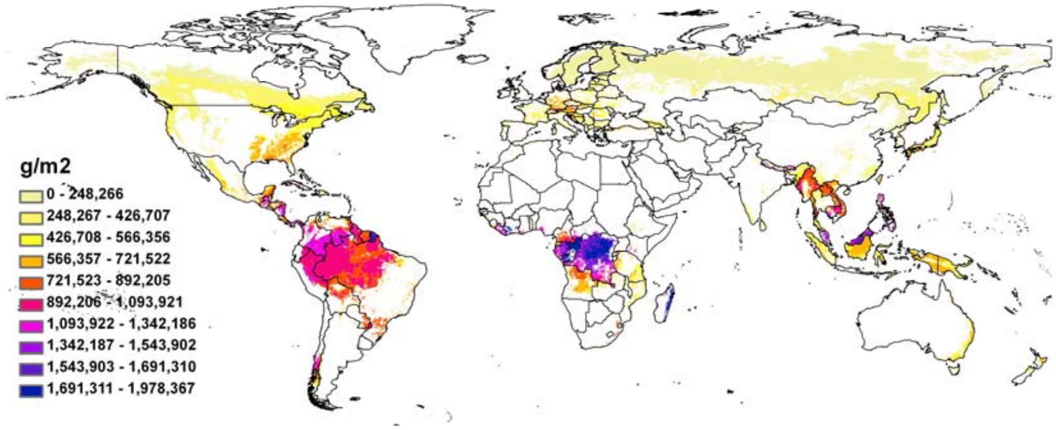

2) Kindermann et al 2008

Figure 4.4: Vegetation carbon estimates from the LPJ (1) and Kindermann et al. (2008) (2) at 5 arc minute grid-scale.

Additionally, forest management options keep forests within a certain range of mean forest age (Nabuurs et al., 2003).The Kindermann et al. (2008) study includes the effects of human influence on forests thereby accounting for forest management. The human influence factor plays a significant role in keeping vegetation carbon estimates at a lower level compared to the estimates on vegetation carbon obtained from LPJ.

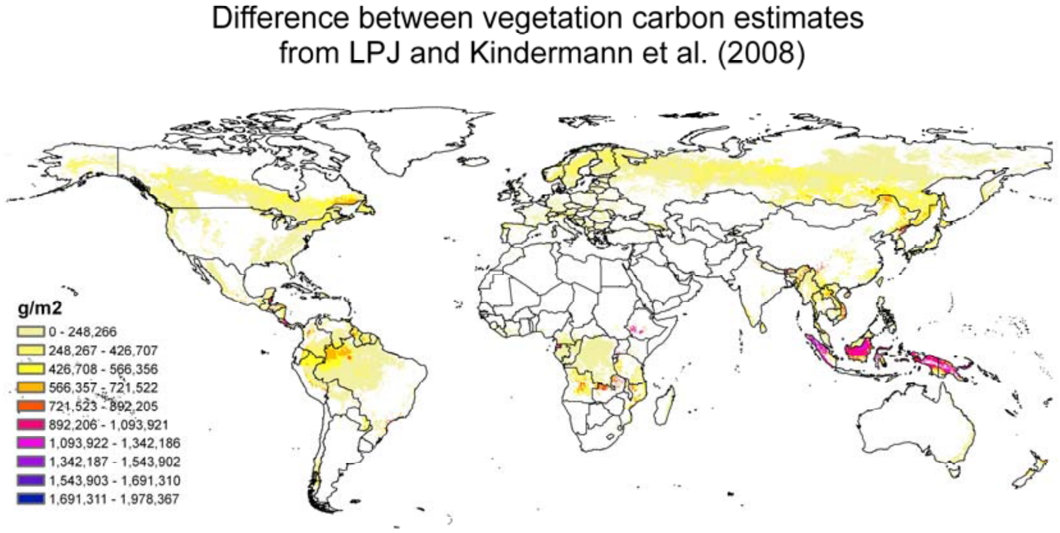

Difference between vegetation carbon estimates from LPJ and Kindermann et al. (2008)

Figure 4.5: Comparison of vegetation carbon estimates from the LPJ (1) with Kindermann et al. (2008) (2) at 5 arc minute grid-scale.

