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Global Potential for Carbon Storage Based on Forest Ecosystems

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Abstract

As our concerns about climate change grow, how much anthropogenic emission biosphere can absorb as a net carbon sink remains an important issue.

This thesis builds a physical model and an economic model of world forest based on the same forest stand growth curves and common assumptions of proper carbon storage method which has enough stability and longevity such as biochar. The aim of the study is to estimate the potential of carbon storage by world forest and the related economic implications.

In the physical model, combined forest management strategies of afforestation, decreased deforestation as well as harvesting and replanting are discussed. The results indicate a global annual potential of carbon sequestration in the range of 1 to 2 Gt of carbon by harvesting, which is significant as compared to the annual global emissions of around 10 Gt of carbon. In the economic model, the major take away is that commercial value as well as carbon value can be created while more carbon is locked through proper use of harvested wood.

Although forest grows relatively slow, the long term potential can be large, especially when technologies such as biochar production become more mature. As a fast but expensive solution, CCS technology has gained little progress so far. Other alternatives of carbon storage should be discussed and studied further.

Keyword: forest, carbon storage, climate

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Chapter 1 Methods

1.1 Study design

This study constitutes of two major parts: physical and economic analysis. Chapter 2 is the introduction of both parts. Part one is covered by Chapter 3 and Chapter 4, which models the growth of world forest under different strategies in order to estimate the corresponding potential for world forests as a carbon storage method. Part two is Chapter 5. This part builds up an economic model calculating the total social value of forest in order to discuss the social cost of carbon and the optimal harvest age of forest stands after the carbon value of forests is also taken into consideration. The model is based on the complete life cycle of standing biomass as well as forest products such as wood construction material and biochar.

Both of these two parts are based on the growth curves obtained in Chapter 3.3. The growth curves function as a major input of both physical and economic models. Additionally both analyses are developed upon the idea of biochar production which is assumed to create certain commercial value and to store carbon in a stable form for indefinite time. This idea allows the harvested wood to be stored properly in a large amount and it expands the function of forest products regarding both commercial and carbon purposes, thus increasing the overall value of forests.

1.2 Measures and Procedures

This study mainly applies model development for both analyses. In Chapter 2, related forest features have been argued or assumed. Basic principles of forestry economic are also introduced.

In Chapter 3, an equation is derived from logistic function in order to describe how the forest stand in different zones will grow with time in terms of carbon content. Then with sufficient data and some assumptions made for the tropical zone due to its biodiversity, three forest stand carbon growth curves for the three forest zones are set. As world forest is segmented into boxes of the same area and the current average forest ages are found out, the three growth curves are summoned in another model which describes how the forest carbon will naturally develop according to its current trend.

In Chapter 4, various strategies including avoiding deforestation, afforestation, harvesting and storing, are applied to the model of the initial forest with the current developing trend. By changing the area decreasing rate in the tropical zone, the effect of alleviated deforestation is demonstrated through tables and figures. Afforestation is managed in the model by adding some new area to the established forest zone every year. The carbon content of the new area will grow according to the growth curve. Harvesting is achieved by resetting the age of the harvested forest stand back to year zero. The harvesting strategy in this study is assumed to be accompanied by immediate replantation afterwards meaning that the land is still functioning as forest land. After these three major strategies are demonstrated separately, Chapter 4.5 discusses the carbon storage potential of world forest when all strategies are combined together.

In Chapter 5, an economic model is developed based on assumptions of the carbon flow in forest as well as in forest products. The model calculated the implied social value of forest ecosystem by tracking the total period from the point when trees start to grow until the moment when the last forest products are turned into carbon dioxide emissions. Various implications are discussed in the end of this chapter.

1.3 Limitations

There are some limitations regarding the nature or the design of this study.

The forest stand carbon growth curve for afforestation is supposed to be slightly different from the growth curve used in the model. In the model it is assumed that the land is already forest land. This may leads to overestimation of the potential of carbon stored by afforestation.

The forest stand carbon growth curve includes only standing biomass but not soil carbon. For the total forest ecosystem, soil carbon is also an important carbon stock and can be a large proportion in some areas such as boreal zone. However, the detailed carbon flows within a forest stand are very complicated and is difficult to model accurately.

For the economic model, the estimates of average commercial profit of wood and biochar are not very accurate due to its natural wide range and variety.

Chapter 2 Introduction

2.1 Carbon cycle and atmospheric CO_2 concentration

2.1.1 Earth carbon cycle

Carbon, which has the atomic number 6, is the core element for life on Earth. It is exchanged among many carbon reservoirs and these movements together are described as the Earth carbon cycle. Major carbon reservoirs are atmosphere, terrestrial biosphere, ocean, sediments (fossil fuels, fresh water systems and non-living organic material such as soil carbon) and the Earth's interior. The quantities of Gt[1] of carbon in each reservoir are as follows: atmosphere 720, oceans 38,400, terrestrial biosphere 2,000. The carbon exchanges between reservoirs occur as a result of various chemical, physical, geological, and biological processes. The global carbon budget is the balance of the carbon exchanges among the reservoirs or between one specific loop of the carbon cycle such as atmosphere and the biosphere. This provides information regarding whether the carbon reservoir functions as a sink or source of carbon.

Of the carbon stored in the geosphere, about 80 % is limestone and its derivatives, which form from the sedimentation of calcium carbonate by marine organisms. The remaining 20 % is stored as kerogens underground. Carbon can be released from geosphere to atmosphere through volcano eruptions and hotspots or by extracting and burning fossil fuels. The latter passageway has been increasing at an astonishing speed in recent decades and has much influence on carbon dioxide in the atmosphere.

By far the largest store of carbon in this system is the deep ocean which stores almost 50 times as much carbon as in the atmosphere and it exists predominantly as bicarbonate ions. Only a tiny amount is stored in marine biomes. Nevertheless, marine biology has a substantial influence on atmospheric CO_2 concentrations because it mediates a flux of carbon into the deep ocean. This flux is responsible for the enrichment of the carbon content of the deep sea and

[1] Giga tonne (Gt)=10^9 tonnes=10^{12} kilograms (kg)

causes an imbalance between CO_2 in the surface ocean and in the atmosphere—the ‘biological pump’ (Royal Society (Great Britain), 2009). The oceans' surface layer holds large amounts of dissolved organic carbon almost as much as the atmospheric carbon which is rapidly exchanged with the atmosphere. Oceanic absorption of CO_2 is one of the most important forms of carbon sequestering limiting the human-caused rise of CO_2 in the atmosphere. This absorption has led to a decline in the average pH of the oceanic surface waters by 0.1 units since the industrial revolution (Royal Society 2005). As the sea water becomes more acidic which slows down biological precipitation of calcium carbonates, it lessens the ocean's capacity of carbon sequestration.

The residence time of carbon varies widely among different reservoirs. On average a carbon atom spends about 5 years in the atmosphere, 10 years in terrestrial vegetation, and 380 years in intermediate and deep ocean water (Solomon, 2007). Apparently slower processes may have longer and bigger effects.

2.1.2 The greenhouse effect

The radiation that the Earth gets from the sun is transferred into various energy forms. As a warm object, Earth’s surface emits long wave thermal radiation which is absorbed by atmospheric greenhouse gases which are mainly water vapor and carbon dioxide. Today nearly 80 % of the radiation emitted by the Earth’ surface is absorbed by atmospheric greenhouse gases (Hansen et al., 2013). The energy retained by these greenhouse gases is re-radiated partly downward which is re-absorbed by the surface thus heating the whole planet. Due to this *greenhouse effect* the temperature of the planet is determined by the balance at the top of the atmosphere between the solar radiation absorbed by Earth and the long-wave radiation emitted to space.

2.1.3 Atmospheric CO_2 concentration

Carbon in the Earth's atmosphere exists in two main forms: carbon dioxide (CO_2) and methane (CH_4). Although both are important greenhouse gases, methane is unstable and has much lower concentration in the atmosphere, making carbon dioxide the most crucial greenhouse gas.

Since the industrial revolution, human activity has modified the carbon cycle by changing its component's functions and directly adding carbon to the atmosphere (Falkowski, 2000). Mainly by burning fossil fuels and manufacturing concrete human has caused the most direct and biggest influence on atmospheric CO_2 concentration. It has increased markedly at a rate of 2.0 ppm[2] per year during 2000–2009 and faster since then. It was 280 ppm in pre-industrial times and has now risen to 392 ppm in 2013[3]. Carbon dioxide leaves the atmosphere in two ways: through photosynthesis or dissolves directly into bodies of water entering the biosphere or ocean. Photosynthesis converts carbon dioxide into organic plant material, whereas bodies of water store carbon in inorganic form. Currently about 57 % of human-emitted CO_2 is removed by the biosphere and oceans (Canadell et al., 2007). The ocean's speed and capacity of carbon sequestration is limited but has longer term effect. On the other hand, organic carbon in plant tissues can remain sequestered for thousands or millions of years if buried in soils, but it may have a shorter residence time (Solomon, 2007).

2.1.4 The Earth's temperature

Any imbalance in the energy flows between the earth and space constitutes a 'radiative forcing' that ultimately causes an adjustment of the global mean temperature. Human activities are estimated to have produced a net radiative forcing of about 1.6 W/m^2 since pre-industrial times. About half of this radiative forcing has been absorbed causing an increase in global mean temperature of 0.8°C to date. Similar amount of additional warming would occur even if CO_2 and other greenhouse gases were immediately stabilized at current levels, which is not possible (Royal Society (Great Britain), 2009). This lag in the response of the global mean temperature is primarily due to the large heat capacity of the oceans. A doubling of the CO_2 concentration from its pre-industrial value to 550 ppm would give a radiative forcing of about 4 W/m^2 and an estimated equilibrium

[2] Ppm is the mass ratio between the pollutant component and the solution.
1 part per million (ppm) = 0.0001 %= 1 mg/kg

[3] Earth System Research Laboratory Global Monitoring Division

global warming of about 3°C (range 2.0 to 4.5°C) (IPCC[4] 2007a).

2.2 Climate problems

2.2.1 Terminology

The term *climate change* means a long-term change in the Earth's climate, or of a region on Earth. It is used to refer specifically to changes caused by human activity instead of by Earth's natural processes.[5] In this sense, the term *climate change* has become synonymous with anthropogenic *global warming* which refers to Earth's surface temperature increase (Conway, 2008). This thesis is focused on the problem of rising CO_2 concentration in the atmosphere which leads to global warming and other climate change evidences through the greenhouse effect.

2.2.2 Anthropogenic causes

The Intergovernmental Panel on Climate Change concluded in 2007 that there's a more than 90 percent probability that human activities over the past 250 years have warmed our planet. Industrialization by humanity has shaped the world today. Human's producing activities such as concrete, steel and chemical production in a large scale have directly emitted enormous amount of greenhouse gases into the atmosphere. With bigger and still-increasing population and a much more developed economy, world energy production today is almost 30 times of what it is two hundred years ago. Meanwhile global CO_2 emissions have rocketed together with the above mentioned activities.

Over the past several centuries, human-caused land use and land cover change (LUCC) has led to the loss of biodiversity, which lowers ecosystems' resilience to environmental stresses and decreases their ability to remove carbon from the atmosphere. More directly, it causes release of carbon from terrestrial ecosystems into the atmosphere. One of the most typical land use change today is

[4] IPCC: United Nations' Intergovernmental Panel on Climate Change
[5] The United Nations Framework Convention on Climate Change 21 March 1994

deforestation. According to FAO[6], deforestation can result from 'a combination of population pressure and stagnating economic, social and technological conditions' (Marcoux, 2000). Subsistence farming is responsible for 48 % of deforestation worldwide; commercial agriculture is responsible for 32 % of deforestation; logging is responsible for 14 % of deforestation and fuel wood removals make up 5 % of deforestation (UNFCC, 2007).

Other human-caused changes to the environment can change the ecosystems' productivity and thus their ability to remove carbon from the atmosphere. For example, a vicious cycle has emerged in the loop between carbon in the soil and in the atmosphere. Air pollution damages plants and soil and accordingly their ability to purify and adjust the environment. Too intensive agricultural practices can lead to higher erosion rates and wash carbon out of soil into water and finally into the air. Higher surface temperatures increase decomposition rates in soil, thus returning CO_2 stored in plant material and soil more quickly to the atmosphere. Such vicious cycle also exists in other loops of the carbon cycle, for example the oceanic carbon cycle. Rising temperatures has modified the ocean's ecosystem. Meanwhile acid rain and polluted runoff from agriculture and industry are changing the ocean's chemical composition. Together with higher concentration of CO_2 in the atmosphere and in the upper layer of ocean surface, oceanic acidification is growing fast which limits the ocean's ability to absorb carbon from the atmosphere and reduces oceanic biodiversity globally.

2.2.3 Consequences

Many facts have been observed in recent decades regarding global warming. Average temperatures have climbed 0.8 degree Celsius around the world since 1880[7]. IPCC has reported that 11 of the past 12 years are among the dozen warmest years since 1850. Average temperatures in Arctic area have risen at twice the global average[8].

There are various consequences awaits a warming climate on Earth. Glaciers and

6 Food and Agriculture Organization of the United Nations
7 NASA's Goddard Institute for Space Studies
8 Arctic Climate Impact Assessment report between 2000 and 2004

mountain snows are melting. An upsurge in the amount of extreme weather events, such as wildfires, heat waves, and strong tropical storms, is also attributed in part to climate change by some experts. Sea level rising, fresh water shortages and more easily spread diseases may also be of big concern in the future. But the aggregate and long term impacts are highly uncertain. Still, we know very little about the outcome of different scenarios.

2.3 Solutions

2.3.1 Non-biological solutions

2.3.1.1 CCS technology

The most direct abatement technology is Carbon Capture and Storage. The main idea of which is to capture carbon dioxide in its gas form from fixed emitters such as fossil fuel power stations, and to store its liquid form safely and permanently underground using natural trapping mechanisms.

When considering future abatement scenarios, CCS technology has often been counted as a mitigation contributor. It has been a key assumption of the "450 Scenario" in the International Energy Agency's annual energy outlook reports, in which the world can meet its energy needs while keeping atmospheric carbon concentration below 450 ppm. However, though transporting liquid CO_2 has technically been a mature step, capture technology is still scarce and finally safe and permanent CO_2 storage in liquid form exists mainly in the laboratory. The high costs originating from expensive equipment which capture, purify (if the CO_2 is to be sold), liquefy, transport and bury the gas. Some has argued that according to the CBO analysis, the LCOE[9] for a CCS-equipped plant is on average 76 % more than for a conventional plant (Chris Nelder 2013).

As far as I am concerned, small scale CCS may create value under specific conditions while large scale CCS is not very likely to solve our problem in the near future.

[9] LCOE: levelized cost of energy

2.3.1.2 Fuel alternatives

Producing power through burning fossil fuels contributes nearly 60 % of global carbon dioxide emissions (IPCC 2007). Accordingly, developing various energy sources has become quite serious task. Renewable energy comes from resources which can naturally replenish on a human timescale such as sunlight, wind, rainfall, tides, waves and geothermal heat. However, there are reasons why we use fossil fuels on a much larger scale.

Solar power has undergone obvious efficiency increases in recent years. But it is still limited by incoming radiation amounting to 240W/m^2 on average at Equator. Once capacity factor and other elements are taken into consideration, the area needed to produce certain amount of energy is extremely huge. Future of solar power might be small scale 'where needed' installations in connections to house warming, water warming etc.

Global installed wind power capacity in 2012 is nine times of what it was ten years ago. Main contributor countries are India, China, Spain, Germany and the United States. However, the fundamental limitations of wind energy are intermittency problems, conversion efficiency of wind turbine and the Betz Law, of which the last one requires long distance between different wind turbines. The estimated global economic wind power potential is 5 TW (Hansen et al., 2013).

Presently we are making use of hydroelectric power of 0.8 TW globally. It has a total potential of about 2 TW (Hansen et al., 2013). Also it can be complementary with other intermittent sources of energy by pumping up and storing water when power is not needed. However, a hydropower project flooding areas with standing plantation biomes may produce methane. Potential dam failure and possible climate and biodiversity change have also boosted the inherent risk of hydropower.

Nuclear power took up 2.7 % of world energy consumption in 2010 and it has long been under dispute. Worldwide there have been 99 accidents at nuclear power plants. Very serious accidents include locations in Fukushima (2011), Chernobyl (1986), Three Mile Island (1979). These accidents have created fear among people and resistance of governments to invest on related technologies. According to Egil Lillestøl who is working at CERN[10], a new nuclear technology based on Thorium- ^{233}Uranium cycle can work with a critical factor k less than one, which could avoid nuclear accidents by fundamental design. This technology is now under development and it has the potential to change nuclear reactors by its very nature.

2.3.1.3 Geoengineering

Most geoengineering proposals aim either to reduce the concentration of CO_2 in the atmosphere (CDR techniques) or to prevent the Earth from absorbing some solar radiation, either by deflecting it in space before it reaches the planet, or by increasing the reflectivity or albedo of the Earth's surface or atmosphere (SRM techniques).

2.3.1.3.1 Solar radiation management techniques (SRM)

SRM aims to offset greenhouse warming and to provide a cooling effect by reducing the incidence and absorption of incoming short-wave solar radiation. Various techniques have been proposed: brightening the Earth's surface, or introducing reflective matter into the atmosphere, or inserting light scattering material in space between the Sun and the Earth.

