

Forests as carbon sinks

A comparison between the boreal forest and the tropical forest



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Cover pictures: Österlen, Sweden. Picture taken by Adelina Osmani, 2009 (left).
Sinharaja, Sri Lanka. Picture taken by Adelina Osmani, 2012 (right).

Preface

This review is a bachelor's thesis in Physical Geography and Ecosystem Analysis. In this review, the importance of forests as carbon sinks is analyzed. Two major forest biomes are therefore analyzed, these being the boreal forest and the tropical forest. Furthermore, the impact of future climate change on these forest biomes and their ability to store carbon is investigated.

This review is written for the Department of Earth and Ecosystem Sciences at Lund's University. The supervisor for this study is Professor Anders Lindroth at Lund's University, who I would like to thank for the help he provided with relevant information, advices and comments on the review.

Abstract

The world's forest biomes have an important role in the global carbon cycle. With an increasing level of atmospheric CO₂ concentration, mainly due to the burning of fossil fuel and deforestation, it is important to analyze the significance of the forests biomes as carbon sinks. This review analyses the boreal forest and the tropical forest by investigating the amount of carbon taken up and where most of the carbon is stored. Also, the future climate impact on these forests and their carbon uptake is investigated.

The carbon storage in the two different forest biomes varies between the different studies. This is mainly due to the variation in total forest extent, and also the different methods used for estimating the carbon concentrations. Furthermore, the boreal forest stores most of its carbon in the soils, whereas the tropical forest stores most of the carbon in the plant biomass.

The future climate changes, caused by the increasing levels of CO₂, will mostly affect the boreal forest by increasing the frequency of natural disturbances such as fire and insect outbreaks. Even though climate change seems to have great impact on the tropical forest and its future ability to take up carbon, anthropogenic disturbances such as deforestation, seems to have a greater effect on this forest type and its ability to store carbon.

Keywords: Geography • Physical geography • Carbon cycle • Climate Change • Boreal forest • Tropical forest

Sammanfattning

Världens skogar spelar en viktig roll i den globala kolcykeln. Med den ökade nivån av CO₂-koncentrationen i atmosfären, orsakad av bränning av fossila bränslen och avskogning, så är det viktigt att analysera skogens roll som global kolsänka. Denna uppsats analyserar den boreala skogen och den tropiska skogen genom att undersöka hur mycket kol som tas upp och var kolen lagras i dessa skogstyper. Utöver det så undersöks effekten av framtida klimatförändringar på den boreala skogen och den tropiska skogen.

Den totala mängden kol som förvaras i de två skogstyperna varierar från studie till studie. Detta är mest på grund av stora variationer i den totala utsträckningen av skogarna, och det faktum att olika metoder används för att beräkna kolkoncentrationerna. Vidare så har det påvisats att den boreala skogen lagrar mest kol i jorden, medan den tropiska skogen lagrar det i vegetationen ovanför jorden.

Framtida klimatförändringar, orsakade av en ökad nivå av CO₂, kommer att påverka den boreala skogen genom en ökad frekvens av naturliga störningar så som bränder och insektsutbrott. Trots att klimatförändringarna kommer att ha stor effekt på den tropiska skogen, så är det antropogena störningar såsom avskogning som spelar störst roll för denna skogstyp och dess kolupptag.

Nyckelord: Geografi • Naturgeografi • Kolcykeln • Klimatförändringar • Boreal skog • Tropisk skog

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Abbreviations

C – Carbon

CO₂ – Carbon dioxide

EC – the eddy covariance method to measure carbon fluxes

GHG – Greenhouse gas

GPP – Gross primary production

Gt – Giga ton (G = 10⁹)

IRGA - Infrared gas analyzer used in eddy covariance techniques

NBP – Net biome production

NEP – Net ecosystem production

NPP – Net primary production

PgC/yr – Petagram Carbon per year (Pg = 10¹⁵ g)