The second method is to compute the Pearson’s correlation coefficient (Rodgers et al., 1988) to examine the “strength” between the two estimates. The Pearson’s correlation coefficient is a well-established statistical measure to evaluate how well the two data under study agree with each other. It indicates the strength of a linear relationship between two variables. The correlation is 1 in the case of an increasing linear relationship, −1 in the case of a decreasing linear relationship, and some value in between in all other cases, indicating the degree of linear dependence between the variables. The closer the coefficient is to either −1 or 1, the stronger the correlation between the variables. The strength between LPJ calculations and Kindermann et al. (2008) is computed to be 0.75 indicating relatively good agreement between model and data. This result suggests that the model can fairly simulate vegetation carbon yields at the grid scale.

Test 2: Comparison of country-scale “observed” vs. calculated vegetation carbon at the global level.

This exercise compares the calculated quantity of vegetation carbon for each country listed in FAOSTAT (2000) with “observed” vegetation carbon for year 2000. For this purpose, calculated values of vegetation carbon from LPJ on the 5 arc minute grid scale are aggregated for every country using the 'Zonal Statistics' feature in ArcGIS 9.2. The cartographic zones are specified by the country shape file. Observed data is taken from the FAO Global Forest Resources Assessment (FRA 2000).

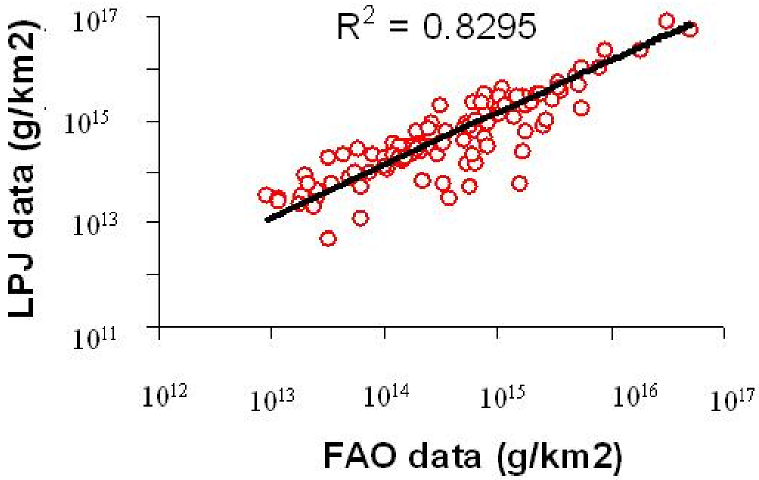


Figure 4.6: Comparison of calculated vegetation carbon estimates from the LPJ (Y-axis) with FAO statistical data (X-axis) at country-scale. Values have been represented in the logarithmic scale.

The measurement of agreement between LPJ calculations and FAO data is the "predicative accuracy" of the model identified by the coefficient of determination (R^2). This is indicated by the "goodness of fit" of the calculated data to the line of perfect agreement as shown in Figure 4.6. The predicative accuracy of LPJ is 0.82 (Figure 4.6) indicating low variability from the "observed" data. This result suggests that the model can fairly compute vegetation carbon for current climate and may get used for scenario analysis in future time periods.

Test 3: Comparison of country-scale "observed" vs. calculated vegetation carbon in India.

In this exercise, the calculated quantity of vegetation carbon in India is compared with "observed" vegetation carbon for the year 2000. Like in Test 2 presented above, calculated values of vegetation carbon on the 5 arc minute grid level are aggregated for India using the 'Zonal Statistics' feature in ArcGIS 9.2. Observed data is taken from the FAO Global Forest Resources Assessment (FRA 2000). According to FRA2000, carbon stock in above/below-ground biomass in forest areas in India is approximately 2,325 million metric tons. Data from LPJ show an aggregate value of 3,212 million metric tons. This calculation is almost 38% higher than the "observed" estimate.

One possible reason for this discrepancy as also mentioned in Test 1 is that LPJ does not include age structure dynamics in its simulations. Another possible reason is that there might be some disagreement in the definition of 'forest' according to FRA2000 and the methodology of estimating it in Loveland et al., 2000 (since the vegetation carbon estimates from LPJ are aggregated for forest cells in in LandSHIFT where the base land-cover map classification is based on Loveland et al., 2000). According to FRA2000, land-cover with greater than 10% tree canopy cover is considered as forest. On the other hand, land-cover classification in Loveland et al., 2000 is based on the unsupervised classification of AVHRR NDVI monthly composites. It is possible that some land-cover with less than 10% tree canopy has also been classified as 'forest' in their study, thereby causing discrepancy in recognition of forest areas.