The SRM methods may provide a useful tool for reducing global temperatures rapidly should the need arise. But all the greenhouse gases remain in the atmosphere and soon after SRM is ceased the warming effect shall still take place. So this method carries with it the termination problem, and could not address ocean acidification or any other CO_2 effects.

2.3.1.3.2 Non-biological Carbon dioxide removal techniques (CDR)

Ocean-based CDR such as ocean fertilization and oceanic upwelling or downwelling modification has quite low societal and political acceptance due to several key drawbacks such as disturbance of oceanic carbon cycle and other undesired side effects.

Land-based CDR has three major categories: physical (air capture), chemical

[10] European Council for Nuclear Research

(enhanced weathering) and biological. Physical CDR aims to capture CO_2 directly from the air. It is expected to be effective but costly. However, the advantages of air capture are: the location can be more flexible compared to CCS, the scale has no upper limit, the environmental risk is quite low and it can also cover CO_2 emissions from hard-to-control sources such as transportation. Chemical CDR accelerates the natural weathering process and stores carbon as a solid mineral. It is expected to be reasonably effective with costs and environmental impacts broadly comparable to those of conventional mineral mining activities.

2.3.2 Biological geoengineering

2.3.2.1 Land use management (Land carbon sinks)

The world's forest ecosystems store more than twice the carbon in the atmosphere (Canadell and Raupach, 2008). Terrestrial ecosystems store about 2100 Gt of carbon in living organisms, leaf litter and soil organic matter, which is almost three times that currently present in the atmosphere. Unfortunately tropical land-use change (forest deforestation and regrowth) alone now accounts for 1.5 Gt of carbon per year and is the fastest rising source of emissions (Canadell et al., 2007). Hence simple strategies of better land use management can enhance natural sequestration of carbon dioxide. The measures include avoided deforestation, afforestation, reforestation, and planting of crops or other vegetation types (Royal Society 2001, 2008b).

But while standing biomass offers multiple benefits such as forest products, carbon sequestration and environmental protection, it also occupies the land beneath. With continuing rising demand for land, especially for agriculture, energy crop production and biodiversity conservation, it is not an easy task to simply reverse the current trend. Thus these land use management methods may be applied in an integrated manner considering competing demand for land. To sum up, the above mentioned approaches are at low risk, feasible but can only achieve small to medium effects on atmospheric concentrations (Royal Society (Great Britain), 2009).

2.3.2.2 Biofuel

Biomass can be harvested and used as fuels so that CO_2 emissions from the biofuel use are roughly balanced by carbon captured in growing energy crops. The use of biofuels can be considered as a means to reduce emissions (Royal Society (Great Britain), 2009). The potential of extra carbon storage rather than balancing emissions is emphasized, thus the use of biofuel will not be discussed further in this thesis.

2.3.2.3 Bioenergy with CCS (BECS)

BECS is a combination of biofuel production and CCS technology and thus inherits the advantages and disadvantages of both technologies. It is now technically feasible but still is highly dependent on mature CCS technology.

2.3.2.4 Biomass for sequestration

The idea of burying directly organic material such as wood, crop waste of charcoal (biochar) can be categorized as biomass for sequestration. Apparently burying biomass underground requires extra energy consumption for transport, processing and burying. Also this can be a disruption of the natural nutrient cycling and ecosystem viability.

However, under the conditions that the cost of climate change is high enough and so is the carbon price, then this alternative becomes more attractive. Additionally when the cost of other carbon sequestration projects are equally high, burying biomass may be comparable and acceptable.

This thesis puts emphasis on the physical potential and economic implications regarding biological carbon sequestration, more specifically the role of forest and wood. Research within this topic is urgently needed to characterize eligible carbon credit mechanism.

2.4 World forest

2.4.1 Photosynthesis

Photosynthesis maintains atmospheric oxygen level and supplies all of the organic compounds and most of the energy necessary for all life on Earth (Bryant and Frigaard, 2006). As mentioned above, it is a major passage for carbon dioxide to leave the atmosphere. It is a process where plants and other organisms use water and light energy, normally from the sun, to produce chemical energy which can later be used to fuel the organisms' activities. There are several factors affecting photosynthesis: water, carbon dioxide concentration, temperature, light and mineral elements. Lack of water supply, sunlight and low temperature will hinder photosynthesis thus limiting plantation growth speed and carbon sequestration rate.

Today the increased levels of CO_2 in the atmosphere can also lead to higher gross primary production in some plant species. This is called CO_2 fertilization which allows the plant to attain specific carbon dioxide concentration level without opening its stomata for too long and losing water molecules. This has important implications on a dynamic model describing forest growth which will be presented later.

2.4.2 Forest resource characteristics

Forests are multifunctional. They directly provide us timber, fuelwood, food, purified water and other forest products. Moreover forests contain roughly 90 % of the world's terrestrial biodiversity (Living Planet Report, 2010). This huge pool of genetic resources is no way replicable. Also, forests offer services such as removal of air pollution, regulation of atmospheric air quality, nutrient cycling, soil creation, habitats for human and wildlife and so on. Thus timber management for any single purpose can easily neglect all the other values and generate external effects.

Natural forests are very productive but the time lag between planting and reaching biological maturity for a tree is usually at least 25 years, which can sometimes be as long as 100 years. Trees are usually harvested in their entirety which means a stand is usually clear cut. However, as the public pressure to count in forests' other value grows stronger, it has become more common to apply selective cut which only harvest trees above certain age.

Unlike fishery resources or mineral deposits, standing trees occupy potentially valuable land. In a privately owned forest land, the opportunity cost can often decide the function of the land. Since not all value is internalized by the market, forest owners will tend to put the land into other use if the opportunity cost of the land is higher than the timber product value. But forests certainly offer more than timber products as discussed above.

2.4.3 Current forest status

2.4.3.1 Area and its rate of changing

Forest land indicates a land spanning more than 0.5 ha[11] with trees higher than 5 meters and a canopy cover of more than 10 percent. (FRA[12] 2005) Today the world forest area is 4.033 billion ha. Europe has the largest share of world's forest thanks to huge extent of forests in Russia which is about 20 % of world forest area. South American has almost the same area of forests as Europe but with higher density of biomass due to different forest types.

[11] Hectare (ha)=10 000 square metres (m^2)= 0.01 square kilometres (km^2)

[12] Global Forest Resources Assessment By FAO

Table 2.1 World forest area and its average annual rate of changing (FRA, 2010)

	Forest area (1000 ha)	% of world forest area	Annual area change 1990-2010 (1000 ha)	Annual area change rate 2005-2010 (% of remaining forest area)
Africa	674,419	16.7	-3740	-0.5
Asia	592,512	14.7	820	0.29
Europe	1,005,001	24.9	776	0.08
Caribbean	6,933	0.17	52	0.6
North and Central America	705,393	17.5	-150	0
Oceania	191,384	4.7	-368	-0.55
South America	864,351	21.4	-4105	-0.41
World	**4,033,060**	100	**-6767**	**-0.14**

In the recent two decades, world forests are diminishing at an alarming rate of 6.7 million ha per year. The trend of forest area change from 2005 to 2010 indicates that except for Asia and Europe, all other regions are experiencing forest loss. Big contributors to this loss are countries in Africa and South America such as Brazil, Mexico, Indonesia and Nigeria. So the loss in tropical areas is bigger than gains in non-tropical areas. Also the gain in plantation forests is not big enough to compensate loss in natural forests. Overall world forest resources has been shrinking and releasing tonnes of carbon dioxide into the atmosphere.

2.4.3.2 Forest types

Table 2.2 Various forest types by different standards and time

Forest function types (FRA 2005)	% of total area	Forest function types (FRA 2010)		Forest ecosystem types 2013	% of total area
Primary forest	36.4 %	Production	30 %	Tropical	48 %
Modified natural forest	52.7 %	Protection of soil and water	8 %	Subtropical	13 %
Semi-natural forest	7.1 %	Conservation of biodiversity	12 %	Boreal	27 %
Productive forest plantation	3 %	Social services	4 %	Temperate	12 %
Protective forest plantation	0.8 %	Multiple use	24 %		
		other	23 %		

Forests are divided by different designated functions. More than one-third of all forests are primary forests of native species in which there exists no visible evidence of human activities, thus the ecological processes are not disturbed. Primary forests are vitally important resources of diverse biological material and they also play a crucial role in regional and global climate. Unfortunately much of this area is converted into modified natural forests through deforestation or selective logging at an average rate of 6 million ha annually. Natural and semi-natural forests account for 96.2 % of total forest area. If managed, they are only for timber production. The plantation area counts less than 5 % of the total forest area, but it is growing quickly at an average rate of 4.2 million ha per year during 2005-2010. Productive plantation not only supplies a lot of wood and fiber for domestic and industrial purposes, but also has significant implication on fuelwood availability. Enough forest plantations can release pressure on natural forests to provide fuelwood.

The UNEP-WCMC's forest category classification system is a simple system that reflects different climatic zones as well as the principal types of trees. It divides the world's forests into 6 broader categories (containing 26 major types): temperate needle-leaf; temperate broadleaf and mixed; tropical moist; tropical dry; sparse trees and parkland and forest plantations. Among those, sparse trees and parkland occur principally in areas of boreal region and in the seasonally dry tropics. So this system goes along with an even more brief description of three major forest categories according to latitude: tropical, temperate and boreal forests.

Tropical forests occur near the equator within an area with distinct seasonality: winter is absent, and there are only dry or rainy seasons. The length of daylight is 12 hours and temperature is on average 20-25°C. This condition varies very little through the year. Annual rainfall usually exceeds 200 cm and is evenly distributed through the year. Soil in tropical forests is nutrient-poor and acidic since decomposition is so rapid that residues can hardly accumulate. Tropical forests are characterized by the greatest diversity of species. Trees, mostly evergreens, are usually 25-35 meters tall, with buttressed trunks, shallow roots and dark green leaves. Canopy is multilayered and continuous, allowing little light penetration (UCMP).

Temperate forests occur in eastern North America, north-eastern Asia, and western and central Europe. Well-defined four seasons with a distinct winter, a moderate climate and a growing season of 140-200 days characterize this forest biome. Temperature varies from -30°C to 30°C. Precipitation is around half of that in tropical areas. Soil in temperate forests is fertile, enriched with decaying litter. Unlike tropical forests' enormously dense biodiversity, there are only 3 or 4 dominating tree species per km^2. Trees in this area with broad leaves that are lost annually include such species as oak, hickory, beech, maple and so on.

Boreal forests, or taiga, represent the largest terrestrial biome. They can be found in the broad belt of Eurasia and North America: two-thirds in Siberia with the rest in Scandinavia, Alaska, and Canada. Seasons are divided into short, moist, and moderately warm summers and long, cold, and dry winters. With a short growing season of 130 days, very low temperatures and little precipitation mainly as snow of 40-100 cm annually, trees grow very slowly. Soil in boreal areas is thin, nutrient-poor, and acidic. Dominant tree species are evergreen conifers with needle-like leaves, such as pine, fir, and spruce.

How efficiently, wisely and practically should we manage different areas and types of the forests in order to internalize the non-timber value and use forests as a powerful mitigation alternative should be our major concern in this thesis.

The areas of different zones are summarized in the following Table 2.3.

Table 2.3 Current forest area of different zones in year 2010 (Chillymanjaro, 2011)

(Calculated from FRA 2010 Table 2.1 and Table 3)

Region	Forest type	Area (1000 ha)
South America	Tropical	864,351
Africa	Tropical	674,419
South and southeast Asia	Tropical	294,373
Central America	Tropical	19,499
Mexico	Tropical	64,802
Total Oceania	Tropical	191,384
Total tropical		**2,111,140**
USA	Temperate	304,022
East Asia	Temperate	254,626
West and central Asia	Temperate	43,513
Europe excluding Scandinavian	Temperate	134,942
Total temperate		**739,415**
Russian Federation	Boreal	809,090
Scandinavian (Norway, Sweden, Finland and Denmark)	Boreal	60,969
Canada	Boreal	310,134
Total boreal		**1,182,505**
Total world		**4,033,060**[13]

2.4.3.3 Forest carbon cycle

By sequestering large amounts of atmospheric carbon, forests play an important role in the global carbon cycle and are thought to offer a mitigation strategy to reduce global warming (Luyssaert et al., 2007).

Carbon is absorbed by the forest ecosystem through photosynthesis, tree growth,

[13] Due to small inevitable errors in assigning different regions to forest types, the total gap of 6939 thousand ha is allocated evenly to three zones to make the world forest area in line with the previous table.

and accumulation of carbon in soils and is released back to the atmosphere through respiration of living biomass, tree mortality, microbial decomposition of litter, oxidation of soil carbon, degradation and disturbance. These processes are influenced by a number of climatic and environmental factors such as temperature, moisture availability and disturbance. Additionally there are large differences between different forest types, which explain why three major forest zones are treated separately in this thesis. For example, in tropical rain forest much less seasonal patterns of carbon intake process exist than in the boreal forest, since the rainfall and temperature is pretty constant near the equator throughout the year. Microbial decomposition of residue is much faster in tropical area creating a very thin layer of soil compared to thick accumulated soil in boreal forest.

Plantation biomass which is mainly contributed by forest land on earth contains around 550 Gt of carbon (Riebeek, 2011). Photosynthesis captures about 120 Gt of carbon every year while respiration and microbial decomposition returns almost the same amount. In recent years the balance has been changed because human activities are adding large amounts of carbon dioxide into the atmosphere while ocean and forest have been taking in carbon as a net carbon sink.

Global emissions of carbon dioxide from the combustion of fossil fuels will reach 36 Gt for the year 2013 (CDIAC, 2013). Despite the rising number of yearly man-made emissions, forest ecosystem is sequestrating about 4.05 Gt of carbon per year from 1990 to 2007 by either volume growth or reforestation. Tropical deforestation (excluding tropical forest regrowth) emits averagely 2.94 Gt of carbon per year from 1990 to 2007(Pan et al., 2011). Overall forest has been acting as a net carbon sink of 1.11 Gt of carbon per year in the carbon cycle helping to reduce climate change in a large scale. If proper management scheme is applied, the forest may well have large potential of carbon storage.

2.5 Forestry economics

The common aim of forestry economic analysis is to find the required managing strategy which maximizes the present value of profits from the forest stand (Perman, 2011). The key to this problem is the proper time after planting at which forest stand is harvested, which is called the rotation length. At the same time, the model being used is crucial. The model used here is a single-rotation forest model and calculates the socially optimal rotation length instead of commercially optimal rotation length.

In a single-rotation model, forest stand will be planted and harvested once. From a commercial value maximizing perspective, it is typical to assume that forests generate value only through timber production and the existence or felling of trees have no external effects (Perman, 2011). Then it is easy to reach the conclusion that optimal harvesting point is when the volume growth of trees equals the interest rate on condition that price and cost levels are constant. It is intuitive that when the opportunity cost of the capital tied up in the growing forest stand is higher than potential gain from timber production, forest owners will choose to harvest the stand.

However, once the value of other external effects such as carbon value is included, the analysis becomes different. The Faustmann Rule is adjusted for optimal harvest of a forest stand in the presence of a social cost of carbon dioxide emissions (Hoel et al., 2012). One of the contributions is to take into account the dynamics and interactions of the forests' multiple carbon pools within an infinite time horizon.

Chapter 3 Model development

3.1 Derivation of the growth equation

The range of equations describing the growth characteristics of trees in general are empirical in their origin such as the logistic equation or its generalization, the Richards equation (Birch, 1999). Other applied growth curves are the Gompertz model and the modified Weibull model (Yan et al., 2009). The derivation of the two former will in the following be performed solely on physical grounds. Our starting point is the assumption that a real forest can be replaced by a set of identical average trees. Each of them has an extractable time dependent wood volume $V(t) \in (0, V_{max})$. Due to various limited resources such as sunlight and water, a forest stand has a theoretically maximum volume. Here V_{max} is the volume gained by the average tree at mature age. Accordingly T implies the age at which the plant starts to spend most of its energy on maintaining its current status rather than on volume growth.

As discussed above in Chapter 2, light energy supplies the necessary energy for photosynthesis. The growth speed is thus determined by a total area of leaves being exposed to the incoming electromagnetic radiation. It seems reasonable to put the volume growth rate proportional to the exposure area $A(t)$. Additionally the living plant needs to transport water and other molecules from the ground up to the region where the photosynthesis is active. The plant also invests its energy to produce offspring once it reaches sexual maturity. Thus, only a fraction $\epsilon(t) \in (0,1)$ of the energy absorbed by the photosynthesis is available for volume growth.

$$\frac{dV}{dt} = \epsilon(t)A(t) \tag{1}$$

As the average tree approaches its mature size, an increasingly amount of internal work has to be performed for sustaining life. Thus, $\epsilon(t)$ must decrease with time. Here we assume that available energy for growth decreases in proportion to the total volume.

$$\epsilon(t) = \epsilon_0 \left(1 - \frac{V(t)}{V_{max}}\right) \tag{2}$$

The area exposed to sunlight $A(t)$ is asssumed to be scaled with the squared average branch length which again is assumed proportional to the squared average height of the main tree trunk. The wood volume on the other hand is given by $A_{trunk}h$ which shows that $A(t) \propto V(t)$ when we assume $A_{trunk} \propto h$. At this point the logistic equation, when collecting all proportionality constants into a single α, is obtained as the following:

$$\frac{dV}{dt} = \alpha V(t)\left(1 - \frac{V(t)}{V_{max}}\right) \tag{3}$$

Equation (3) is the logistic growth equation. Note by assuming a non-linear efficiency function for $\epsilon(t)$ the Richards equation is obtained. The solution of the logistic growth equation is:

$$V(t) = V_{max}(1 + e^{-\alpha(t-t_p)})^{-1} \tag{4}$$

where t_p is the time at which the volume growth rate is the highest.