Ppm – Parts per million

R_a – Autotrophic respiration

R_h – Heterotrophic respiration

Introduction

The world's climate is undergoing significant change and the trends show that the future will face warmer climate than the world is currently experiencing. Emissions released by human activities are constantly feeding the atmosphere with pollutants and gases that have a long life cycle (IPCC Fourth Assessment Report, 2007). The anthropogenic activities, such as deforestation and the burning of fossil fuel, are amongst the main factors which contribute to the release of gas emissions into the atmosphere (Griffiths & Jarvis, 2005., Pearman, 1988). One of the gases that is released into the atmosphere is the greenhouse gas carbon dioxide (CO₂), which traps heat in the lower parts of the atmosphere. This gas is naturally occurring in the atmosphere, but with increasing levels since the Industrial Revolution in the mid-18th century, CO₂ is one of the major gases which contribute to the changing climate in the world (IPCC Fourth Assessment Report, 2007).

Besides the atmosphere, there are other carbon sinks in the world which play an important role in the global carbon cycle. These other sinks are the world's oceans and the terrestrial biosphere (Schimel, 1995). Around 8.9 Pg C/yr is exchanged between the atmosphere, the oceans and the terrestrial biosphere. Most of these emissions are due to fossil fuel emissions, which contribute about 7.6 Pg C/yr. The second contributing factor comes from land use changes, such as deforestation, which contribute about 1.2 Pg C/yr. These sources of carbon emissions are almost balanced out by an uptake from the oceans, the terrestrial biosphere and the atmosphere itself (Pan et al., 2011).

The two main processes which affect the carbon cycle in the terrestrial biosphere are plant photosynthesis and respiration. Photosynthesis is the process which stands for most of the input of carbon to an ecosystem (Schulze, 2006). Respiratory processes, on the other hand, stand for an ecosystems output of carbon into the air (IPCC Third Assessment Report, 2001., Lugo & Brown, 1992).

Forests are biomes which cover about 30 % of the terrestrial biosphere and have an important role in the global carbon cycle (UNEP/GRID-Arendal, Vital forest graphics, 2009). The boreal forest and the tropical forest are the two terrestrial forest biomes which store most carbon (Kasischke & Stocks, 2000). The boreal forest has a higher soil carbon stock, compared with the tropical forest, which stores most of its carbon in the vegetation (IPCC Third Assessment Report, 2001., Kasischke & Stocks, 2000).

This review will focus on the forest as a carbon sink. More specifically, two forest types will be analyzed and compared. The two forest types which will be analyzed in this review are the boreal forest in the high latitudes in the northern parts of the world, and the tropical forest around the equator (DeAngelis, 2008., Stork et al. 2007). The review will compare the carbon uptake by the boreal forest respectively the tropical forest. Furthermore, the impact of future climate change on the boreal forest and the tropical forest will also be analyzed in this review.

Aim

The aim of this review is to determine the importance of the boreal and the tropical forests as carbon sinks and which of them takes up more carbon. This review also examines which impact the future climate has on these two forest types.

To reach the aim of the review the following questions are analyzed:

- How much carbon is taken up by the boreal forest?
- How much carbon is taken up by the tropical forest?
- How does the difference in total forest area affect the total carbon uptake by the boreal, respectively, the tropical forest?
- Is most of the carbon taken up by the vegetation or by the soils in the boreal, respectively the tropical forest?
- How will future climate changes affect the carbon uptake in the boreal, respectively, the tropical forest?

Limitations

This review does not include any in-depth analysis of the impact of natural disturbance on the forest, such as insects, fires and storms. The natural disturbances will only be mentioned briefly. The analysis will be focused on the boreal forest and the tropical forest, other forest biomes, such as temperate forest, are not included in this study. Furthermore, the methane which also has an important role in the global carbon cycle will not be investigated in the review. The focus of the global carbon cycle will be on the carbon in the form of carbon dioxide.

Method

This review is done by a literary study, analyzing carbon uptake in the boreal forest and the tropical forest and the impact the climate change has on these forests. The material used in this study is books, articles and reports. The information from the “The Carbon Balance of Forest Biomes” book by Griffiths & Jarvis (2005) has been used throughout this review. Other sources used in the study are included in the reference list below.