Test 4: Comparison of gridded maps of "observed" vs. calculated vegetation carbon in India.

In this test, the spatial patterns of the distribution of vegetation carbon from LPJ and Kindermann et al. (2008) are compared. Figure 4.7 shows the total vegetation carbon computed from LPJ and the estimated total vegetation carbon from Kindermann et al. (2008) for India. Both the maps have a resolution of 5 arc minutes. The comparison of spatial patterns in Figure 4.7 shows that total vegetation carbon computed with the LPJ is substantially higher than the estimated total vegetation carbon from Kindermann et al. (2008) in most locations.

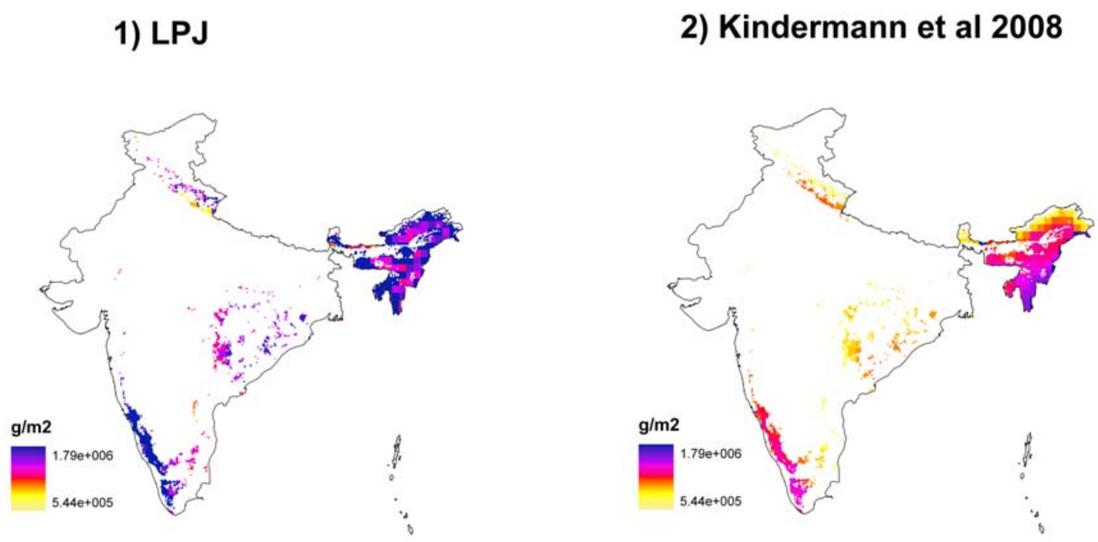


Figure 4.7: Comparison of vegetation carbon estimates from the LPJ (1) with Kindermann et al. 2008 (2) at 5 arc minute grid-scale for India.

There are several possible reasons for this.

- Forests in India are extremely diverse and heterogeneous in nature, and it is difficult to classify them into a small number of categories in LPJ. More so, different species respond differently to changes in climate (Shukla et al., 2003). In LPJ, the use of equilibrium is characterized by data limitations related to climate parameters, soil characteristics and plant physiological functions. Thus, the projections of calculated vegetation carbon by LPJ can be characterized by a certain amount of uncertainty.
- Kindermann et al., (2008) presents vegetation carbon maps that have been produced by downscaling aggregated results from FRA2005. Since the methodology is based on an amalgamation of different datasets, uncertainties may exist in the actual interpretation of vegetation carbon quantities at the grid scale.
- LPJ does not account for forest management and age structure dynamics in its calculations. This has a high impact on the simulation of vegetation carbon stocks as also mentioned in Test 1 above.

4.7 References

Alcamo, J., and R. Schaldach, 2006. LandShift: Global Modeling to Assess Land Use Change, paper presented at EnviroInfo2006, Graz, Austria, September 6-9, 2006.

Alcamo, J., Leemans, R., Kreileman, E., 1998. Global Change Scenarios of the 21st Century. Results from the IMAGE 2.1 Model. Elsevier, Amsterdam, 296 pp.

Achard, F., Eva, H.D, Mayaux, P., Stibig, H.-J., Belward, A. 2004. Improved estimates of net carbon emissions from land cover change in the tropics for the 1990s. Global Biogeochemical Cycles. 18 (2) GB2008 10.1029/2003GB002142.