3.2 Growth equation for trees

The energy production per ha of various plantations depends on climatic, soil, and management conditions (Goldemberg et al., 2000). According to the World Energy Assessment 2000, Net Energy Yield (NEY) for wood is from 30 to 80 GJ[14] per ha per year. This can be converted to a Net Biopower (NB) of 0.1 to 0.254 watt per square meter (W/m^2).

This NB is derived from the NEY which is what the plant has been continuously converting from solar energy to bioenergy and what we can finally harvest after a period of time. Since different zones have different solar radiation intensity, climate and soil conditions, the efficiency of biomass production is also various. In this thesis we apply 0.24 W/m^2 (75.69 GJ per ha per year) for tropical zone since the solar radiation is highest near the equator, 0.24*cos(35°)=0.196 W/m^2 (62 GJ per ha per year) for temperate zone 0.24*cos(60°)=0.12 W/m^2 (37.84 GJ per ha per year) for boreal zone according to specific zone latitude.

From a physical perspective, the maximum amount of wood with certain mass

[14] GJ=gigajoules=10^9 J

and volume is the result of continuous energy transformation by photosynthesis. The V_{max} can thus be calculated for different zones with different biopower.

$$V_{max} * \rho_{wood} * calorific\ value_{wood} = NYE * T$$
$$= NB * \mu * T * area \quad (5)$$

Based on existing studies about trees, it is assumed that T of tropical, temperate and boreal zones are 200, 150 and 140 years respectively. $Area$ (10^4m^2/ha) is simply a transition from square meter to ha regarding the final unit; μ indicates the number of seconds per year which is $365 * 24 * 3600$. The density of dry wood can vary from 0.16 to 1.33 tonne[15]/m^3 due to species differences [16]. A common knowledge is that the bigger the tree, the lower the latitude, the higher the density (Elert). But this is mainly caused by more moisture inside the tree in tropical area. Since the dry wood density and calorific value are applied here, it is reasonable to assume an average density of 0.6 tonne/m^3. The calorific value by mass of dry wood is different for various species but for simplicity we apply 20 10^9J/tonne for all three zones[17].

$$V_{max} = NYE * T/(\rho_{wood} * calorific\ value_{wood}) \quad (6)$$

$$V(t) = NYE * T/\rho_{wood} * caorific\ value_{wood} * (1 + e^{-\alpha(t-t_p)}) \quad (7)$$

With above information V_{max} and accordingly $V(t)$ can be calculated, of which the unit is cubic meter per ha (m^3/ha).

3.3 Growth curves for an average tree in different zones

3.3.1 Data sources

The data for the following selected species are time series up to 125 years for both the timber volume and carbon content per ha (Smith et al., 2006). This data set is chosen for its accuracy of forest research in the United States and the large area of representative boreal and temperate forests. From these typical species of forest stands in the boreal and temperate areas we calculate the growth curve parameters for the average tree.

[15] 1 tonne=10^3 kg
[16] Engineeringtoolbox
[17] Typical calorific values of fuels from Biomass Energy Center

Table 3.1 Selected species for boreal forests (Smith et al., 2006)

Species	Location in the USA
Spruce-balsam fir	Northeast
White-red-jack pine	Northern Lake States
Oak-pine	Northern Prairie States
Fir-spruce-mountain hemlock	Pacific Northwest, East
Fir-spruce-mountain hemlock	Pacific Northwest, West
Fir-spruce-mountain hemlock	Pacific Southwest
Douglas-fir	Rocky Mountain, North
Loblolly-shortleaf pine	Southeast
Longleaf-slash pine	Southeast
Loblolly-shortleaf pine	South Central

Data source: APPENDIX A from Smith et al. (2006)

Table 3.2 Selected species for temperate forests (Smith et al., 2006)

Species	Location in the USA
Maple-beech-birch	Northeast
Aspen-birch	Northern Lake States
Maple-beech-birch	Northern Prairie States
Alder-maple	Pacific Northwest, East
Western oak	Pacific Southwest
Aspen-birch	Rocky Mountain, South
Oak-hickory	Southeast
Oak-hickory	South Central

Data source: APPENDIX A from Smith et al. (2006)

Due to high biodiversity in the tropical forests, it is very difficult to describe the whole ecosystem with several dominating species. What can be argued is that tropical trees tend to have a linear growth curve with a slightly higher growth speed in the first 100 years. Then the growth rate starts to drop and the tree slowly reaches its maximum size (Lieberman and Lieberman, 1985) (see Figure 3.1). The projected lifespan of 46 species in wet tropical forest was analyzed and the resulted average life span for tropical trees is 250 years (Lieberman et al., 1985). In this thesis, the number is adjusted to 200 years to describe when the tropical trees stop to focus on volume growing.

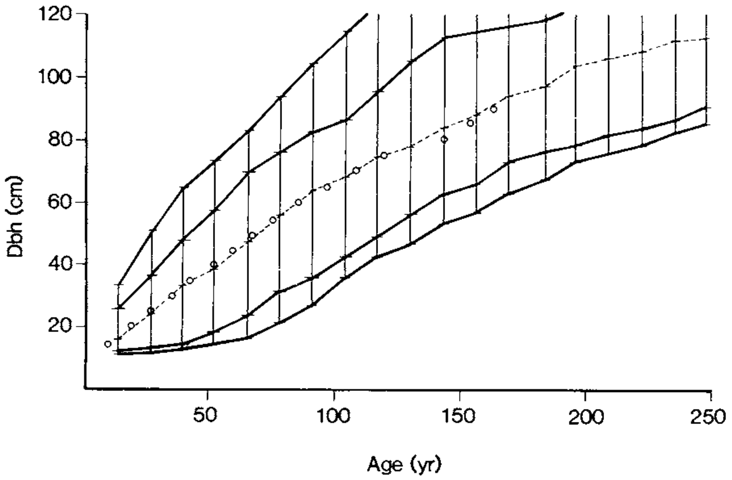


Figure 3.1 Result of 1000 growth simulation runs using data from *Pentaclethra macroloba* (Dominant canopy tree in La Selva, Costa Rica). ° results of PAI analysis.

3.3.2 Parameters

The following table of parameters and equations are in line with the data set referred to. Figure 3.2 is a more visible expression of three different growth curves.

Table 3.3 Parameters and corresponding equation (7) gained from the dataset (Smith et al., 2006) for three forest zones respectively

Zones	T (years)	t_p	α	NEY (GJ/ha*year)	Equation for V(t) (m^3/ha).
Boreal zone	140	40	0.02	37.84	$V(t)_{bor} = 37.84 * 140 * (0.6 * 20)^{-1} * \left(1 + e^{-0.02(t-40)}\right)^{-1}$
Temperate zone	150	50	0.015	62	$V(t)_{temp} = 62 * 150 * (0.6 * 20)^{-1} * (1 + e^{-0.015(t-50)})^{-1}$
Tropical zone	200	80	0.013	75.69	$V(t)_{trop} = 75.69 * 200 * (0.6 * 20)^{-1} * (1 + e^{-0.013(t-80)})^{-1}$

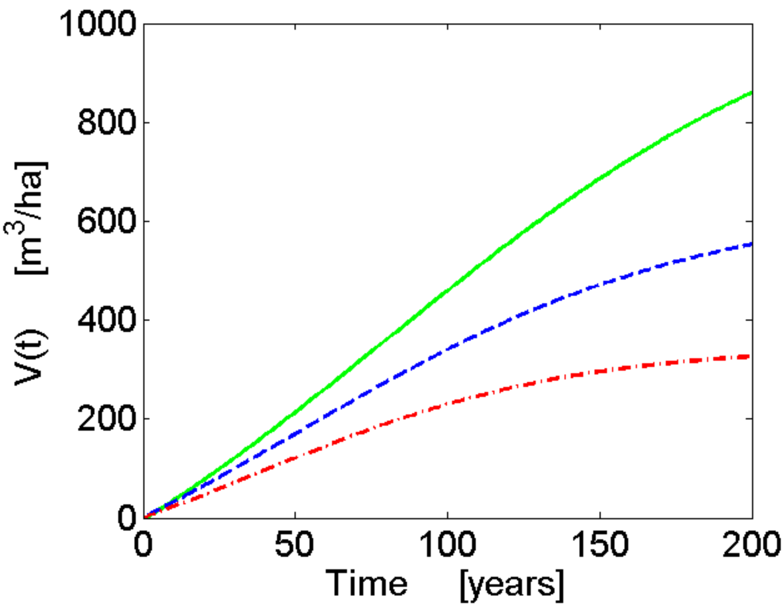


Figure 3.2 Typical growth curves for tropical (green—), temperate (blue--) and boreal (red-·) zones by applying parameter values in Table 3.3 to equation (7).

3.4 Initiate current forest status

3.4.1 Box number

According to Table 2.3, it is reasonable to define one box as an area of 10^5 ha. There will be approximately 21111, 7394 and 11825 boxes respectively in tropical, temperate and boreal zone. Within one zone, all boxes are assumed to have the same growth curve.

3.4.2 Initial average age

It is possible to calculate the implied average age for each zone by locating their positions along the growth curve as shown in Figure 3.3. It is assumed that on average half of wood dry weight is carbon. Then the carbon growth curve can be re-calculated resulting in the unit of tonnes of carbon per ha. However, this is only the carbon stored in the living biomass. The carbon stored in soil can be quite a huge pool in some areas. For example, tropical and boreal forests store the most carbon, but there is a fundamental difference in their carbon structures: Tropical forests have 56 % of carbon stored in biomass and 32 % in soil, whereas boreal forests have only 20 % in biomass and 60 % in soil. Overall nearly 42 % of carbon is stored in living biomass (Pan et al., 2011). Thus it is assumed that in temperate forests 37 % of carbon stored in biomass.

Table 3.4 Current forest carbon content of different zones (Pan et al., 2011)

	Tropical	Temperate	Boreal	World
Carbon storage (Gt)	471±93	119±6	272±23	861±66
Fraction of carbon in biomass	56 %	37 %	20 %	42 %
Carbon stored in biomass (Gt)	264	44	55	
Total carbon density (tonne/ha)	242	155	239	
Biomass carbon density (tonne/ha)	135.52	57.35	47.8	
Implied average age	**94**	**57**	**65**	

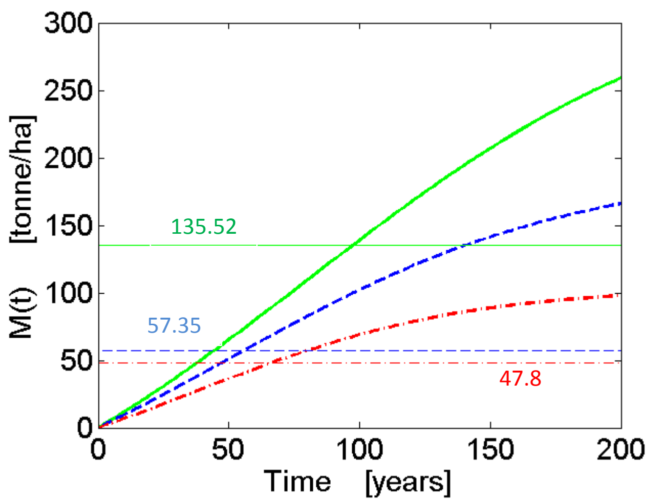


Figure 3.3 Curves (originated from Figure 3.2): Carbon stored in biomass in different forest zones (tropical green—, temperate blue--, boreal red -·) Horizontal lines: Average density of the carbon stored in biomass in different zones in year 2011

Based on Figure 3.2, the mass instead of volume of living biomass is re-calculated in Figure 3.3. With the given total carbon density as well as the biomass carbon density, the implied average age of different zones becomes available.

It is worth noticing that implied areas of each zone according to Table 3.4 (19463, 7677 and 11381 boxes respectively in tropical, temperate and boreal zone) are slightly different from what is applied in this thesis (21111, 7394 and 11825 boxes respectively). Due to the big variance of measured total carbon storage, it is more liable to use the area data directly from FRA 2010.

3.5 Model verification

This part is devoted to drawing the big picture of forest under the current development trend without any specific harvesting or planting strategy. This implied that the forest is assumed to provide the world with enough forest products such as timber, to continue current preservation programs and planting programs and to carry the present deforestation rate. The initial time is set to 2010 due to data sources used.

It is worth noticing that forest can either expand or shrink in different zones, so the total number of boxes may increase or decrease. Since tropical deforestation is severe in the real world thus the box number in tropical area is set to decrease at a constant speed of 0.44 % of original area. This is reached by calculating the weighted average of area decreasing speed in Africa and South America (FRA2010). This number incorporates the natural regrowth of tropical area which is about 1.64 Gt of carbon per year from 1990 to 2007(Pan et al., 2011) as well as deforestation. In boreal zone the average area increasing speed is 0.1 % of original area according to recent 5 year data in boreal countries. Accordingly the temperate area expanding rate is 0.264 % of original area every year. These two numbers indicates natural forest expansions in boreal and temperate areas as well as certain plantation programs currently in operation.

First, the growth curves are applied to each box located in different zones. Thus the volume of wood or the carbon content of wood in each box can be determined with the parameter of time. Second, the initial ages of various zones are set accordingly in order to mimic the current forest status. Third, the unit of the curve has been changed from cubic meter per ha in Figure 3.2 to Gt of carbon content for the convenience of further discussion. Lastly, the total numbers of boxes in each zone are set to either increase or decrease by a constant number every year in order to model the growing area in boreal and temperate forests as well as the shrinking area in tropical forest. Trees in the new added areas will grow from year 1.

Note also that from now on only the carbon in standing biomass is discussed excluding soil carbon. In reality soil in forests has great potential to store large amounts of carbon but in this thesis more emphasis is put on various harvesting and storage strategy of wood. Additionally the complicated forest ecosystems make the estimates of average forest soil carbon quite inaccurate on a global scale.

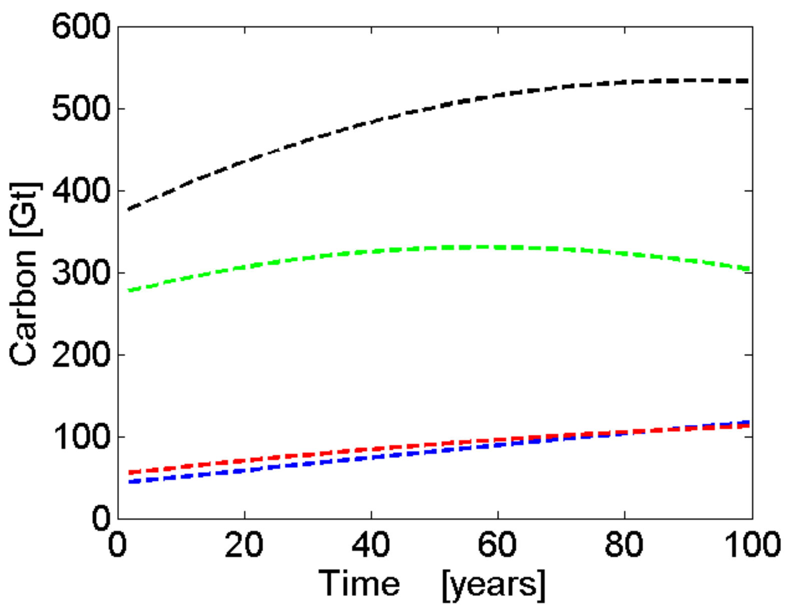


Figure 3.4 Dynamic carbon content in tropical zone (green), temperate zone (blue), boreal zone (red) and world forest (black)

As shown in the Figure 3.4, the numbers and unit here are quite reasonable. Tropical forest carbon will be increasing in the first half of period due to the photosynthesis and growth in established forests. Then as forests become older and grow slower, forest carbon will start to decrease due to deforestation which can no longer be compensated by growth. Temperate and boreal forests will be having both area and carbon growth all the time out of natural growth and expansion.

World forest starts with 373.4 (tropical 275.5; temperate 43.2; boreal 54.7) Gt of carbon in 2010 which goes in line with Table 3.4 and ends up with 532.4 (tropical 303; temperate 116.8; boreal 112.6) Gt of carbon in 2110. According to this result world forest biomass may increase 42.5 % in 100 years under current deforestation speed as well as offering enough forest products production. This number also implies an average net carbon sink of 1.59 Gt of carbon per year by forest biomass growth. This number goes in line with an average net carbon sink of 1.1 Gt per year from 1990 to 2007 (Pan et al., 2011).

Apparently terrestrial forest is a crucial ecosystem in the carbon cycle that has huge influence on atmospheric carbon concentration. However, the assumptions that tropical deforestation is to continue at current rate as well as the assumption of constant temperate forest growth which China’s plantation programs have contributed a lot to are not likely to stay static in the 100 years to come. In the following discussions more dynamic strategies will be applied for further discussion.