In the result section, the NEP values for Kasischke and Stocks (2000), IPCC (2001), Griffiths and Jarvis (2005), Shvidenko and Apps (2006), Malhi (2010) and Pen et al. (2011), were calculated by dividing the provided information about the total forest area, with the provided information about the yearly carbon uptake.

Background

The purpose of this chapter is to address the important background material for later analysis and to give a better understanding of which processes have an impact on the boreal forest and the tropical forest. Global warming will briefly be described, along with the global carbon cycle, the methods used for measuring carbon fluxes and finally a description of the boreal forest and the tropical forest.

Global warming and the increasing level of carbon dioxide

Humans have influenced their environment by activities such as burning fossil fuel and changes in land-use (e.g. deforestation). Although the level of the impact which the human activities had on its surroundings remained fairly constant up until the Industrial Revolution around the middle of the 18th century (IPCC Third Assessment Report, 2001., Pearman, 1988). Before the Industrial Revolution, the concentration of carbon dioxide (CO₂) in the atmosphere had remained on a level from 180 ppm during glacial periods to 280 ppm during interglacial periods. But after the mid-18th century, the burning of fossil fuel from industries increased, hence increasing the amount of CO₂ released into the atmosphere. The current level of CO₂ in the atmosphere is over 390 ppm (NOAA, 2012).

CO₂ is a gas that occurs naturally in the atmosphere. This gas help keep the temperature on Earth warmer than it otherwise would be. It does so by being transparent to the incoming solar radiation, mostly shortwave radiation, and by absorbing some of the outgoing terrestrial infrared radiation. The CO₂ gas and other gases that have similar chemical compositions, such as methane (CH₄), nitrous oxide (N₂O), ozone (O₃) and water vapor (H₂O), trap heat which gives the Earth its warm and life-supporting temperature. These gases which warm up the Earth are referred to as greenhouse gases (GHGs) (Kasischke & Stocks, 2000., Pearman, 1988). The carbon uptake by the ocean and by the terrestrial biosphere is directly influencing the level of atmospheric CO₂ concentration. Hence, these carbon sinks or sources have a direct influence of the Earth's temperature (Barkhatov et al., 2011).

The increase of CO₂ concentration and other GHGs in the atmosphere results in an increase of global temperature. During the last 100 years, the increase in temperature has been about 0.6°C and it is estimated to increase between 1.5 – 5.8°C during this century (IPCC Third Assessment Report, 2001., Stork et al. 2007., Wuebbles & Edmonds, 1991). The level which the atmospheric CO₂ concentrations will reach by the end of 2100s differs from scenario to scenario; the range varies from a level of 500 ppm up to 1000 ppm (Stork et al. 2007). The amount of carbon released to the atmosphere by fossil fuel is around 7.6 Pg C/yr and the amount added by deforestation varies from 0 to 3 Pg C/yr (Pan et al., 2011., Wuebbles & Edmonds, 1991).

The Global Carbon Cycle

The exchange of carbon between the atmosphere, oceans and the terrestrial biosphere is what make up the global carbon cycle. Most of the carbon in the carbon cycle moves in the form of CO₂. CO₂ emissions, which mainly come from fossil fuel and deforestation, are released into the air and then transported throughout the atmosphere (Pearman, 1988).

Of all the carbon dioxide emissions released out into the atmosphere, only around 50% of it stays in the atmosphere itself. This indicates that there are existing carbon sinks which account for the rest of the carbon uptake (Pan et al. 2011., Griffiths & Jarvis, 2005). About half of the carbon dioxide emitted from the fossil fuel emission and the deforestation of the tropical forests is taken up by the atmosphere. The rest of the emissions are absorbed by the ocean and by the terrestrial biosphere (e.g. forests) (Goodale et al. 2002).