Bondeau, A., Smith, P.C., Zaehle, S., Schaphoff, S., Lucht, W. et al., 2007. Modelling the role of agriculture for the 20th century global terrestrial carbon balance. Global Change Biology 13, 679-706.

Buongiorno, J., S. Zhu, D. Zhang, J.A. Turner, and J. Tomberlin. 2003. The Global Forest Products Model: Structure, Estimation and Applications. San Diego, CA: Academic Press.

Cassman, K., S. Wood, P. S. Choo, H. D. Cooper, C. Devendra, J. Dixon, J. Gaskell et al. 2005. Cultivated systems. In Millennium Ecosystem Assessment, Ecosystems and human well-being: current state and trends, Vol. 1, 745–94. Washington, DC: Island Press.

Chattopadhyay S., and Sasidharan, C. K., 1996. Changing pattern of agricultural land use in Kerala. A case study in environmental perspective. In: R. B. Singh (Ed.) Disasters, Environment and Development, 479-484.

Defries R., and D. Pandey. 2009. Urbanization, the energy ladder and forest transitions in India's emerging economy. Land Use Policy, In Press, Corrected Proof, Available online 31 July 2009, ISSN 0264-8377, DOI: 10.1016/j.landusepol.2009.07.003.

Erbrecht T, Lucht W. 2006. Impacts of large-scale climatic disturbances on the terrestrial carbon cycle. Carbon Balance and Management 1:7, doi:10.1186/1750-0680-1-7 (open access).

FAO (Food and Agriculture Organization), 2006. Statistical databases: FAOSTAT, FAO, United Nations, Rome.

FAO (Food and Agriculture Organization), 2005. Global Forest Resources Assessment 2005, Progress towards sustainable forest management. Vol. 147 of FAO Forestry Paper. Food and Agriculture Organization of the United Nations, Rome.

FAO 2000: FAOSTAT. Food and Agriculture Organization, United Nations, Rome.

Foley, J.A., R. Defries et al., 2005. Global Consequences of Land use, Science Vol 309, 570 – 574.

FAO (Food and Agriculture Organization) 2001a. Global Forest Resources Assessment 2000, Main report. FAO Forestry Paper No. 140, Food and Agriculture Organization, United Nations, Rome.

Forest Survey of India (2001) State of Forest Report 2001. Ministry of Environment and Forests, Government of India, Dehradun. Website: http://envfor.nic.in/fsi/sfr99/sfr.html.

Forest Survey of India (2000) State of Forest Report 2001. Ministry of Environment and Forests, Government of India, Dehradun. Website: http://envfor.nic.in/fsi/sfr99/sfr.html.

Geist, H. J., and E. F. Lambin, 2002. Proximate causes and underlying driving forces of tropical deforestation, BioScience, 52(2), 143-150.

Geneletti, D., 2004. A GIS-based decision support system to identify nature conservation priorities in an alpine valley, Land Use Policy, 21, 149-160.

Heistermann, M., 2006. Modelling the Global Dynamics of rain-fed and Irrigated Croplands. Reports of Earth System Science, 37/2006. Max Planck Institute for Meteorology, Hamburg.

Heistermann, M., Müller, C. Ronneberger, K., 2006. Land in Sight? Achievements, Deficits and Potentials of Continental to Global Scale Land Use Modeling. Agriculture Ecosystems and Environment 114, 141-158.

Hughes, B., 1999. The International Futures (IFs) Modeling Project. Simulation Gaming 30, doi:10.1177/104687819903000306.

IIASA and FAO, 2000. Global Agroecological Zones: Plate 9 – Median of Terrain Slopes. Global Agro-Ecological Zones CD-ROM, IIASA and FAO, Laxenburg and Rome.

IPCC 2006. Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme (Eggleston HS, Buendia L, Miwa K, Ngara T, Tanabe K eds). IGES, Japan.

ITTO (International Tropical Timber Organization) 2008. Annual review and Assessment of the World Timber Situation 2008. Website: http://www.itto.int/en/annual_review/.

Jha CS, Dutt CBS and Bawa KS, 2000. Deforestation and land use changes in Western Ghats, India. Curr Sci 79(2):231–238.

Joshi, M. and P.P. Singh, 2003. Applying natural resource economics to forest degradation: Lessons from India. Proceedings of the 12th World Forestry Congress, Quebec, Canada, Volume A, p.127.