Chapter 4 Modeling the carbon potential of forest

4.1 Decreased deforestation

If the area of tropical forests stays constant instead of decreasing for the next hundred years, the following figure shows a possible outcome.

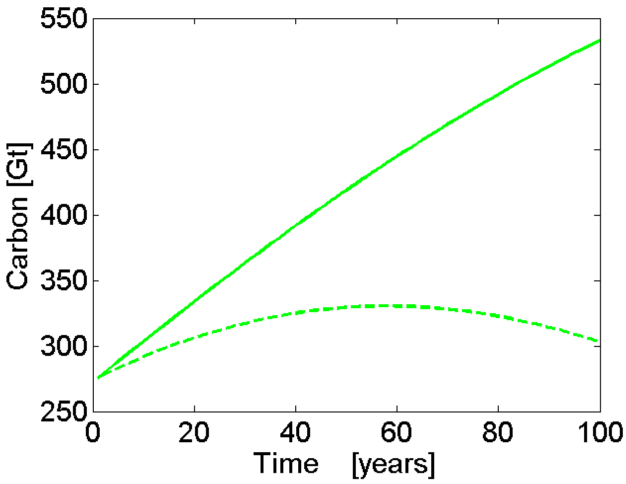


Figure 4.1 Dynamic carbon content in tropical zone with current deforestation rate (dotted); Dynamic carbon content in tropical zone with constant area (solid)

The global deforestation accelerated sharply from around 1852. It has been estimated that about half of the Earth's mature tropical forests that until 1947 covered the planet is now destroyed (Nielsen, 2006). It was estimated that although the Earth's total forest area continues to decrease at about 13 million ha per year, the global rate of deforestation has recently been slowing. Still others claim that rainforests are being destroyed at an ever-quickening pace (FRA, 2000). Due to this contradicting perception, the model assumes that tropical area will decrease by a constant rate of the current tropical forest area every year.

Since the model refer to deforestation as the total tropical land use change including the sum of deforestation and natural regrowth and expansion, with a 'zero deforestation scenario' it is still possible to cut trees in the tropical area instead of avoiding all harvesting in the tropical forest. However, with a smaller scale of deforestation the natural regrowth will also decrease thus the model integrates both regrowth and deforestation in one number which indicates the area change of tropical forest.

Table 4.1 Effect of various deforestation rates in tropical zone

Deforestation rate (%/year)	Disappearing area (10^5 ha/year)	Carbon in tropical zone 2110 (Gt)	Sequestrated carbon in 2110 compared to current deforestation speed in	
			Gt	Gt/year
0	**0**	**533**	**230**	**2.3**
0.1	21.1	480	177	1.7
0.2	42.2	423	120	1.2
0.3	63.3	376	73	0.73
0.4	84.4	323	20	0.2
0.44	**92.9**	**303**	**0**	**0**

In the case of zero deforestation, an extra of 230 Gt of carbon will be stored within tropical forests after 100 years resulting in a carbon sink of 2.3 Gt per year. Global emissions from fossil fuels combustion currently are about 10 Gt of carbon per year. Comparatively the total avoidance of tropical deforestation has the potential to greatly mitigate climate change. Table 4.1 shows that once the annual tropical loss is lessened by half, it is possible to store an extra of 1 Gt of carbon per year. However, to what extend can the tropical deforestation be stopped or alleviated remains in question and is related to the opportunity cost of land, global agriculture status and economic situations in each country.

4.2 Afforestation

Afforestation is the establishment of a forest or stand of trees in an area where there was no forest. China currently has the highest afforestation rate of any country or region in the world, with an area of 47 boxes of afforestation in 2008 (Yang Lina, 2009). Still, the government has the ambition to continue such programs in the long term. The European Union has paid farmers for afforestation since 1990, offering grants to turn farmland back into forest.

Between 1993 and 1997, EU afforestation policies made possible the re-forestation of an area corresponding to more than 5 boxes of land. A second program, running between 2000 and 2006, afforested more than 1 box of land. In tropical areas the efforts of afforestation will result in a smaller rate of deforestation. To sum up, though currently operating afforestation programs have been included in the initial forest change rate argued in Chapter 3.5, it is possible to propose some additional planting of forests every year.

Table 4.2 Two sets of afforestation parameters

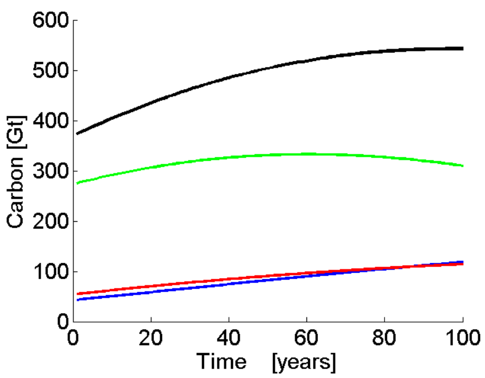
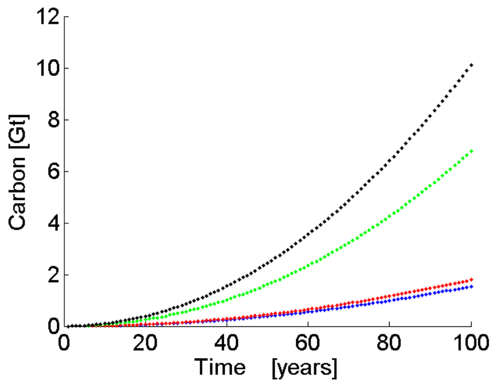
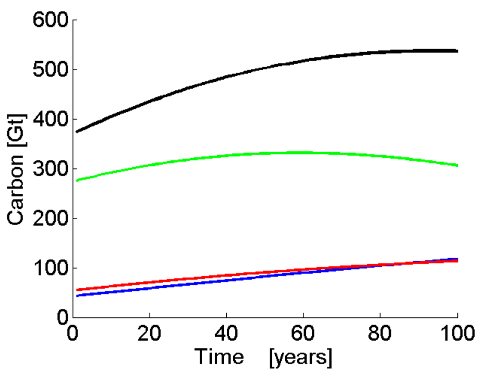
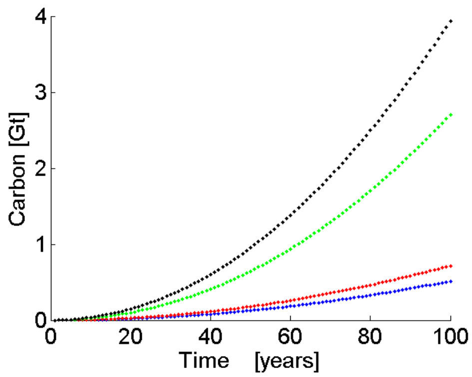
Note that 1 and 2 indicates strategy number. 'Plant' means the percentage of original area of each zone that is planted each year. 'Box' is the number of boxes added each year to each zone. 'Area' indicates the total area of forest of each zone divided by the original area within each zone after 100 years.

Strategy / Zone	1			2		
	Plant		Area	Plant		Area
	%	box		%	box	
Boreal	0.05	5	1.135	0.02	2	1.11
Temperate	0.05	3	1.298	0.02	1	1.27
Tropical	0.05	10	0.612	0.02	4	0.583

Forest cover is darker than other earth surface thus has a potential effect on earth Albedo. This may decrease the cooling effect of afforestation. Researchers in Canada argued that afforestation of all the climatically viable cropland gave a global temperature reduction of 0.45 ℃ by the end of this century which is smaller than the possible increase of temperature (Arora and Montenegro, 2011). The climate impact of forests is very much location dependent. It is also worth noticing that the "temperature benefit" per unit of afforestation in tropical regions was around three times greater than that in northern-temperate or boreal regions mainly due to fastest growing speed and evapotranspiration(Arora and Montenegro, 2011). In this model having the same percentage of afforestation gives tropical zone the biggest afforestation area.

The following figures are produced using parameters from Table 4.2 as an illustration of how various afforestation programs would affect global forest.

Table 4.3 Figures produced by applying the two sets of afforestation parameters from Table 4.2

	Forest carbon (tropical green, temperate blue, boreal red, total black)	Accumulated afforestation carbon (tropical green, temperate blue, boreal red, total black)
1		
2		

4.3 Harvesting and storage

4.3.1 Carbon potential of harvesting

By harvesting one box of specific zone, the area of that box is assumed to be clear cut first and then replanted with typical species of that zone in the same year. Here in Chapter 4.3 all harvesting strategies are applied onto the initial forest described in Chapter 3.5. Table 4.4 illustrates the sets of parameters chosen for each strategy which will be demonstrated more directly in Table 4.5

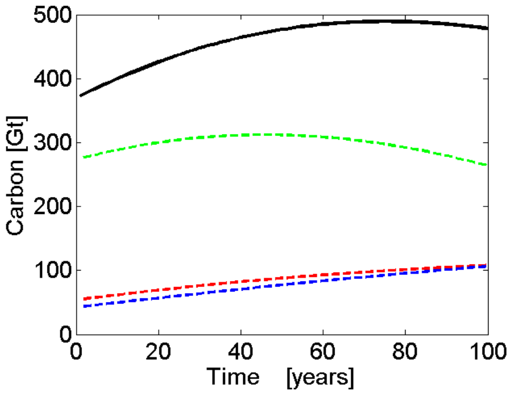
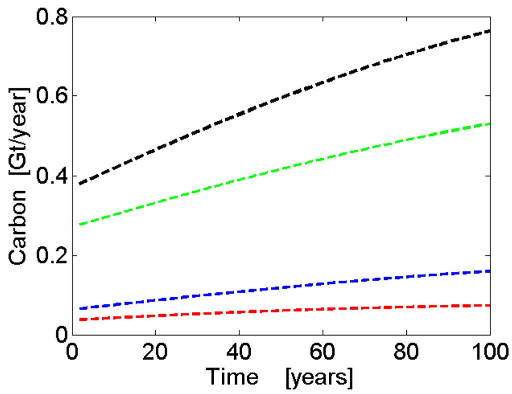
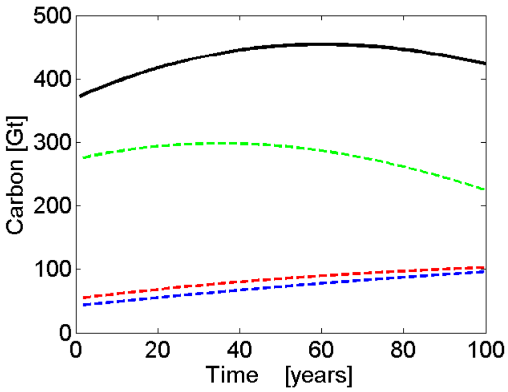
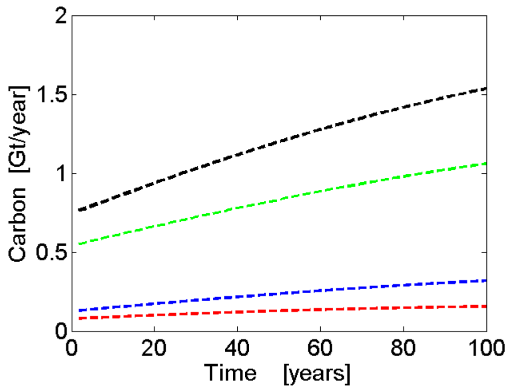
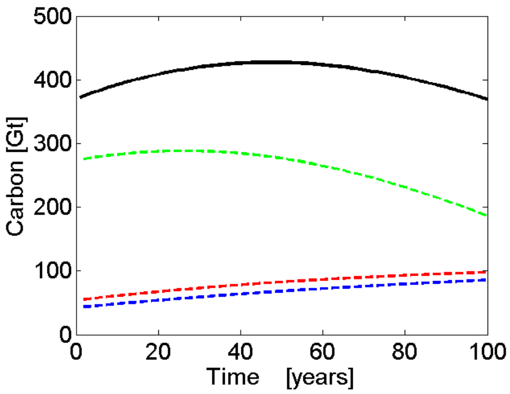
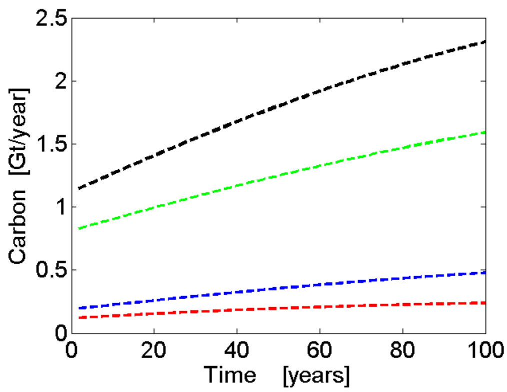
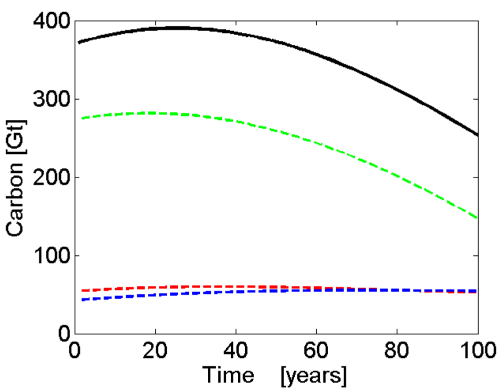
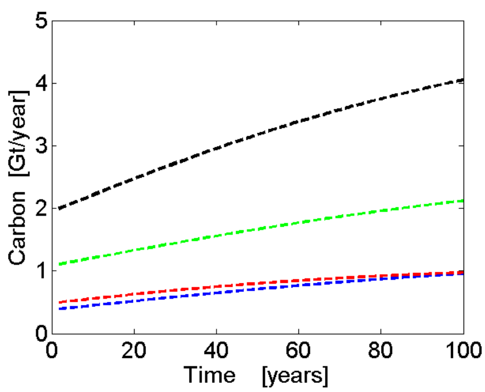
Table 4.4 Four sets of harvesting parameters (% of each zone area originally)

Strategy / Zone	**1 (base case)**	2 (2 times of base case)	3 (3 times of base case)	4 (extreme case)
Boreal	**0.075**	0.15	0.225	0.9
Temperate	**0.15**	0.3	0.45	0.9
Tropical	**0.1**	0.2	0.3	0.4
Forest carbon 2110	**478.3 Gt**	423.7 Gt	369.1 Gt	253.4 Gt

These four sets of parameters are chosen based on several concerns: first, the overall growing speed of temperate forest is faster than boreal forest; second, the total area of boreal forest is much larger than temperate which will compensate the difference in percentage terms; third, the harvesting costs may be lower in temperate and tropical regions as most developed countries with higher price levels lie in the north. So it is more reasonable to harvest more in temperate than in boreal forest. Also tropical forest is disappearing at a rate of 0.44 % (Chapter 3.5) including regrowth. So the current annual harvest of tropical forest is larger than 0.44 % of total area. It is reasonable to argue for a number around 0.2 % of tropical forests to be cut and managed in a proper way every year.

In the left row of Table 4.5 four figures of the total forest carbon is shown corresponding to four sets of parameters chosen. In the right row the harvested carbon every year is drawn accordingly. For example strategy number 2 indicates that after 100 years of operation, 15 % of boreal area, 30 % of temperate area and 20 % of tropical area will be harvested and replanted once. So this method does not interfere with current total forest area.

Table 4.5 Figures from the four sets of harvesting parameters from Table 4.4

	Forest carbon (tropical green, temperate blue, boreal red, total black)	Yearly harvested carbon (tropical green, temperate blue, boreal red, total black)
1		
2		
3		
4		

In the first strategy, three zones are all slightly harvested which results in an average of 0.6 Gt of carbon harvested per year. During this 100 years forest carbon grows from roughly 373 to 480 Gt of carbon implying a net carbon sink of around 1 Gt per year. Similar light harvesting strategies can thus be said to press no extra danger towards current forest especially with the assumption of current deforestation speed as the initial forest. If deforestation is somehow alleviated during the 100 years then forest carbon would have been even higher in the end.

In the second strategy, from year 20 the harvested carbon will exceed 1 Gt per year and the standing forest will grow from 373 to 424 Gt of carbon which indicates a net carbon sink of 0.5 Gt per year. This strategy has a moderate long term influence on the standing forests as well as a relatively good gain with harvested carbon.

In the third strategy, parameters are chosen in order to make the standing forest of almost the same amount of carbon after 100 years. Harvested carbon starts from 1.1 Gt per year and slowly rises with time and will reach 2.3 Gt per year at the end of the period. The average harvested carbon of 1.7 Gt is 17 % of current annual emissions which will have a significant effect if implemented.

In the last strategy, standing forest will fall to 253 Gt of carbon under heavy harvesting but harvested carbon will be increasing from 2 to 4 Gt per year. Apparently this strategy is not very safe and practical but is a good illustration of consequences of too much harvesting.

Not all harvested carbon is supposed to be sequestrated forever. The residence times of carbon under various methods are very different. Next more details about possible ways to store carbon and its corresponding cost and benefits will be discussed.

4.3.2 Carbon storage after harvesting

4.3.2.1 Biochar

Biochar is created when organic matter undergoes heating without air (pyrolysis) and ends up in biochar and biofuels. It has the potential to benefit farming as well as to mitigate climate change.