Around 8.9 Pg carbon is yearly exchanged between the atmosphere, the world's oceans and the terrestrial biosphere. Most of the carbon emissions are released from the burning of fossil fuel, which stand for a source of 7.6 Pg C/yr. The other major carbon source is land use changes, mainly deforestation, which stand for a source of about 1.2 Pg C/yr. The carbon which is released into the air each year is exchanged and almost balanced out with the three major carbon sinks of the world, which are mentioned above. The atmospheric CO₂ concentrations are about 4.1 Pg C/yr. The oceans stand for a sink of 2.3 Pg C/yr. Forests which play an important role in the global carbon budget account for a net uptake of about 2.4 Pg C/yr (Pan et al., 2011, Ometto et al. 2005).

The exchange of carbon in the terrestrial biosphere occurs through photosynthetic and respiratory processes (Pearman, 1988). The main process which stands for most of the carbon input in an ecosystem is plant photosynthesis (Schulze, 2006). The total amount of carbon which is produced by photosynthetic plants is the gross primary production (GPP) (IPCC Third Assessment Report, 2001). Autotrophic respiration (R_a), which is the respiration from plant tissue, is one of the process which returns the carbon from the terrestrial biosphere out to the air (IPCC Third Assessment Report, 2001., Lugo & Brown, 1992). Heterotrophic respiration (R_h) is another process which releases carbon from the ecosystem to the air. In this process, carbon is released from the ecosystem by decomposers (such as bacteria) feeding on dead tissue (IPCC Third Assessment Report, 2001).

The difference between the GPP and the R_a in an ecosystem, are what determine the growth of plants, i.e. net primary production (NPP) (Schulze, 2006 & IPCC Third Assessment Report, 2001). The NPP in an ecosystem increases with the diversity of plant species, where 50% of species loss is equal to a loss of 20% of the NPP. This shows that the amount of carbon released to the atmosphere depends upon the capacity of these other reservoirs to take up carbon (Schulze, 2006). The net ecosystem production (NEP) (i.e. the carbon balance in an ecosystem) is determined by the difference between the NPP and the R_h . Lastly, the net land uptake of carbon is determined by the net biome production (NBP), which is equal to the NEP

minus the carbon losses due to disturbances such as fire. The NBP is the carbon which is accumulated in the terrestrial biosphere, which in the 1990s was a sink of 1.4 ± 0.7 Pg C/yr (as mentioned above) (IPCC Third Assessment Report, 2001).

The carbon cycle is altered by many different factors. Disturbances, both anthropogenic and natural, affect the amount of carbon that is taken up or released by the terrestrial biosphere. Land use changes, such as deforestation, contribute to the release of carbon dioxide to the atmosphere. The high rate of deforestation in the tropical forest is one of the main sources of anthropogenic CO₂ emissions (Malhi 2010., IPCC Third Assessment Report, 2001). Natural disturbances in forests, e.g. fire, insect outbreaks and storms, reduce the amount of carbon taken up by the biosphere. The large amount of dead wood, which is a result of fire outbreak, causes a release of carbon out to the atmosphere, thus, turning forest from carbon sinks to carbon sources (Lindroth et al. 2009., Goodale et al. 2002).

Methods for measuring Carbon fluxes

Measuring the net CO₂ flux between the atmosphere and the terrestrial biosphere is important in order to understand the global patterns of carbon. FLUXNET is a global network which measures the exchange of carbon between the terrestrial biosphere and the atmosphere (Friend et al. 2007). This global network consists of micrometeorological towers that measure the CO₂ fluxes. Measuring these fluxes is important since the amount of carbon dioxide released into the atmosphere plays an important role for the future climate. Today, there are over 140 sites which are working on a continuous basis. Other fluxes that are being measured are water vapor flows and the energy flows between the biosphere and the atmosphere. Sites that are undergoing these measurements include boreal forest, temperate forest, tropical forest, wetlands, tundra etc. (Baldocchi et al. 2001).