Kaufmann, D., A. Kraay, and M. Mastruzzi, 2005. Governance Matters IV: Governance Indicators for 1996-2004, World Bank Policy Research Working Paper Series No. 3630, World Bank, Washington, D.C.

Kindermann , G.E. , McCallum , I. , Fritz , S. and Obersteiner , M., 2008. A global forest growing stock, biomass and carbon map based on FAO statistics. Silva Fennica, 42**,** 387 – 396 .

Klein Goldewijk, K. and G. van Drecht, 2006. HYDE 3: Current and historical population and land cover. MNP (2006) (Edited by A.F. Bouwman, T. Kram and K. Klein Goldewijk), Integrated modelling of global environmental change. An overview of IMAGE 2.4. Netherlands Environmental Assessment Agency (MNP), Bilthoven, The Netherlands.

Klein Goldewijk, K., 2005. Three Centuries of Global Population Growth: A Spatial Referenced Population (Density) Database for 1700 – 2000. Population and Environment 26 (5): 343-367.

Kucharik, C.J., Barford, C.C., El Maayar, M., Wofsy, S.C., Monson, R.K. & Baldocchi, D.D., 2006. A multiyear evaluation of a Dynamic Global Vegetation Model at three AmeriFlux forest sites: Vegetation structure, phenology, soil temperature, and CO2 and H2O vapor exchange. Ecological Modelling 196(1–2): 1–31.

Lambin, E.F. and Geist, H. (eds), 2006. Land-use and land-cover change: local processes and global impacts. Springer: Berlin, Heidelberg, GE, 204 pp.

Lepers, E., E.F. Lambin, A.C. Janetos, R. DeFries, F. Achard, N. Ramankutty, and R.J. Scholes., 2005. A synthesis of information on rapid land-cover change for the period 1981-2000. *Bioscience* 55: 115-124.

Loveland, T.R., Reed, B.C., Brown, J.F., Ohlen, D.O., Zhu, J, Yang, L., and Merchant, J.W., 2000. Development of a Global Land Cover Characteristics Database and IGBP DISCover from 1-km AVHRR Data: International Journal of Remote Sensing 21(6/7), 1303-1330.

Mitchell, T. D. and Jones P. D., 2005. An improved method of constructing a database of monthly climate observations and associated high resolution grids, Int. J. Climatology, 25(6), 693–712, doi: 10.1002/joc.1181.

Nabuurs, G.J., Schelhaas, M.J., Mohren, G.M.J., and Field, C.B., 2000. Temporal evolution of the European forest sector carbon sink from 1950 to 1999, Global Change Biology, 9 (2): 152{160.

Ojima D. S., Galván N. and Turner B. L. II., 1994. The Global Impact of Land-use Change. Bioscience, Vol. 44, No. 5, pp. 300-304.

Olson, D.M., Dinerstein, E., Wikramanayake, E.D., Burgess, N.D., Powell, G.V.N., Underwood, E.C., D'amico, J.A., Itoua, I., Strand, H.E., Morrison, J.C., Loucks, C.J., Allnutt, T.F., Ricketts, T.H., Kura, Y., Lamoreux, J.F., Wettengel, W.W., Hedao, P. &

Kassem, K.R., 2001. Terrestrial ecoregions of the world: a new map of life on earth. BioScience 51(11): 933–938.

Rodgers, J. L. and Nicewander, W. A., 1988. "Thirteen ways to look at the correlation coefficient". The American Statistician 42: 59–66. doi:10.2307/2685263.

Rosegrant, M.W., Ringler, C., Msangi, S., Sulser, T.B., Zhu, T., Cline, S.A., 2008. International Model for Policy Analysis of Agricultural Commodities and Trade (IMPACT): Model Description. International Food Policy research Institute, Washington, D.C.

Rothman, D., J. Agard, Alcamo, J., 2008. Chapter 9: The Future Today. Pages 395-454 in UNEP (United Nations Environment Programme), editor. Global Environmental Outlook-4. EarthPrint Limited, Stevenage, Hertfordshire, UK.

Ruesch, A.S. and H, K. Gibbs., 2008. New global biomass carbon map for the year 2000 based on IPCC Tier Methodology. ORNL-CDIAC.

Ryan, M.G., Binkley, D., and Fownes, J.H., 1997. Age-related decline in forest productivity: Pattern and process, Advances in Ecological Research, 27: 213{262.

Schaldach, R., Alcamo, J., Koch, J., Kölking, C., Lapola, D., Priess, J., 2009. LandSHIFT: Modeling land use change on the continental and global scale Part I. Model development. Environmental Modelling and Software (submitted).