Inside biochar the carbon atoms are bound together with a much stronger inter-atomic force. With such chemical stability, biochar can reside in soils for hundreds of thousands of years (UK Biochar Research Centre). This can be regarded as a stable lock up of atmospheric carbon. Meanwhile, a key attraction of biochar is that it can enhance the fertility and resilience of agricultural land. If biochar production could be made profitable through its use in agriculture, this would distinguish it from expensive geoengineering measures (Sohi, 2012). However, the exact time that biochar remains stable in the soil is still not completely resolved. And a complete system where the byproducts such as gases are used in operating pyrolysis is still scarce. Strategies for deploying biochar must also consider the practical and logistical issues of storage, transport, and incorporation into soil (Sohi, 2012).

Many argued that the key question regarding biochar lies in whether to "bury or burn"? Actually either burying biochar or replacing coal power plants with biomass power plant contributes to controlling the rising atmospheric carbon concentration today.

4.3.2.2 Empty mines

Mining is required to obtain any material that cannot be grown through agricultural processes, or created artificially. Ores recovered by mining include metals, coal, oil shale, gemstones, limestone, dimension stone, rock salt, potash, gravel, clay, petroleum, natural gas or even water.There are two major types of the techniques: surface mining or underground mining. The second type creates large empty pits, rooms, and tunnels and caves which is often abandoned afterwards. In some mine concentrated areas such as China's Shanxi province, it is reported that coal mining leaving behind empty mines prone to either collapse or sinkholes has caused one-seventh of the land in the north-central of the province to sink.

The idea of storing wood or biochar in such empty mines has upsides as well as downsides. First, it implies a huge amount of volume or space globally. There are up to 560,000 abandoned mines on public and privately owned lands in the

United States alone (Kertes, 1996). Accumulated world coal production from 1981 to 2010 is about 150 Gt of commercial solid fuels[18]. After deducting surface mining and adding mines of other material, it is rational to argue for a global empty volume of 100 Gt of carbon in solid form, which goes in line with a carbon storage potential of 1 Gt per year for 100 years. Still coal production is continuing at a rising speed. Second, wood or biochar as carbon-rich solid materials are easy to process: harvest, transport, cut and put into the mines. Despite fire concerns, there exists few strict conditions regarding storing them. So it is technically applicable for most of the countries and areas. Comparatively transporting and storage of carbon dioxide in liquid form requires mature technology, skilled human resources and high costs. Third, by putting matter back into empty mines can possibly help to alleviate the problem of land subsidence as well as water and soil loss. And there are no dangerous chemicals or techniques needed in the process.

However, storing wood instead of biochar may create problems regarding nutrients circulation. Extra fertilizer may be needed if large amounts of wood are locked underground. Also abandoned mines may contain certain gases so that proper knowledge and safety training will be needed before exploring them. Additionally the mismatching of mine-rich areas and forest-rich areas may alter the profitability of the project. As the biggest concern, the cost of the empty mines strategy will be discussed in detail later.

4.3.2.3 Wood products

What purposes does wood serve after it is harvested? In 2010 about 45 % of total wood consumption goes to industrial round wood which can be used to build houses, and furniture, to make paper or for other industrial purposes. The rest of 55 % is burned as wood fuel (FRA2010). In terms of carbon residence time, some furniture and buildings may last for hundreds of years while wood chips or carbon inside paper products may only stays for months or several years. So from the climate perspective, the usage of wood with longer residence time will be

[18] Bituminous coal and anthracite (hard coal), and lignite and brown (sub-bituminous) coal.

preferred.

Overall, world construction spending grew by 0.5 % to $4.6 trillion in 2011 (Horta et al., 2012). The global construction materials market had total revenues of $664.4 billion in 2011. Average value for wood removed (volume of round wood over bark) for production of goods and services other than energy production (wood fuel) during 2003–2007 is $86.092 billion (FRA2010). It can be argued that wood use in construction industry is roughly 15 % of the whole material market. There may be huge potential in switching the building materials from carbon intensive ones such as concrete and steel into wood. This switching may well end in better outcome from a carbon point of view. But the scale of which is limited due to relative price of using the two materials as well as the technical limit of doing so.

4.3.2.4 BECS

To burn the harvested wood as fuel in place of fossil fuels and sequestrate the carbon dioxide with CCS technology is also one possibility of usage and storage after harvesting. However, problems come along with CCS technology as described in Chapter 2.3.1.

4.4 Matlab implementation

4.4.1 Initial forest

The following Table 4.6 simply sums up parameters argued in Chapter 3.5.

Table 4.6 Initial annual area change rates in three forest zones

Zone	Original area (10^5 ha)	Annual change rate (%)	Changed area (10^5 ha)
Boreal	11825	+0.1	+11
Temperate	7394	+0.264	+19
Tropical	21111	-0.44	-92

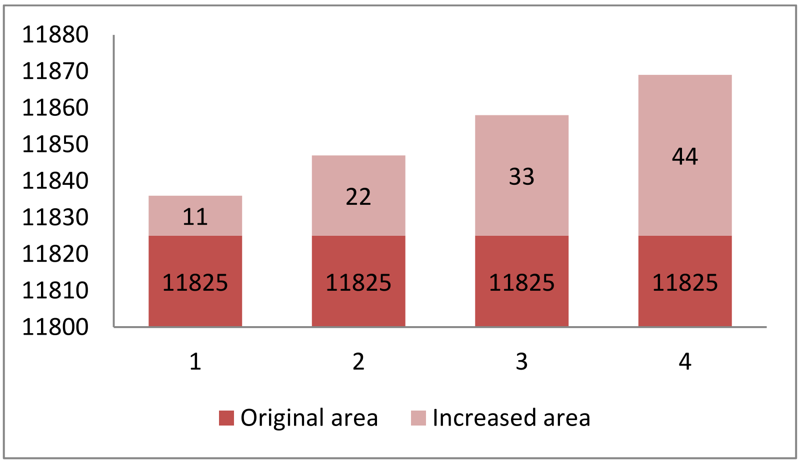


Figure 4.2 Change in number of boxes of boreal zone in the first 4 years

According to assumptions regarding the initial forest in Chapter 3.5, boreal forest is supposed to gradually expand every year by 11 boxes

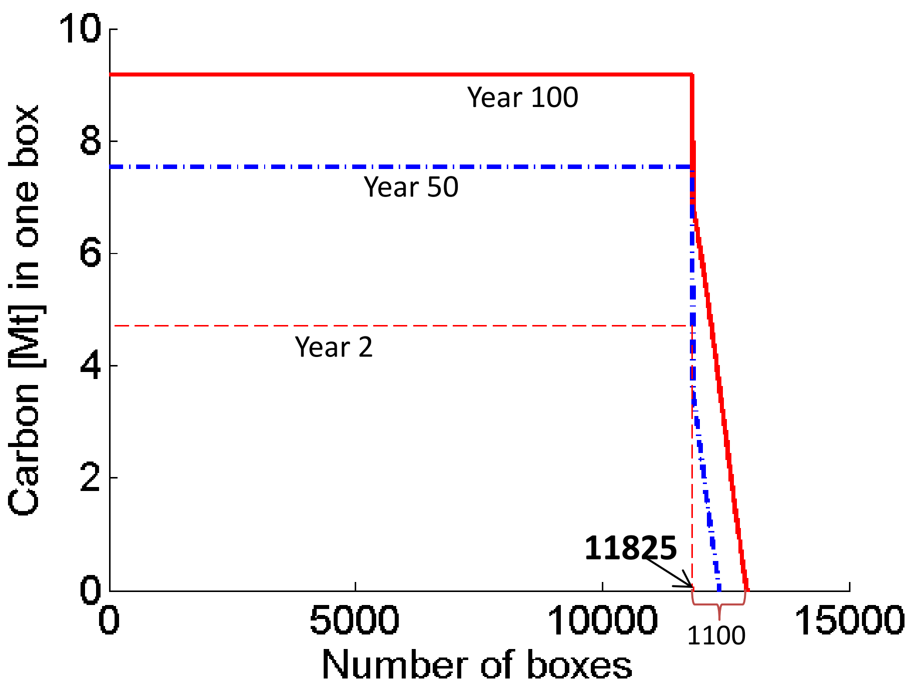


Figure 4.3 Carbon content per box in boreal zone

This figure compares the status of all boreal boxes in the second year to that at 50th year as well as the end of the period. All initial 11825 boxes of forests grow according to the growth curve from 4 to 9 Mt of carbon. Additionally 1100 more boxes are added at the end of the array with the speed of 11 more boxes each year.

(Dotted red line: year 2; dotted blue line: year 50; full red line: year 100)

For tropical zone, 92 boxes will be eliminated each year.

4.4.2 Decreased deforestation and afforestation

For decreased deforestation, what is needed in the model is simply to change the number of 0.44 % to a smaller one so that each year less than 92 boxes will be erased in the tropical zone.

For afforestation, strategy 1 in Table 4.2 indicates that each year 5 new boxes will be planted. After 100 years there will be an extra of 500 boxes in addition to 11825+1100=12925 boxes. Once planted or added in the model the box will grow according to the growth curves in different zones as time goes by.

4.4.3 Harvesting

In the model, harvesting indicates that the age of the box is reset to zero and the trees then grow according to the growth curve again.

Here one example of parameter is used to illustrate the Matlab implementation of harvesting in Chapter 4.3. In strategy 1 of Table 4.4 0.075 % of the original 11825 boxes of boreal zone which is 8 boxes will be harvest and replanted each year. At the same time the area will grow according to the initial forest by 11 boxes per year.

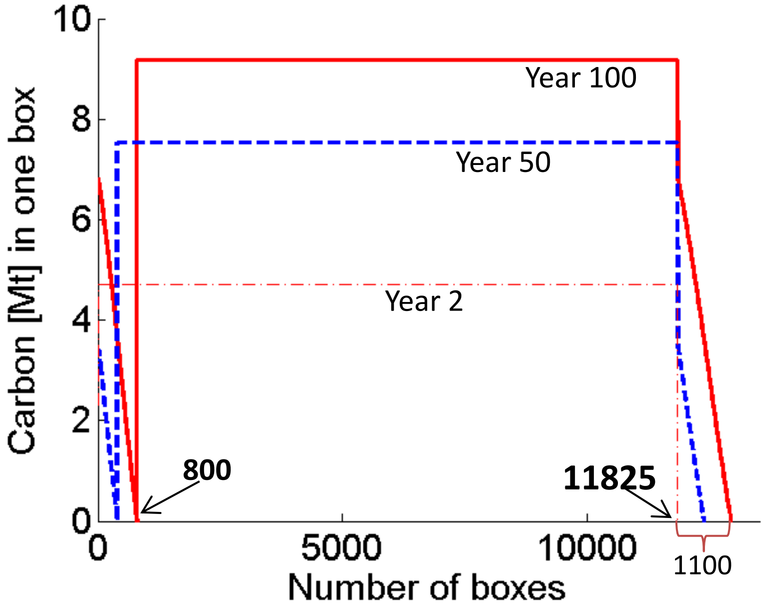


Figure 4.4 Carbon content in each box of boreal zone

This figure compares the status of all boreal boxes in the second year to that at 50th year as well as the end of the period. Every year 8 boxes will be harvested and replanted afterwards. The first box is harvested in the first year and has grown to around 7 Mt of carbon at the end of the period. The 800th box is harvested in the last year and is still of zero carbon content. At the same time the area will grow by 11 boxes per year. The area under the full red line indicates the carbon stored by boreal forest under the harvesting strategy number 1.

(Dotted red line: year 2; dotted blue line: year 50; full red line: year 100)

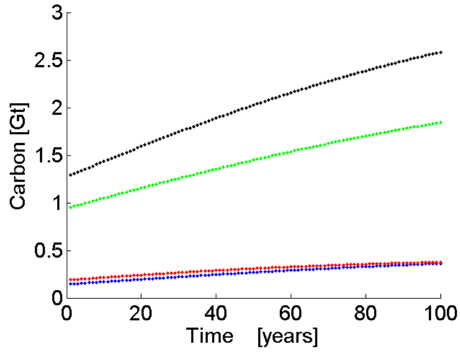
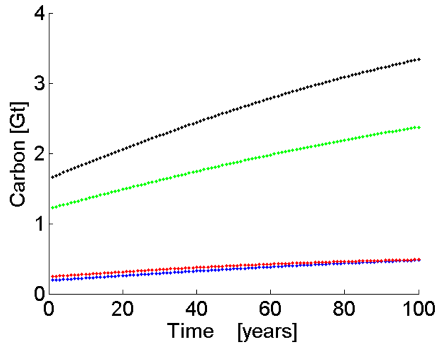
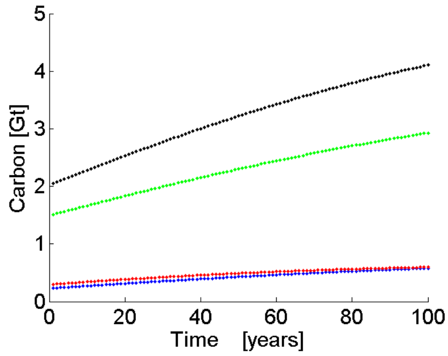
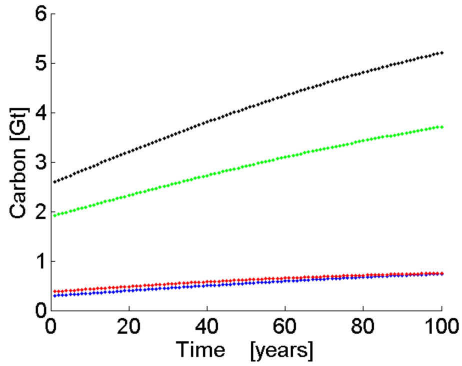
In Figure 4.4, the first source of change is harvesting which does not influence the total area of the forest. The second source of change here is the assumed growth or expansion which turns new area into forest.

4.5 Harvesting, afforestation and decreased deforestation

4.5.1 Comparison to Chapter 4.3

When combining three methods described respectively in Chapter 4.1, 4.2 and 4.3 as well as demonstrated in Chapter 4.4, one could argue for many options regarding parameters. Here the moderate strategy of both decreased deforestation and afforestation are chose: deforestation rate is 0.2 % and afforestation is 0.02 %. As a result, four sets of harvesting parameters are picked accordingly in order to mimic the total forest carbon in Chapter 4.3 for comparison. For the sake of simplicity, all three zones are assumed to have the same harvesting parameter in Chapter 4.5.

Table 4.7 Four implied harvesting parameters and yearly harvested carbon under the condition of the same forest carbon in year 2110 as in Chapter 4.3

<table>
<tr><th colspan="2">Implied Harvesting parameter for all zones (%)</th><th>Yearly harvested carbon
(tropical green, temperate blue, boreal red, total black)</th></tr>
<tr><td>1</td><td>0.35</td><td>
</td></tr>
<tr><td>2</td><td>0.4505</td><td>
</td></tr>
<tr><td>3</td><td>0.55</td><td>
</td></tr>
<tr><td>4</td><td>0.7</td><td>
</td></tr>
</table>

As compared to Table 4.5, it is easy to notice the overall level of harvested carbon is roughly 1 Gt higher in Table 4.7 due to contribution of moderate efforts from afforestation and controlling of deforestation. It also becomes possible to harvest larger areas of forest once new areas of land are turned into forest.