One method used for estimating the CO₂ fluxes is eddy covariance measurements which provides values of the direct exchange of carbon between the land surface and the atmosphere. The eddy covariance (EC) technique uses sensors, which are placed above vegetation canopies, to measure the carbon exchange and contains of an infrared gas analyzer (IRGA) and a sonic anemometer, shown in Figure 1 (Griffiths & Jarvis, 2005, Baldocchi et al. 2001, Grace et al., 1996). It provides the NEP values over a specific ecosystem area between 0.1 and 1.0 m². The method is based on the CO₂ concentration of the surface layers of the vegetation, and the fluctuation of the vertical wind. The measurements of fluxes can be taken over both short-term periods of hours and days, to long- term periods, of month to years (Friend et al., 2007, Griffiths & Jarvis, 2005, Baldocchi et al., 2001). However, this method has its limitations as it is generally restricted to phases when the atmosphere is under steady conditions. Another limitation is that the method only can be used



Figure 1. The figure shows an image of an eddy covariance tower (ITC, 2010).

on rather flat areas. This means that the method cannot be used rough areas such as mountain terrains (Baldocchi et al. 2001).

Other methods used for measuring CO₂ and other fluxes are, for instance, atmospheric inversion models which are used to estimate carbon dioxide sources and sinks. This method is used on continental and global scales. Here, tall towers with infra-red gas analyzers are used. These can accurate concentration values as small as 0.1 ppm. This method can provide carbon uptake measurements over large areas in periods of hour – by – hour (Griffiths & Jarvis, 2005, Baldocchi et al. 2001).

Another method for viewing the Earth in total and evaluating the carbon fluxes on the land surface are remote sensing measurements. Here, instruments are applied on satellite platforms. These instruments are depended on factures such as the frequency of satellite images and the accuracy of the model algorithms. Furthermore, the data from the satellite sensors are restricted to fair weather conditions, and the data resolutions can be restricted of only a few ppm (Griffiths & Jarvis, 2005, Baldocchi et al. 2001). A range of other methods are used to estimate CO₂ fluxes; these are further described by Griffiths & Jarvis (2005) and Baldocchi et al. (2001).

The boreal forest belt and the tropical forest

As mentioned above, the main source of carbon input into a terrestrial ecosystem is plant photosynthesis and respiration (Kasischke & Stocks, 2000). In the terrestrial ecosystem, forests, such as boreal, temperate and tropical forest, represent major carbon sinks. Although, this review only focuses on the boreal forest and the tropical forest, which means that the temperate forest will not be analyzed for further discussions. The definition of forests and the forest boundaries vary from author to author, and country to country. Goodale et al. (2002), defines a forest as an area where the land surface is covered by the minimum tree cover of 10-30 %.

The land area covered by the boreal forest is approximately 12×10^6 km², which covers about 17 % of the Earth's land surface (Brey Meyer et al. 1996., Kasischke & Stocks, 2000). Figure 2 also shows the global distribution of the boreal forest belt. According to Griffiths & Jarvis (2005), the boreal ecosystem accounts approximately 21% of the forest areas of the world. Other studies suggest that the total area covered by the boreal biome accounts for about 33% of the global forest areas (Shvidenko & Apps, 2006).