Schaldach, R., J. Alcamo, and M. Heistermann, 2006. The multiple-scale land use change model LandShift: a scenario analysis of land use change and environmental consequences in Africa, in A. Voinov, et al. (Eds.): *Proceedings of the iEMSs Third Biennial Meeting: "Summit on Environmental Modelling and Software"*, International Environmental Modelling and Software Society, Burlington, USA.

Seiler, W., and P. Crutzen, 1980. Estimates of gross and net fluxes of carbon between the biosphere and the atmosphere from biomass burning. Climatic Change **2**:207-247.

Shukla, P.R., Subodh, K Sharma., Ravindranath, N.H., Amid Garg and Sumana Bhattacharya, 2003. Climate Change and India: Vulnerability Assessment and Adaptation, University Press (India) Pvt. Ltd. Hyderabad. 454.

Sitch, S., Smith, B., Prentice, I.C. et al., 2003. Evaluation of ecosystem dynamics, plant geography and terrestrial carbon cycling in the LPJ dynamic global vegetation model. Global Change Biology 9, 161-185.

United Nations Environment Programme (UNEP) 2007. Global Environment Outlook GEO4: environment for development. UN-UNEP, Valletta, Malta, 572 p.

USGS, 1998. Global 30 arc-second Digital Elevation Model (GTOPO30), United States Geological Survey, Sioux Falls, USA.

Voss, F., 2009. personal communication

WDPA Consortium, 2004. World Database on Protected Areas.

World Rainforest Movement, 1998. Special Issue on Analysis of Underlying Causes of Deforestation, WRM Bulletin Number 9, February 1998. Web-site: http://www.wrm.org

World Wildlife Fund (WWF), 2004. How effective are protected areas? 24 pp., WWF International, Gland, Switzerland.

CHAPTER 5

Synthesis

Summary

The major objective of this thesis was to develop data sets and methodologies for the simulation of forest area changes based on wood extraction. This work is the first version of the incorporation and implementation of forest sector dynamics in the LandSHIFT modeling framework. For this purpose, the key research tasks identified were: a review of available global scale economic forest sector models, the simulation of global wood production and the modeling of spatial dynamics in forests. This chapter summarizes the findings related to the aforementioned issues. It also highlights some important research needs that emerge from the integrated consideration of all chapters.

5.1 Summary of findings

A review of Global Scale Economic Forest Sector Models

Chapter 2 presents a review on three global forest sector models namely the ‘CINTRAFOR Global Trade Model’, the ‘Global Forest Products Model’ and the ‘Timber Supply Model’. All these economic approaches provide a formalised structure to represent the demand and supply of forest products. These are also highly suited to reflect on the shift of land requirements between geographical regions as a consequence of increasing wood demands in the future. However, since natural forest resources are depleting at a significant rate (FAO 2007) and wood demands are on the spur (FAOStat 2008), it is also important to consider how the timber market will respond to changes in wood supply in the future. The main question that arises out of this consideration is ‘*which regions will supply industrial timber in the coming decades*’. While models like the ‘Global Forest Products Model’ and ‘CINTRAFOR Global Trade Model’ have an impact on the quantity of timber harvests in different regions due to international trade, the Timber Supply Model (TSM) has a profound impact on the pattern of timber harvests from region to region. In the TSM, regional differences relate mainly to changes in the age distribution of timber inventories with time. If the role of plantations continues to expand in global markets, then optimal control models like the TSM may be particularly useful in projecting long-term regional harvests and supply, as the age distributions of plantations around the globe will vary based on planting rates and timber type.

Simulation of Global Wood Production

Chapter 3 presents the adaptation and implementation of the Global Forest Products Model to simulate country-scale wood production data for the global forestry sector. The capability of the model to provide country level output makes it easy to produce different regional aggregates as required. The model is found to be quite effective in the formalisation and integration of drivers on the demand side and in representing international trade. It is also found to be very capable of implementing technological change in the form of wood saving technology. A comparison of the model output to other existing long-term scenarios on wood demand shows that the model is capable of generating future wood demands. However, the model does not account for land-use competition, either from within the industry or from agriculture and other land uses. It only accounts for exogenous adjustments to the resource base (e.g. change in forest stocks over time), which is not a convincing way of accounting for change in the availability of land and timber. Further, the model does not yet fully realize its potential in addressing technology change by considering product substitution possibilities (e.g. substitution of fuelwood with biofuels). Therefore it is desirable to integrate forest economy models with large-scale global land-use/cover change models like LandSHIFT. This will facilitate the assessment of feedbacks between the terrestrial environment and the global economy within one consistent framework.