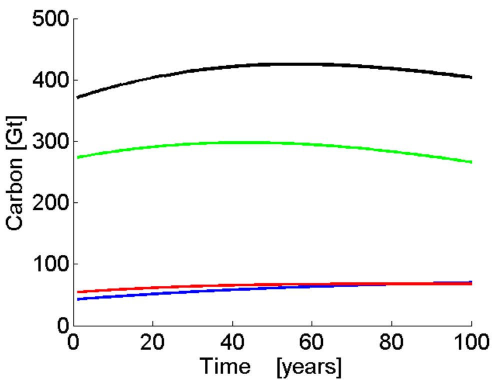
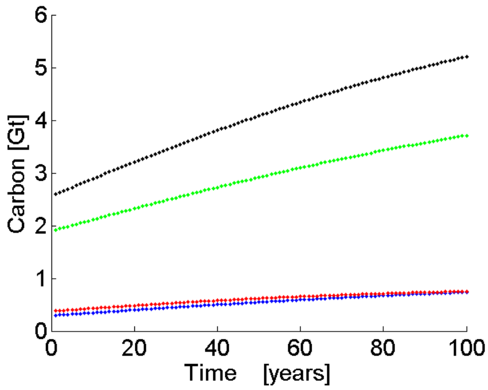
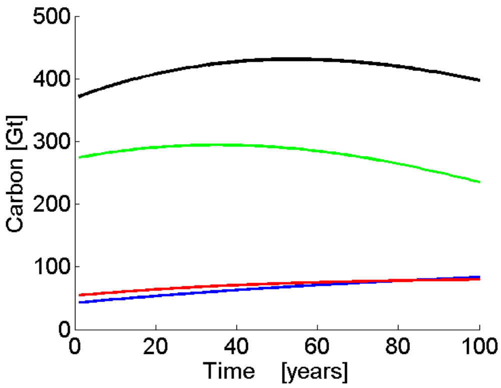
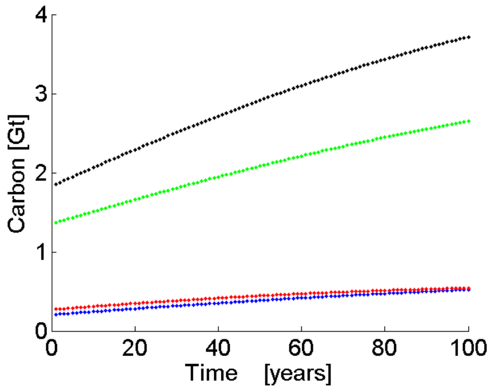
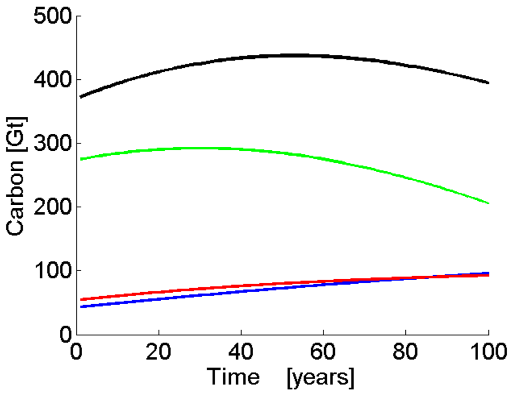
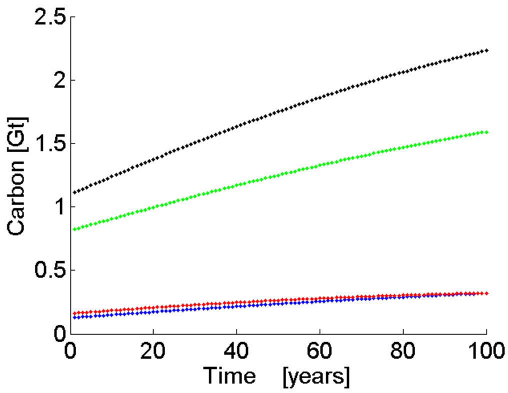
4.5.2 Same forest carbon in year 2010 and 2110

In order to argue for a safe strategy which ensures that the forest ecosystem is not damaged, parameters of deforestation, afforestation and harvest are chosen on the basis of having the same total forest carbon in year 2010 as in year 2110. At the same time, the three sets of parameters imply a difference regarding the effort put into world forest management.

Table 4.8 Three sets of parameters that can result in the same total forest carbon in year 2010 as in year 2110 (% of original world forest area)

Strategy / Parameters	1	2	3
Deforestation	0	0.2	0.04
Afforestation	0.05	0.02	0
Harvest	0.7	0.5	0.3

Table 4.9 Figures produced by applying the three sets of parameters from Table 4.8

	Forest carbon (tropical green, temperate blue, boreal red, total black)	Yearly harvested carbon (tropical green, temperate blue, boreal red, total black)
1		
2		
3		

In strategy 1, deforestation has been improved a lot while afforestation is also assumed to be as high as strategy 1 in Chapter 4.2. In this case 0.7 % of total forest area can be harvested once resulting in almost the same amount of carbon in standing forests after 100 years. This will lead to an average of around 4 Gt of carbon harvested per year.

In strategy 2, deforestation continues at a halved speed while afforestation is also at a moderate level in line with strategy 2 in Chapter 4.2. In this case about 0.5 % of forest is harvested in order to make the standing forest carbon the same after 100 years. This will end up in 3 Gt of harvested carbon per year.

In strategy 3 where relevant efforts are the least: deforestation only decreased a little to 0.04 % every year and afforestation is zero which means no extra planting program is carried out. To create a similar situation where standing forest carbon does not change after 100 years, 0.3 % of forest is harvested annually resulting in roughly 1.7 Gt of harvested carbon.

It is reasonable to argue that stronger efforts to maintain the forest and to gain more plantation growth such as preventing deforestation and afforestation can be companied by heavier harvesting strategies without depleting the standing forest resources. In the last strategy, little efforts are made, but still there exists a big potential of harvesting.

4.6 Summary

As an important carbon pool having continuous dynamic interchange with the atmospheric carbon, world forest ecosystem has the potential to store more carbon. Under various forest managing strategies, the annual harvested carbon as well as the standing forest carbon is quite different. However it is safe to argue for a number of 1 to 2 Gt of harvested carbon every year from the forest without harming the forest ecosystem. This is about 10% to 20% of current annual global emissions. It is also found that the afforestation programs proposed are not very effective at increasing overall forest carbon but the efforts to diminish deforestation seem to have a better payoff.

The analysis is based on the assumption of proper carbon storage method which ensures the sequestration of carbon atoms in years to come. Though these assumptions may bring overestimation of the carbon storage potential into the model, this model is a global dynamic model which is very flexible towards changes of parameters.

Chapter 5 Modeling the social value of forest

5.1 Model introduction

Based on the commercially optimized single-rotation model mentioned in Chapter 2.5, this study includes the social value of carbon in forest and its products. In this study, the part of the forests which can be harvested is only standing biomass excluding residues. Also, all standing biomass are treated equally no matter it is big trunk or small branch in order to match the previous study in this thesis. Other small adjustments are made. Most importantly, this model includes biochar which is assumed to be produced from forest wood and can stay as it is for example inside soil or stored underground for infinite time. Another contribution is to focus on the net carbon value of forest by realizing both the benefit of carbon being sequestrated for one year and the damage or cost of carbon being emitted as carbon dioxide in the atmosphere for one year.

5.2 Model development

Since deforestation happens most in the tropical zone, in Chapter 5 only the growth curve from tropical forest is applied in economic analysis. The growth curve in Figure 3.2 is transferred from $V(t)$ measured in m^3/ha to $G(t)$ measured in tonne/ha indicating the carbon mass per ha of tropical forest. This is done by using similar method as in Chapter 3.4.2.

$$G(t) = V(t)_{trop} * 0.5 * 0.6(\text{tonne}/m^3) \tag{8}$$

It is assumed that at year T, the forest stand will be harvested so the rotation length of this one rotation model is T. When harvesting, only $G(t) \cdot \sigma$ biomass is harvested leaving $G(T) \cdot (1 - \sigma)$ residues inside forest such as leaves and tiny branches. For the harvested biomass, $G(t) \cdot \sigma \cdot \beta$ is used as building materials, $G(t) \cdot \sigma \cdot \delta$ is used for biochar production and the rest of the harvested biomass $G(t) \cdot \sigma \cdot (1 - \beta - \delta)$ is burned right away as woodfuel. For the wood used as building materials, it is assumed that every year τ of the remaining material is scrapped and combusted. So the building materials will last for $\frac{1}{\tau}$ years sequestrating carbon during this period. As the forest grows, it generates γ of the total standing biomass as residue. This rate is a positive net accumulation of residues including the effect of decomposing each year. This assumption is reasonable because even in very old forests there is a net accumulation of natural deadwood (Luyssaert et al., 2008). It is also assumed that every year ω of the total residues (both residues generated as forest grows and residues from harvesting) decomposes and emits carbon dioxide. The commercial value of wood as building material is p, measured in Euro per tonne of carbon. The commercial value of biochar is b, measured in Euro per tonne of carbon. The commercial value of wood that is burned directly after being harvested is considered zero. Both costs and benefits may occur during the process of collecting and burning the woodfuel, but it is assumed that no extra commercial value is created accordingly.

The discount rate is r. The social carbon cost (SCC) measured in Euro per tonne of carbon dioxide is c. It is assumed that once emitted, carbon dioxide emissions rest in the atmosphere forever. Hence, the equilibrium dynamics between carbon dioxide in atmosphere and ocean is not considered. Thus, the value created or the damage avoided of one tonne of carbon dioxide being locked up for one year is $\mathrm{s} = c * r$.

The net social value generated by the first rotation cycle is the sum of all related values:

$$\boldsymbol{V_{value}(T, c, \delta, p, b)} = V_W + V_B - V_F + V_{SW} - V_{MS} + V_{RM} - V_{DR} + V_{RR} + V_{RB} \tag{9}$$

The present value of the commercial profits from harvesting wood as building materials (Hoel et al., 2012):

$$V_W(T, p, \sigma, \beta) = e^{-rT} pG(T)\sigma\beta \tag{10}$$

The present value of the commercial profits from producing biochar from harvested wood (Hoel et al., 2012):

$$V_B(T,b,\sigma,\delta) = e^{-rT} bG(T)\sigma\delta \tag{11}$$

The present social cost of immediate burning after the harvest:

$$V_F(T,c,\sigma,\beta) = e^{-rT} cG(T)\sigma(1-\beta-\delta) \tag{12}$$

The present social value of carbon sequestrated in standing biomass during the T years:

$$V_{SW}(T,s) = s\int_0^T e^{-rt} G(t)\, dt \tag{13}$$

The amount of building materials being scrapped each year:

$$M_{MS}(T) = \tau G(T)\sigma\beta \tag{14}$$

The present social cost of the emissions from scrapping and burning building τ of the total building materials every year:

$$V_{MS}(T,c,\tau,\sigma,\beta) = e^{-rT} c\int_0^{1/\tau} e^{-rt} \tau G(T)\sigma\beta\, dt \tag{15}$$

which can be simplified into:

$$V_{MS}(T,c,\tau,\sigma,\beta) = e^{-rT} c\, \tau G(T)\sigma\beta \frac{1}{r}(1-e^{-r/\tau}) \tag{16}$$

The present social value of the remaining building materials:

$$V_{RM}(T,s,\tau,\sigma,\beta) = e^{-rT} s\int_0^{1/\tau} e^{-rt}(1-t\tau)G(T)\sigma\beta\, dt \tag{17}$$

The amount of accumulated residues at time t:

$$M_{AR}(t) = \int_0^t \gamma G(t)dt \quad t \in [0,T] \tag{18}$$

The amount of total residues at time T, including residues generated through the period and residues created from the harvesting:

$$M_{TR}(T) = M_{AR}(T) + G(T)\cdot(1-\sigma) = \int_0^T \gamma G(t)dt + G(T)\cdot(1-\sigma) \tag{19}$$

The present social cost of the emissions from decomposing residues:

$$V_{DR}(T,c,\omega,\gamma,\sigma) = e^{-rT} c\int_0^{1/\omega} e^{-rt}\omega M_{TR}(T)\, dt \tag{20}$$

which can be simplified into:

$$V_{DR}(T,c,\omega,\gamma,\sigma) = e^{-rT} c\omega M_{TR}(T) e^{-r}\left(1-e^{-\frac{r}{\omega}}\right)/(1-e^{-r}) \tag{21}$$

The present social value of the remaining total residues:

$$V_{RR}(T,s,\omega,\gamma,\sigma) = e^{-rT} s\int_0^{1/\omega} e^{-rt} M_{TR}(T)(1-t\omega)\; dt \tag{22}$$

which can be simplified into:

$$V_{RR}(T,s,\omega,\gamma,\sigma) = e^{-rT} s M_{TR}(T)\left[\frac{\omega e^{-r}\left(1-e^{-\frac{r}{\omega}}\right)}{1-e^{-r}} + 1 - e^{-r}\right] \quad (23)$$

The present social value of the biochar:

$$V_{RB}(T,s,\sigma,\delta) = e^{-rT}\frac{s}{r}G(T)\sigma\delta \quad (24)$$

Since the growth curve from Chapter 3 is discrete, the discounting method used here is also discrete. Trees grow slowly so it does not make a big difference by calculating year by year instead of continuously.

5.3 Parameters for base case

It is assumed that $\sigma = 0.85$ of all standing biomass is harvested and used in various ways at year T, leaving 0.15 of the standing biomass in the forest soil as residues which will decompose in the years to come. Out of the harvested wood, $\beta = 0.3$ is used as building materials (NCPA, 2011). It is assumed in the base case that $\delta = 0.4$ which indicates that 0.4 of the harvested wood is produced into biochar. Here it is assumed that wood used as construction material can last on average for 100 years or $\tau = 0.01$, meaning that every year 0.01 of the original wood materials will be scrapped. An assumption of $\gamma = 0.001$ is in accordance with what is found in Luyssaert et al (2008). The decomposing rate is set to $\omega = 0.04$ (Hoel et al., 2012). It is found in wood wholesale market that price for normal wood is around 117 Euro/tonne of wood which can be transformed into 390 Euro/tonne of carbon or 106 Euro/tonne of carbon dioxide emitted. According to a report from The Biochar Company, the average price for all kinds of retail biochar is 1.67 dollar/lb or 2700 Euro/tonne of biochar. The wholesale price is assumed to be a bit lower of 2500 Euro/tonne. Assume that the commercial benefit of producing biochar is around 10 % of the price, and then $\mathrm{b} = 250$ Euro/tonne of biochar or $\mathrm{b} = 68$ Euro/tonne of carbon dioxide emitted.

5.4 Results for base case

After applying the parameters of the base case to the model, $\boldsymbol{V_{value}}$ in Equation (9) is obtained as a matrix of 200 by 200.

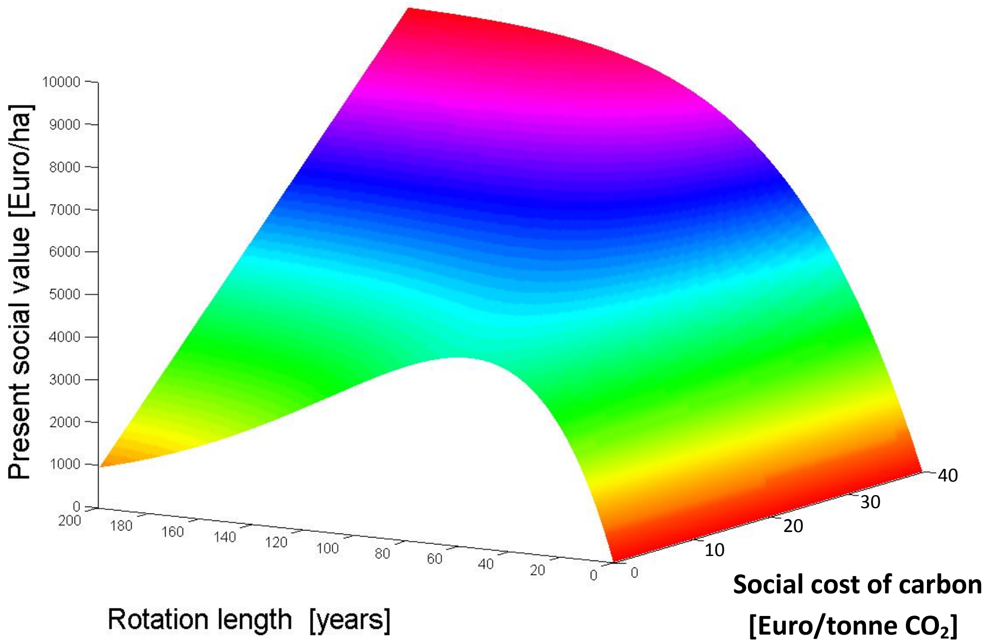


Figure 5.1 3-dimensional figure of matrix V_{value}

Optimal rotation length T is an array of time from 1 to 200 years. Social cost of carbon c is an array changing from 0.2 to 40 Euro/tonne of carbon dioxide. The *z* axis indicates the value of the matrix V_{value}.

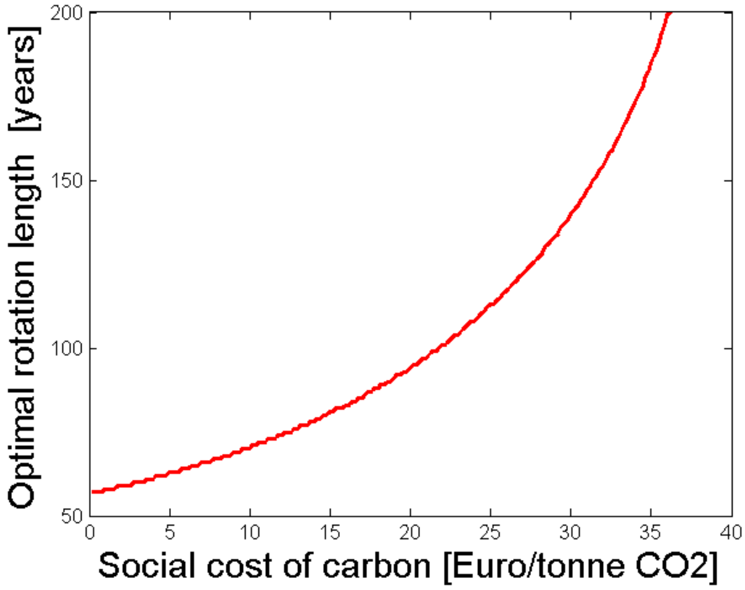


Figure 5.2 Relationship between the social cost of carbon c and the optimal rotation length T of the base case

The year T which maximizes the V_{value} under different social costs of carbon is called the optimal rotation length in this single-rotation model. As the cost or damage created by carbon emissions becomes large, the optimal rotation length also prolongs, meaning that it is best to postpone the harvesting. When the cost becomes large enough, meaning that emissions cause big enough damages to the climate, it is then best to never harvest the forest. This is called 'dominant use forestry' (Perman, 2011).

In this model the existence of trees sequestrating carbon or the existence of wood building materials or biochar is paid or rewarded at the price s every year, and the emissions of burned trees or building materials are charged or punished at the price of c. Current carbon price within EU Emissions Trading System (EU ETS) is around 5 Euro/tonne of carbon dioxide (Pointcarbon) which is 18.3 Euro/tonne of carbon. Current optimal rotation length with this carbon price is roughly 90 years.