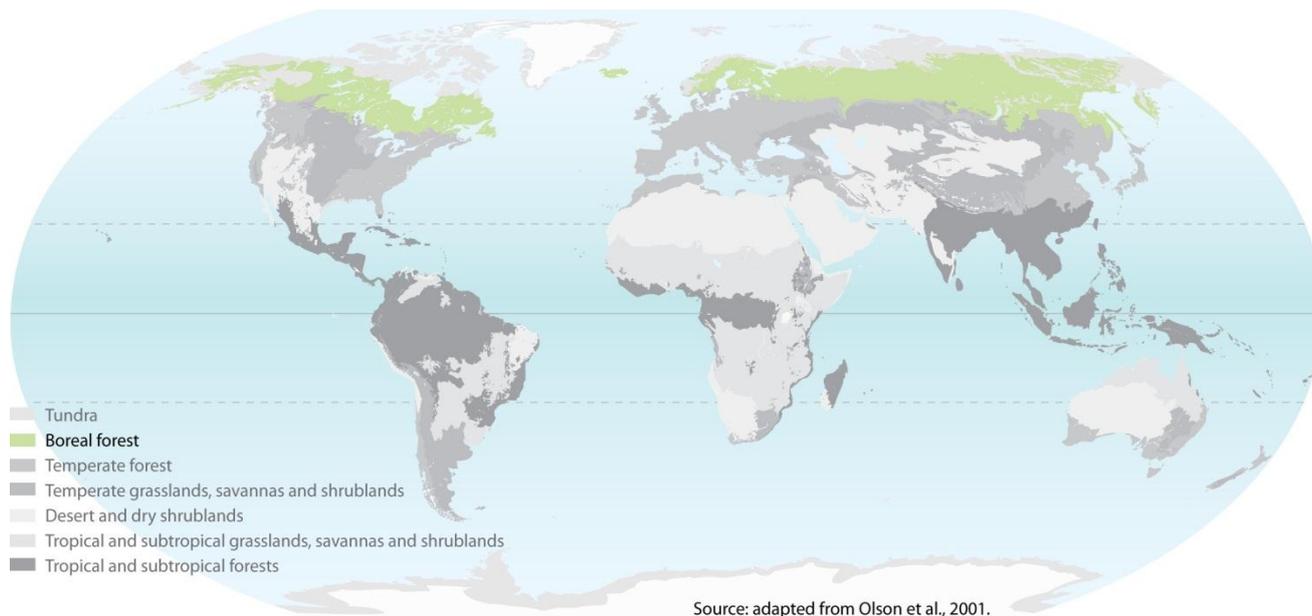


Figure 2. The figure shows a map of the extent of the boreal forest in the high latitudes of the Northern Hemisphere. The extent of the forest is shown in a green color (UNEP/GRID - Arendal, 2012).

In a geographical view, the boreal forest biome is found on the latitudes from 45° to 70° north. This biome is often referred to as the ‘taiga’ region (DeAngelis, 2008). This covers the areas Siberia, Europe and North America. Siberia stands for 43% of the total areas covered by the boreal ecosystem, while Europe and North America accounts for 21% respectively 36%. The species diversity in the boreal region is scarce, the primary tree species are spruce (*Picea*), pine (*Pinus*) and larch (*Larix*) (Griffiths & Jarvis, 2005., Kasischke & Stocks, 2000).

The growing season for the vegetation in the boreal forest is shorter than it is for other regions, e.g. the tropical forest areas. This is due to the solar irradiation and the temperature in these regions. There are less than 90 days of frost free periods in these areas, during which, the periods of extreme daylight can be up to 24 hours in regions above 66° north latitude. As a result, the temperature in certain regions can be very warm and the daily NPP rates in the boreal forest can be as high as they are in the tropical rainforest, although the total NPP in the boreal forest is much lower than in the tropics. This is due to the shorter growing seasons in the region. This large area of forest takes up much of the carbon dioxide released by emissions from human activities. Most of the carbon taken up in the boreal forest belt is stored under the ground in soils. That is due to the cold climate which leads to the formation of permafrost below the ground. The cold conditions reduce the decomposition rates and result in deep and undecomposed organic soils (Kasischke & Stocks, 2000).

The other forest biome which is important for the terrestrial carbon cycle is the tropical forest. Most of the world’s tropical forests receive over 2000 mm precipitation a year and occurs in the latitudes between 15° to 20° on both sides of the equator (Stork et al. 2007). The area

which is covered by the tropical forest also varies amongst authors. According to Stork et al. (2007) and Lewis et al. (2009) the tropical forests cover about 6 to 10% of the Earth's surface. According to Griffiths & Jarvis (2005), the area of tropical forest is approximately $17 \times 10^6 \text{ km}^2$. This area includes lowland evergreen forests, moist and dry deciduous forests, and montane forests. Figure 3 below, shows the distribution of the tropical forest. Here both the tropical forest and the subtropical forest are included. In the review by Malhi (2010), the land area covered by the tropics occupies about $56 \times 10^6 \text{ km}^2$, which is mainly divided by three continents. These are Central and South America, Africa and finally South-East Asia. Of the $56 \times 10^6 \text{ km}^2$, about 24 % is covered by humid forests, which equals to about $13 \times 10^6 \text{ km}^2$.