Application and Testing of LPJ

The Lund-Potsdam-Jena (LPJ) dynamic global vegetation model was utilized to provide estimates of potential vegetation carbon stocks for the forested locations in LandSHIFT. The information is used as a base to allocate the demands for forest products. A comparison of the simulation results against FAO census data shows that the LPJ can fairly compute vegetation carbon estimates for current climate and may get used for scenario analysis in future time periods. However, the vegetation carbon estimates from LPJ are substantially high. This is because LPJ does not include forest management in its calculations and this has a high impact on forest carbon stocks. Hence, it is desirable to integrate the LPJ-DGVM into LandSHIFT in order to include dynamic vegetation carbon calculations as a function of climate and forest management.

Implementation of forest module in LandSHIFT

Chapter 4 addresses wood extraction as a proximate driver causing deforestation in many areas around the globe. This study is a first attempt to integrate this activity in a large-scale land-use/cover change model and address its significance in causing deforestation. The approach endeavors to integrate and expand the modeling capabilities of LandSHIFT with wood scenario data from a global forest economy model and forest stock data from a global vegetation model. To achieve this objective, a methodology is developed and implemented to simulate the spatial dynamics of forest areas based on wood extraction within the LandSHIFT framework. Simulated changes in forest areas are exogenously driven by wood demands at country scale. The spatial allocation of wood demands on a five-arc minutes grid is governed by a set of spatial factors such as forest stock or terrain slopes which are evaluated by means of Multi-Criteria-Analysis. The model already captures important drivers of land-use change like cropland and urban expansion. The methodology is tested and applied in an exemplary simulation experiment for India based on a Global Environmental Outlook scenario. The simulation results show that wood extraction is not a significant source of deforestation in India. The predominant cause of deforestation is agricultural expansion followed by urbanization. This result corresponds to many case studies and assessment reports made for analyzing the causes of deforestation in India. However, the basis of this result is not very realistic and well established in this version of LandSHIFT since the module is currently based on a few coarse assumptions. The module is being designed to study the effects of wood extraction on a global basis. Therefore, it is important to incorporate several other issues like plantation establishments and age structure in forests in order to assess the impacts of wood extraction on deforestation in a more established manner.

5.2 Outlook for Future Research

One important conclusion can be drawn from the findings mentioned above is an enhanced and systemized perception of wood extraction and its related dynamics needs to be further included in LandSHIFT. Certain aspects such as incorporation of plantation establishments, identification of age structure as well as recognition of forest management practices are not yet considered in a consistent context. Furthermore, it is important to distinguish between industrial roundwood and fuelwood demand pools because of the following reasons. (1) Commercial logging will always continue in order to satisfy timber demands; but in case of fuelwood consumption, some studies have concluded that many developing countries might change from fuel wood and charcoal to commercial energy - mainly fossil fuel (Nilsson and Bull, 2005). (2) Almost all kinds of wood species can be used for fuelwood but in case of industrial roundwood only certain species in a specific age class are desired.

Forest plantations are seen as a secure source of wood supply for industrial needs in many countries. According to the Seventh Biennial Issue of *State of the World's Forests* of the global forestry sector (FAO 2007), plantations establishments, especially in developing countries are increasing. Therefore wood supply from plantations needs to be considered in LandSHIFT. In order to make reliable estimates for the supply from forest plantations, actual age classes are needed. The Global Trade Analysis Project (GTAP) forest database contains country-level information on the amount of carbon stocks available in different age classes (Sohngen and Colleen, 2007). In addition to the age class distributions, the carbon located in different timber types is defined for specific agro-ecological zones (AEZ's). This information has been integrated at the 5-arc minute grid level in LandSHIFT and will be used in a next version of the forest module development.

Forest management plays a significant role in affecting the total carbon stock of various forest pools including trees, debris, soil and products (White et al., 2005). Therefore, long-term changes in forest ecosystem carbon stocks need to be assessed under various forest management practices in LandSHIFT. This will also provide an improved understanding of the contribution of forests to the global carbon cycle. For this purpose, a country-scale tabular database of historical forest management practices has been generated (See Appendix A). This database not only provides information on forest management practices at country scale but also distinguishes between these practices for major tree species in each country. Furthermore, data on wood density, felling cycle and rotation age for each tree species is also present. For the next version of the forest module in LandSHIFT, this database will be integrated with the forest database from GTAP (see above). The resulting database will then contain information on carbon stocks defined by forest management practices and age structure under the different AEZ's at the 5_arc minute grid scale.