However, it is noticeable that the price c here is not exactly the carbon price charged by the EU ETS system. It is the damage caused by permanent emissions and it is related to the benefits of sequestration for one year $(s = c * r)$. The current EU ETS system does not reward the existence of forest.

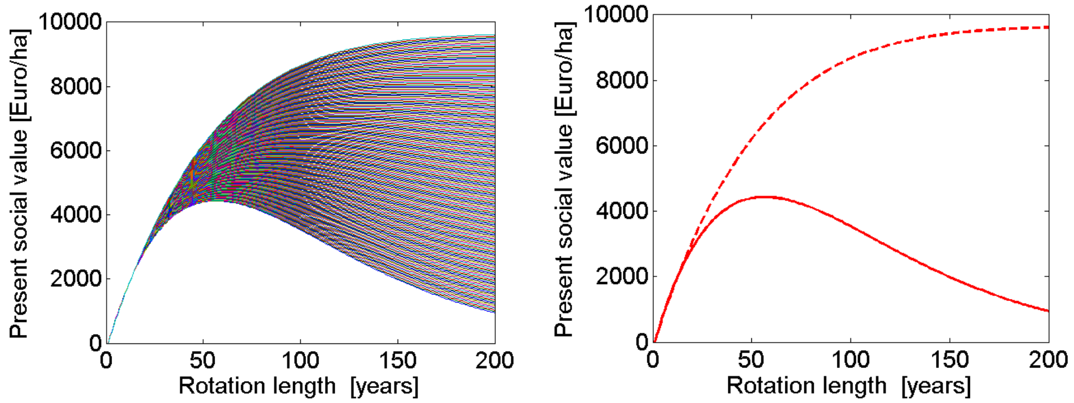


Figure 5.3 Relationship between the optimal rotation length T and the present social value V_{value}

Left: The net social value of forest under 200 different social costs of carbon plotted against changing rotation length

Right: The net social value of forest plotted against changing rotation length (dotted line: maximum social cost of carbon, solid line: minimum social cost of carbon)

According to the definition of resource rent, it is the difference between the price at which an output from a resource can be sold and its respective extraction and production costs, including normal return (Scherzer et al.). From a bigger perspective, when all the related costs and benefits of forest products and carbon are realized in real terms, the value calculated above is the rent of the forests as a multi-function resource. When the optimal rotation length is 90 years, the sum of the net carbon value and net commercial value of forest is roughly 6000 Euro per ha in this single rotation model with an infinite time horizon. This is the value created by forest as a natural, or rent in a larger concept.

5.5 Controlling variable

It is interesting to explore the effect on the value or optimal rotation length of the forest by changes of certain variables.

5.5.1 Biochar production

The proportion of harvested forest used for biochar production δ is set to 0.3, 0.4 and 0.5 respectively in the model. It requires less regarding the size and quality of the harvested wood once the purpose is for biochar production. Biochar production technology is also assumed to become more mature in the future as the concern for climate change grows bigger. Since biochar is also a good with commercial value which can be used in various ways for example in agricultural production, it is reasonable to assume a production proportional to the current building material production.

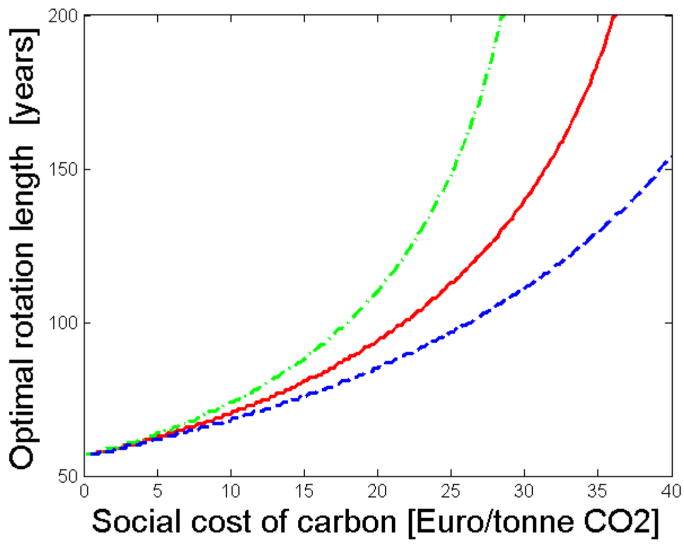


Figure 5.4 Relationship between the social cost of carbon c and the optimal rotation length T with three different biochar production proportions (green-. $\delta = 0.3$; base case: red- $\delta = 0.4$; blue-- $\delta = 0.5$)

For the same social cost of carbon, higher level of biochar production will lead to a shorter rotation period. As more of the harvested wood switch from direct burning after harvest to biochar products which last forever under current assumptions, less emissions will be made, leading to the possibility to harvest faster. For the same rotation length, it requires a higher biochar production to justify for the rising social cost of carbon. The same rotation length can be taken as the current habit of forest management or the present way human being treating the forests being kept. As the consequences of climate change grow bigger, the carbon value rises. In order to deal with the climate problem while maintaining the forest management fashion, more biochar should be produced.

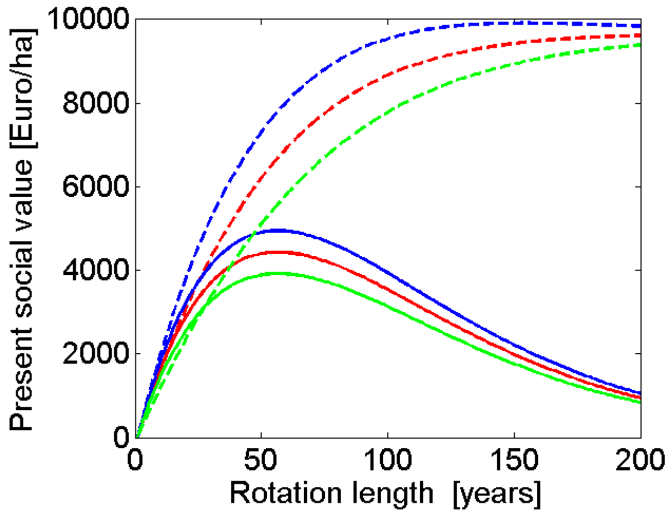


Figure 5.5 Relationship between the net social value of forest and rotation length (dotted line: maximum social cost of carbon, solid line: minimum social cost of carbon) (green $\delta = 0.3$; base case: red $\delta = 0.4$; blue $\delta = 0.5$)

It is shown in Figure 5.5 that as biochar production increases, the value of the forest stand also rises. It is apparent that production of biochar will lead to a higher value than to burn the harvested wood or residues right away. However, this increase may be lessened by the drop in biochar price once the supply is sufficient.

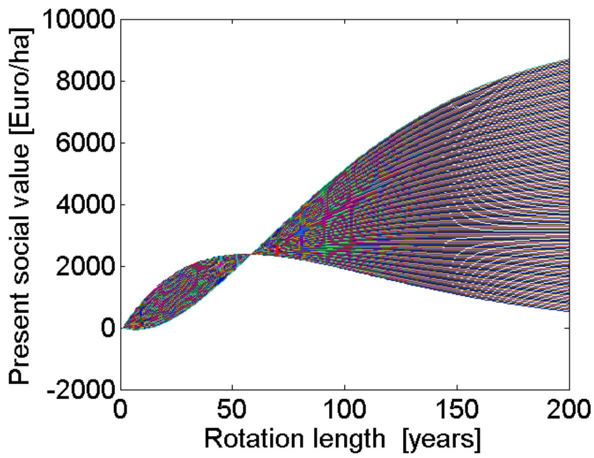


Figure 5.6 Relationship between the optimal rotation length T and the present social value V_{value} when no biochar is produced (Net social value of forest under 200 different social costs of carbon plotted against changing rotation length)

In this case δ is set to zero. Then the value of forests drops to around 4000 Euro per ha. The major contribution to this drop comes from the commercial value of biochar instead of the carbon sequestration value of biochar. This indicates that to make use of harvested wood properly instead of burning it as woodfuel is very crucial to the total value of forest.

Since the use of wood as construction materials is strongly related to global construction industry. It is not easy to assume big changes in the production of wood as a building material in this study.

5.5.2 Discount rate

The effect of small changes in discount rate on the relationship between the social cost of carbon and the optimal rotation length is large. A lower discount rate of 1 % indicates a higher emphasis on the future which results in a higher optimal rotation length by about 40 years on average in Figure 5.6. A higher discount rate of 3% indicates a lower emphasis on the future which results in a lower rotation length by about 20 years on average.

Here, only one discount rate is applied in the model, but the value flows discounted have two different features. On one hand, for the commercial profits of wood and biochar, the discount rate is supposed to be the interested rate in the bank, which is the opportunity cost of the forest owner for keeping their assets as forest instead of as earnings deposited in the bank. On the other hand, the social cost of carbon dioxide emissions or the social benefit of carbon sequestration should be discounted with the social discount rate (SDR) and $SDR = \eta g + \delta$ (Ramsey equation) where g represents the growth rate of the economy. It implies how rich the future generation can get thus how powerful they can be in terms of ability to defend climate problems. The higher the ability, the lower level of concern for future there will be. Secondly δ is the discount rate for utility between generations which is supposed to be very small ethically. A higher δ means a less weight on future generations. Lastly η can be interpreted as the percentage change in marginal utility derived from one percentage change in income, which means the level of risk averse and degree of flexibility towards the future. A high η indicates low flexibility towards the future and the emphasis on present consumptions over the future consumptions.

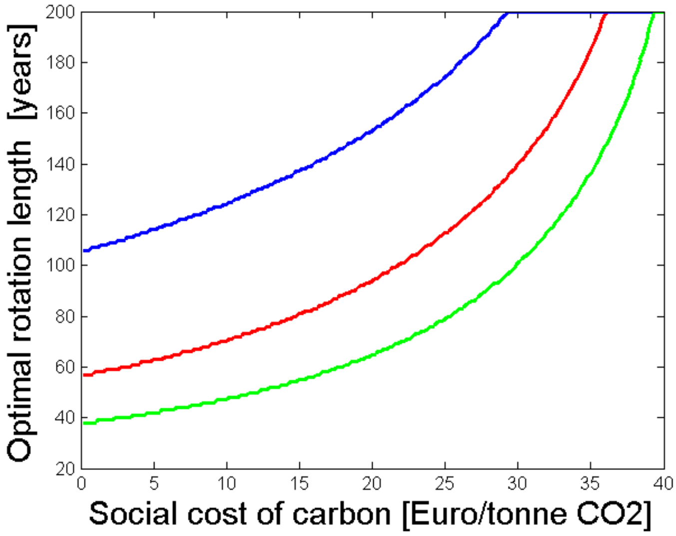


Figure 5.7 Relationship between the social cost of carbon and the optimal rotation length (blue: $r = 0.01$; red: $r = 0.02$; green: $r = 0.03$)

When future is more emphasized and concerned, the rotation length of forest should be longer, preservation of forests becomes more important. In this model one discount rate of 2 % is applied for simplicity.

5.5.3 Wood price

When the commercial profit for wood as building material is adjusted by ± 20 % to 127.2 and 84.6 respectively, the optimal rotation length also changes.

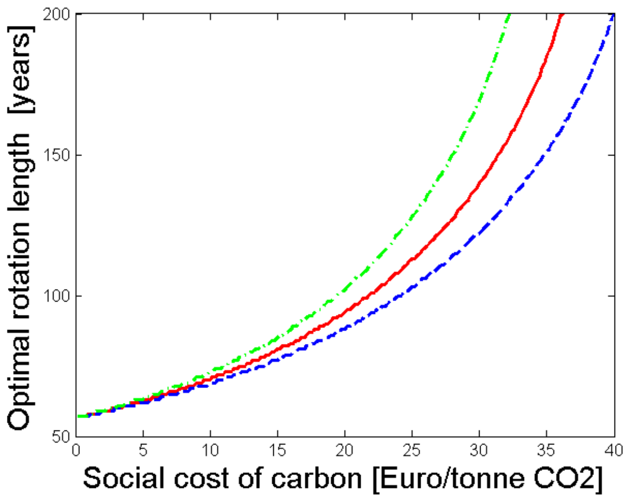


Figure 5.8 Relationship between the social cost of carbon and the optimal rotation length (green-. $p = 84.6$; base case: red $p = 106$; blue-- $p = 127.2$)

When carbon value is excluded, the optimal rotation length is dependent on the natural growth curve of the tree. As long as the wood price stays constant, it is best to harvest the forest when the growth rate of forest volume equals the interest rate (Perman, 2011). However, when the constant wood price level increases, it is wise to harvest it sooner under the same social cost of carbon and vice versa (Figure 5.8). This is because the model incorporates both wood commercial value and all related carbon value.

The value change is not very big due to the changes in wood price (Figure 5.9). Apparently the forest value rises when the wood as a construction material becomes more valuable.

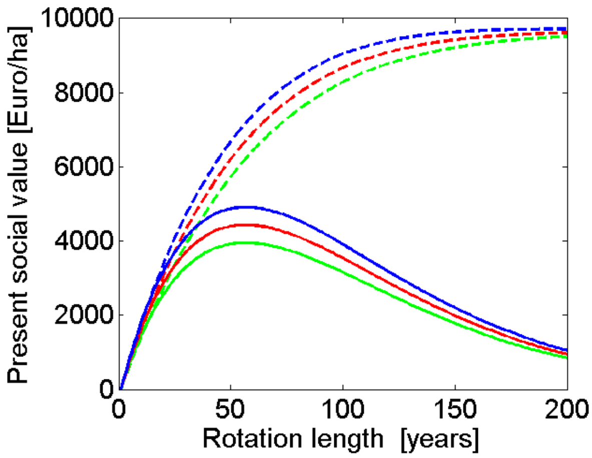


Figure 5.9 Relationship between the net social value of forest and rotation length (dotted line: maximum social cost of carbon, solid line: minimum social cost of carbon) (green $p = 84.6$; base case: red $p = 106$; blue $p = 127.2$)

5.6 Summary

In Chapter 5 a single-rotation forestry economic model is built to analyze the relationship between the optimal rotation length, net social value of forest and the social cost of carbon. It is found that when the damages of carbon emissions are large enough, it is best never to harvest the forest. However it is not likely for human society to avoid any forest products. This only occurs under extreme climate damages caused by carbon emissions. It is also found that when future is emphasized by current generation, it is reasonable to postpone harvesting of forest. So forest reservation is generally an important issue. Most importantly the biochar production has big influence on the optimal rotation length. When more biochar is produced, the forests can be harvested more often. The social value of forest increases significantly with proper proportion of biochar production.

One may argue that according to the linear relation discovered between the biochar production proportion and the forest value, it should be optimal to produce as much biochar as possible. This study has only analyzed reasonable range of biochar production based on the assumptions that biochar production should not harm the production of wood building materials as well as the assumption of mature biochar technology in the future.

Under the present assumptions of biochar, it is reasonable to argue based on results above that production of biochar not only increases carbon storage but also enhances the overall value of forest. Thus value is created while carbon storage is achieved.

Chapter 6 Conclusions

This thesis has studied both physical and economic aspects of the world forest focusing on its potential of carbon storage as a long term alternative solution to the climate change problem. In the first model, with reasonable assumptions of afforestation and deforestation, there exists a potential of 1 to 2 Gt of carbon harvested and stored every year. This is roughly 10 % to 20 % of annual global emission nowadays. However it may include overestimation of the potential. As a complicated as well as vulnerable ecosystem, forest can be interfered by both human harvesting activities and changing climate conditions. So the growth curves used may harbor some overestimation. The assumptions regarding biochar as a carbon storage means also requires better available technologies. These drawbacks are not fully analyzed in this study but can be studied in the future.

CCS technology is hotly discussed as the solution of carbon storage in recent years. Today it still involves much uncertainty and even potential danger. The process of capturing and liquefying carbon dioxide is costly and functions not thoroughly as a final solution to transfer and lock the carbon atoms. Over the years of storage underground, carbon dioxide may be released back into the atmosphere again through geographical changes. As a net carbon sink, world forest plays an important role in the carbon cycle. Although the growth rates of trees are low, the interchanges of carbon atoms between the forest ecosystem and the atmosphere are very active and large. So the potential of forest as an alternative of carbon storage solutions is by nature quite big.

From the second economic model, it is found that it is possible to harvest the forest and store more carbon in certain form such as biochar while gaining social value of both carbon and commercial goods. This can only be realized when related technologies allows such storage means to be economically feasible in a large scale. More importantly there are implications regarding policies. Forest belongs to each country according to the political boarder on this planet. Thus, managing world forest in an optimal way also requires international cooperation. The multiple social values of forest were not seriously considered until recent climate problem becomes more serious. The need of a complete evaluation system of the value of forest is large. Only by admitting the carbon value attached to forest and forest products can world forest be managed in a more rational fashion.

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Appendix

The following is the Matlab code which creates the figures and models in this thesis. The first one is the model for forest stand growth curve. The second one is the total forest carbon in three zones with the initial forest area changing rates. The last one is the economic model which calculates the value of one ha of forest with the parameters of the base case.