5.3 References

Center for Sustainability and the Global Environment (SAGE), Gaylord Nelson Institute for Environmental Studies, University of Wisconsin, Madison, U.S.A. Website: http://www.sage.wisc.edu.

FAO 2008: FAOStat. Food and Agriculture Organization, United Nations, Rome

FAO (Food and Agriculture Organization of the United Nations). 2007. Seventh Biennial Issue of the State of the World's Forests.

Nilsson S. And G.Q. Bull, 2005 Global wood supply analysis: changing conditions Vancouver, Canada, 31st May 2005. Item 7 – Future Fibre Supply. Available at: http://www.fao.org/forestry/foris/data/ACPWP/46/Futurefibresupply.pdf. 16pp., FAO Advisory Committee on Paper and Wood Products. 46th Session.

Ramankutty, N. and Foley J. 1999. Estimating Historical Changes in Global Land Cover: Croplands from 1700 to 1992. Global Biogeochemical Cycles, 13(4): 997-1027.

Sohngen B., and Colleen T., 2007. Global Specific Global Forest Data Set Version 5, The Ohio State University, Department of Agricultural, Environmental and Development Economics.

White, M.K., S.T. Gower and D.E., 2005. Life cycle inventories for roundwood production in northern Wisconsin: inputs into an industrial forest carbon budget, Forest Ecol. Manage. 219 pp. 13–28.

Appendix A: Country-scale Forest Management Database

Table A.1: Structure of forest management database.

Field	Variables	Description
1)	***Country_ID***	LandSHIFT country code.
2)	***Eco_Code***	4-character Bailey ecoregion code. (See Field 3 for code descriptions). L100, L200, L300, L400, M100, M200, M300, M400, Nodata
3)	***Ecoregion***	Full name of Bailey ecoregion L100 – Boreal lowland L200 – Humid temperate lowland L300 – Dry tropical and temperate L400 – Humid tropical lowland M100 – Boreal upland M200 – Humid temperate upland M300 – Dry tropical and temperate upland M400 – Humid tropical upland Nodata
4)	***Practice_Code***	2-digit forest practice code. (See Field 5 for practice names). 10, 20, 30, 40, 60, 70, 80, Nodata.
5)	***Practice***	Full name of forest practice. <u>CODE – PRACTICE NAME</u> 10 – Reforestation 20 – Afforestation 30 – Plantation 40 – Natural Regeneration 60 – Silviculture 70 – Short Rotation 80 – Agroforestry Nodata
6)	***Species_Code***	4-character forest species code. (This database includes major tree species only).
7)	***Species_Name***	Full name of the species grown or found in a particular Bailey ecoregion in each country. (This database includes major tree species only).

8)	***LPJ_Class***	Classification of the species in Fields 6 and 7 based on the Lund-Potsdam-Jena classification of plant functional types.
9)	***Felling_Cycle (years)***	The planned period, in years, within which all parts of a forest zoned for wood production and being managed under a selected silvicultural system should be selectively cut for logs. The term is synonymous with ***Cutting Cycle*** (FAO forestry paper 135 – Guidelines for the management of tropical forests).
10)	***Min_DBH (centimeters)***	The specified minimum diameter at breast height measurement of a tree in order for it to be considered for merchantable logging.
11)	***Wood_Density (g/cm^3)***	Wood density of tree species based on dry weight per unit of fresh volume of wood. (Some species have different densities depending on region).
12)	***Rotation_Length***	Rotation length of the species in years.
13)	***Wood_Use***	Wood use of the forest species. (Industrial Roundwood / Fuelwood / Industrial Roundwood, Fuelwood). The Global Forest Products Model generates datasets of Industrial Roundwood and Fuelwood production till 2050 for MA and GEO4 scenarios. This production data will be used in LandSHIFT to identify the quantity of wood removals in each simulation year. Hence, the ‘Wood Use’ column has been included in the forest management database to identify for which particular type of wood (Industrial Roundwood / Fuelwood / Industrial Roundwood + Fuelwood) a suitable grid cell will be utilized.