Matlab code for Figure 3.2

```
clear all; close all;
% ESTABLISH GROWTH CURVES:
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% TROPICAL:
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% time parameters:
N_year_trop=200; t=1:N_year_trop; alpha_trop=0.013;
T_trop=N_year_trop; t_trop=80;
% wood parameters:
rho_trop=0.6;    % density of typical tropical tree in SI units ton/m^3
power_trop=75.69; % average calorific value harvested in tropical region(GJ per ha per
year)
calorific_value_trop=20; % calorific value of wood (J per ton)
% calculate growth curve:
Vmax_trop=power_trop*N_year_trop/(rho_trop*calorific_value_trop)                    *
(1+exp(-alpha_trop*(N_year_trop-t_trop)));
V_trop=Vmax_trop./(1+exp(-alpha_trop*(t-t_trop)));
V_trop=V_trop-V_trop(1);
figure(1); hold on; plot(t,V_trop,'g','linewidth',2);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% TEMPORAL:
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% time parameters:
N_year_temp=150; t=1:N_year_temp; alpha_temp=0.015;
T_temp=N_year_temp; t_temp=50;
% wood parameters:
rho_temp=0.6;    % density of typical temperal tree in SI units ton/m^3
power_temp=62;    % average calorific value harvested in temperal region (GJ per ha per
year)
calorific_value_temp=20; % calorific value of wood (J per ton)
% calculate growth curve:
```

```
Vmax_temp=power_temp*N_year_temp/(rho_temp*calorific_value_temp) *
(1+exp(-alpha_temp*(N_year_temp-t_temp)));
t=0:N_year_trop;
V_temp=Vmax_temp./(1+exp(-alpha_temp*(t-t_temp)));
V_temp=V_temp-V_temp(1);
figure(1); hold on; plot(t,V_temp,'b--','linewidth',2);
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% BOREAL:
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% time parameters:
N_year_bor=140; t=1:N_year_bor; alpha_bor=0.02;
T_bor=N_year_bor; t_bor=40;
% wood parameters:
rho_bor=0.6;    % density of typical boreal tree in SI units ton/m^3
power_bor=37.84;    % average calorific value harvested in boreal region (GJ per ha per
year)
calorific_value_bor=20; % calorific value of wood (J per ton)
% calculate growth curve:
Vmax_bor=power_bor*N_year_bor/(rho_bor*calorific_value_bor) *
(1+exp(-alpha_bor*(N_year_bor-t_bor)));
t=0:N_year_trop;
V_bor=Vmax_bor./(1+exp(-alpha_bor*(t-t_bor)));
V_bor=V_bor-V_bor(1);
figure(1); hold on; plot(t,V_bor,'r-.','linewidth',2);
% MAKE NICE PLOT:
set(gca,'fontsize',18);
box on;
xlabel('Time          [years]','fontsize',18)
ylabel('V(t)          [m^3/ha]','fontsize',18)
```

Matlab code for Figure 3.4

```
growth_curves_nofigure           %initiate V(t) for each sone
% global variables:
nyears=100; % number of years to harvest.
% NBNBNB: Each box has area = 10^5 ha = 10^9 m^2;
boxarea=10^5;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
  Carbon harvest from BOREAL zone
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% %box_bor(1:Nbox_bor) : vector and number of entries representing boreal forest
%at any time
% timebox_bor(1:Nbox_bor) : vector showing the local time of each box (local time is
%set to zero when
```

```
%box is harvested, and forest is assumed replanted and grows according to
%growth curve afterwards)
% Mnat_bor(1:nyears)     : vector containing the wood volume change after a year
%of biomass growing and harvest
% Mharvest_bor(1:nyears) : vector containing the harvested wood volume
% harvest_fraction_bor      : fraction of boxes to be harvested each year
% harvest_start_bor            : help variable to store which index harvesting starts from


% Initiate - forest of all boxes set to status after 46.6% of N_year_bor in growth_curves.
Psentbio_bor=0.464;
Nbox_bor=11825;
tstart_bor=floor(N_year_bor*Psentbio_bor);
box_bor=ones(1,Nbox_bor)*V_bor(tstart_bor);
timebox_bor=tstart_bor*ones(1,Nbox_bor);
Mnat_bor=zeros(1,nyears); Mharvest_bor=zeros(1,nyears);
Newboxes_bor=floor(0.001*Nbox_bor);    % 0.1percent of new forest boxes each year
harvest_start_bor=1;  harvest_fraction_bor=0;    % percent of boreal boxes harvested
each year
% only allow all initial boreal forest to be harvested once:
if harvest_fraction_bor*nyears > 1
    ['Too few boxes or too hard harvesting - results may become shitty....']
end;
clear t; t=tstart_bor;

% obs: this loop assumes nyears*harvest_fraction_bor < Nbox_bor. Crash if not!!!
    Mstand_bor=sum(box_bor);
    Gtonunit=0.5*rho_bor*boxarea*1e-9;
for j=1:nyears
    timebox_bor=timebox_bor+1;
% growth:
    box_bor=V_bor(timebox_bor);                                              %%%before:
box_temp=V_temp(floor(timebox_temp*Psentbio_temp));
% harvest a fraction from correct boxes;
        harvest_end_bor=harvest_start_bor+floor(11825*harvest_fraction_bor);
        Mharvest_bor(j)=sum(box_bor(harvest_start_bor:harvest_end_bor-1))*Gtonunit;
        timebox_bor(harvest_start_bor:harvest_end_bor-1)=1;
harvest_start_bor=harvest_end_bor;
        box_bor=V_bor(timebox_bor);

Mnat_bor(j)=sum(box_bor)*Gtonunit;    %%%Mnat_bor(j)=(sum(box_bor)-Mstand_bor)*
Gtonunit;
        % add new boxes:
        box_bor=[box_bor zeros(1,Newboxes_bor)];
```

```
    timebox_bor=[timebox_bor ones(1,Newboxes_bor)];
    Nbox_bor=Nbox_bor+Newboxes_bor;
end;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Carbon harvest from TEMPERATE zone
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%box_temp(1:Nbox_bor) : vector and number of entries representing temperate
%forest at any time
%timebox_temp(1:Nbox_temp) : vector showing the local time of each box
%set to zero when
%box is harvested, and forest is assumed replanted and grows according to
%growth curve afterwards)
% Mnat_temp(1:nyears)    : vector containing the wood volume change after a year
%of biomass growing and harvest
% Mharvest_temp(1:nyears) : vector containing the harvested wood volume
% harvest_fraction_temp      : fraction of boxes to be harvested each year
% harvest_start_temp           : help variable to store which index harvesting starts from

% Initiate - forest of all boxes set to status after 38% of N_year_bor in growth_curves.
Psentbio_temp=0.38;
Nbox_temp=7394;
tstart_temp=floor(N_year_temp*Psentbio_temp);
box_temp=ones(1,Nbox_temp)*V_temp(tstart_temp);
timebox_temp=tstart_temp*ones(1,Nbox_temp);
Mnat_temp=zeros(1,nyears); Mharvest_temp=zeros(1,nyears);
Newboxes_temp=floor(0.00264*Nbox_temp); % 0.264 percent of new forest boxes each
year
harvest_start_temp=1; harvest_fraction_temp=0;    % percent of boreal boxes harvested
each year

% only allow all initial temperate forest to be harvested once:
if harvest_fraction_temp*nyears > 1
  ['Too few boxes or too hard harvesting - results may become shitty....']
end;
clear t; t=tstart_temp;
                              % obs: this loop assumes nyears*harvest_fraction_bor <
Nbox_bor. Crash if not!!!
Mstand_temp=sum(box_temp);
Gtonunit=0.5*rho_temp*boxarea*1e-9;
for j=1:nyears
  timebox_temp=timebox_temp+1;
% growth:
  box_temp=V_temp(timebox_temp);
% harvest a fraction from correct boxes;
```

```
        harvest_end_temp=harvest_start_temp+floor(7394*harvest_fraction_temp);

Mharvest_temp(j)=sum(box_temp(harvest_start_temp:harvest_end_temp-1))*Gtonunit;
        timebox_temp(harvest_start_temp:harvest_end_temp-1)=1;
harvest_start_temp=harvest_end_temp;
        box_temp=V_temp(timebox_temp);

Mnat_temp(j)=sum(box_temp)*Gtonunit;%%Mnat_temp(j)=(sum(box_temp)-Mstand_te
mp)*Gtonunit;
% add new boxes:
        box_temp=[box_temp zeros(1,Newboxes_temp)];
        timebox_temp=[timebox_temp ones(1,Newboxes_temp)];
        Nbox_temp=Nbox_temp+Newboxes_temp;
end;
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Carbon harvest from TROPICAL zone
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% box_trop(1:Nbox_trop) : vector and number of entries representing tropical forest
%at any time
% timebox_trop(1:Nbox_trop) : vector showing the local time of each box (local time
%is set to zero when
%box is harvested, and forest is assumed replanted and grows according to
%growth curve afterwards)
% Mnat_trop(1:nyears)    : vector containing the wood volume change after a year
%of biomass growing and harvest
% Mharvest_trop(1:nyears) : vector containing the harvested wood volume
% harvest_fraction_trop      : fraction of boxes to be harvested each year
% harvest_start_trop           : help variable to store which index harvesting starts from

% Initiate - forest of all boxes set to status after 47% of N_year_bor in growth_curves.
Psentbio_trop=0.47;
Nbox_trop=21111;
tstart_trop=floor(N_year_trop*Psentbio_trop);
box_trop=ones(1,Nbox_trop)*V_trop(tstart_trop);
timebox_trop=tstart_trop*ones(1,Nbox_trop);
Mnat_trop=zeros(1,nyears); Mharvest_trop=zeros(1,nyears);
harvest_start_trop=1; harvest_fraction_trop=0;    % percent of tropical boxes harvested
each year
Newboxes_trop=floor(0.0044*Nbox_trop);    % percent of new forest boxes each year

% only allow all initial tropical forest to be harvested once:
if harvest_fraction_trop*nyears > 1
    ['Too few boxes or too hard harvesting - results may become shitty....']
end;
```

```
clear t; t=tstart_trop;
% obs: this loop assumes nyears*harvest_fraction_bor < Nbox_bor. Crash if not!!!
Mstand_trop=sum(box_trop);
Gtonunit=0.5*rho_trop*boxarea*1e-9;
for j=1:nyears
    timebox_trop=timebox_trop+1;
% growth:

box_trop=V_trop(timebox_trop); %%%box_bor=V_bor(floor(timebox_bor*Psentbio_bor)
);
% harvest a fraction from correct boxes;
        harvest_end_trop=harvest_start_trop+floor(21111*harvest_fraction_trop);
        Mharvest_trop(j)=sum(box_trop(harvest_start_trop:harvest_end_trop-1))*Gtonunit;
        timebox_trop(harvest_start_trop:harvest_end_trop-1)=1;
harvest_start_trop=harvest_end_trop;
        box_trop=V_trop(timebox_trop);
        Mnat_trop(j)=sum(box_trop)*Gtonunit;
        % disappearing old boxes:
        box_trop=box_trop(1:Nbox_trop-Newboxes_trop);    % adding: box_trop=[box_trop
zeros(1,Newboxes_year_trop)];
        timebox_trop=timebox_trop(1:Nbox_trop-Newboxes_trop);                    %    add:
timebox_trop=[timebox_trop ones(1,Newboxes_year_trop)];
        Nbox_trop=Nbox_trop-Newboxes_trop;

end;

plottime=1:nyears;
figure (11); hold on;
plot(plottime,Mnat_temp,'b--','linewidth',2);
plot(plottime,Mnat_trop,'g--','linewidth',2);
plot(plottime,Mnat_temp+Mnat_trop+Mnat_bor,'k--','linewidth',2);
plot(plottime,Mnat_bor,'r--','linewidth',2);
set(gca,'fontsize',18);
box on;
xlabel('Time        [years]','fontsize',18)
ylabel('Carbon [Gt]','fontsize',18)
```

Matlab code for economic model

```
clear all; close all;
% ESTABLISH GROWTH CURVES:
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% TROPICAL:
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```

```
% time parameters:
N_year_trop=200; t=1:N_year_trop; alpha_trop=0.013;
T_trop=N_year_trop; t_trop=80;
% wood parameters:
rho_trop=0.6;    % density of typical tropical tree in SI units ton/m^3
power_trop=75.69; % average calorific value harvested in tropical region(GJ per ha per
year)
calorific_value_trop=20; % calorific value of wood (J per ton)
% calculate growth curve:
Vmax_trop=power_trop*N_year_trop/(rho_trop*calorific_value_trop)                    *
(1+exp(-alpha_trop*(N_year_trop-t_trop)));
V_trop=Vmax_trop./(1+exp(-alpha_trop*(t-t_trop)));
V_trop=V_trop-V_trop(1);
rho=0.6;    % density of typical boreal tree in SI units ton/m^3
unit=0.5*rho*3.67;
G_trop=V_trop*unit;%%%in tonnes of C02 per hectare
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
harvest=0.85;    %harvesting share of the total standing biomass
build=0.3;    %share of the harvested wood which is used for building material
bio=0.4;      %share of the harvested wood which is used for biochar production
(1-build-bio); %share of harvested wood which is directly burnt
r=0.02; %discount rate
Nc=200;%%number of possible carbon price values
c1=1:Nc;
c=c1*0.2;%%adjusting the range of c, social carbon cost of permanent emissions
delta=0;%%%emission depreciation rate
s=(r-delta)*c;%%%%%%Social carbon cost per ton per year
w=0.04; %decompose rate
y=0.001;    %Net Residue generated of the total standing biomass
p=106;    %Commercial value of wood as building material
b=68;    %Commercial value of biochar
j=0.01;    %Share of the building materials being scrapped and combusted each year
dis=(1+r).^(-t);%%discounting parameters
%%%%%%1%%%%%The present value of the commercial profits from harvesting
%wood as building materials (1+r)^(-t)
V_W1=G_trop.*dis*p*harvest*build;
V_W=repmat(V_W1',1,Nc);
%%%%%%2%%%%%The present value of the commercial profits from
%producing biochar from harvested wood
V_B1=G_trop.*dis*b*harvest*bio;
V_B=repmat(V_B1',1,Nc);
%%%%%3%%%%%%The present value of social cost of immediate burning after
%the harvest
V_F=transpose(dis.*G_trop)*c*harvest*(1-build-bio);%%%%%%V_fire=max(transpose(
```

```
exp(-r*t).*G_trop(t))*s*harvest*(1-build-bio))
%%%%%4%%%%%The social present value of carbon sequestrated in
%standing biomass during the T years
for z=1:N_year_trop
  for x=1:Nc
  if z > x
  A(z,x)=0;
  else
  A(z,x)=1;
  end
  end
end
V_SW=transpose(dis.*G_trop*A)*s;
%%%%%5%%%%%%The present social cost of the emissions from
%scrapping building materials
V_MS=transpose(dis.*G_trop)*c*(1-exp(-r/j))*j*harvest*build*1/r;
%%%%6%%%%The present social value of the remaining building materials
V_RM=transpose(dis.*G_trop)*s*harvest*build*(1-exp(-r)+j*exp(-r)*(1-exp(-r/j))/(1-ex
p(-r)));
%%%%%7%%%%%Amount of total residues at time T, including residues
%generated through the period and residues created from the harvesting
M_TR=(1-harvest)*G_trop+G_trop*A*y;
%%%%%%%The present social cost of the emissions from decomposing
%residues
V_DR=transpose(dis.*M_TR)*c*w*exp(-r)*(1-exp(-r/w))/(1-exp(-r));
%%%%%8%%%%%%The present social value of the remaining total residues
V_RR=transpose(dis.*M_TR)*s*(1-exp(-r)+w*exp(-r)*(1-exp(-r/w))/(1-exp(-r)));
%%%%%%9%%%%%%%he present social value of the remaining biochar
V_RB=transpose(dis.*G_trop)*s*harvest*bio/r;
%%%%%%%%present value of one rotation%%%%%%%%%
V_value=V_W+V_B-V_F+V_SW-V_MS+V_RM-V_DR+V_RR+V_RB;
for a=1:Nc
  B(a)=max(V_value(:,a));
end
for a=1:Nc
  for d=1:Nc
  if V_value(d,a)==B(a);
  E(a)=d;
end
end
end

figure (1); hold on;
set(gca,'fontsize',18);
```

```
plot(t,V_value);
box on;
xlabel('Rotation length    [years]','fontsize',18)
ylabel('Present social value [Euro/ha]','fontsize',18)
figure (2); hold on;
set(gca,'fontsize',18);
plot(t,V_value(:,1),'b','linewidth',2);
plot(t,V_value(:,200),'b--','linewidth',2);
box on;
xlabel('Rotation length    [years]','fontsize',18)
ylabel('Present social value [Euro/ha]','fontsize',18)
figure (3);hold on;
plot(c,E,'g-.','linewidth',2)
box on;
xlabel('Social cost of carbon [Euro/tonne CO2]','fontsize',18)
ylabel('Optimal rotation length    [years]','fontsize',18)
figure (4);hold on;
surf(V_value)
shading interp
xlabel('Social cost of carbon [0.2Euro/tonne CO2]','fontsize',12)
ylabel('Optimal rotation length    [years]','fontsize',12)
zlabel('Present social value [Euro/ha]','fontsize',12)
colormap HSV
```