When including tropical savannahs, the tropical forest accounts for about 60% of the terrestrial photosynthesis and is said to be home to about 44% of the world's vascular plants and 35% of the vertebrates (Griffiths & Jarvis, 2005., Stork et al. 2007). The growth rate of the plants in these forests is higher than in the boreal forests, due to the warm and moist climate. Most of the carbon is stored in the vegetation, with an estimation of around 170-250 t C per ha. The carbon stored in soils is somewhat lower than the above-ground carbon storage, with an estimation of around 90-200 t C per ha (UNEP/GRID-Arendal, 2011). The main factors which affect the amount of carbon taken up by the tropical forest are the extent of the forest area, the developmental stages in the forest, the capacity to take up carbon by the different forest species, the rate of the primary production in the forest and finally, the rate of deforestation (Soepadmo, 1993).

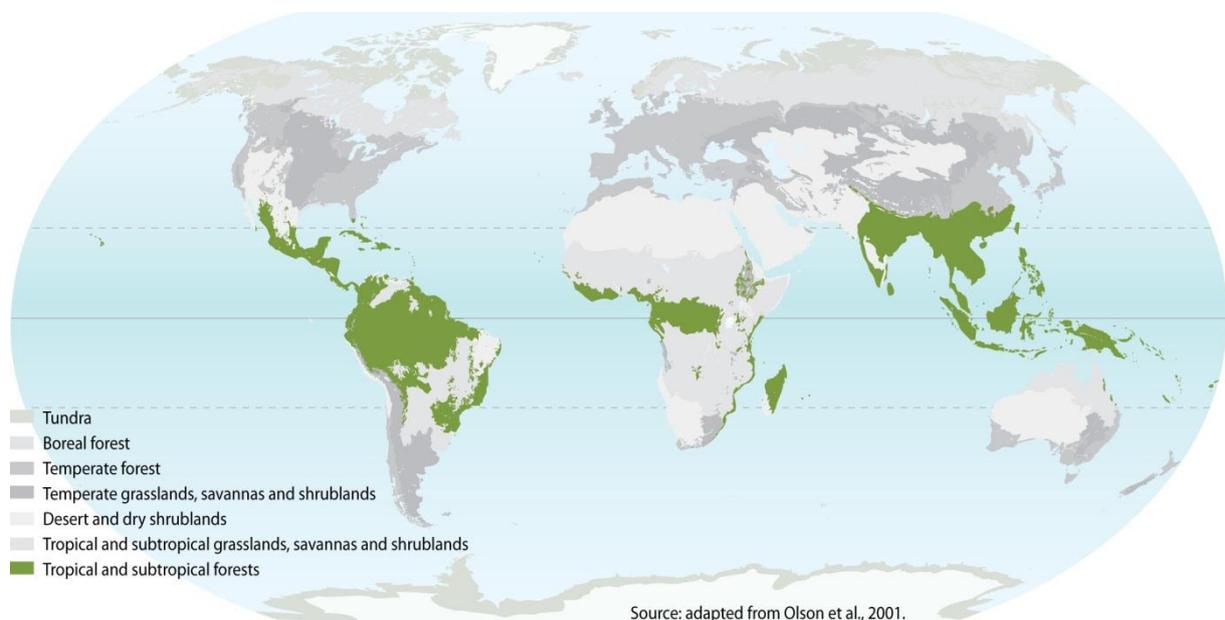


Figure 3. The figure shows a map of the extent of the tropical and subtropical forests around the equator. The extent of the forests is shown in the green color (UNEP/GRID – Arendal, 2012).

Results

This chapter will focus on how much carbon is stored and taken up by the boreal forest respectively the tropical forest. The climate impact on these forests will also be represented here.

The carbon uptake in the boreal forest

The estimations of the amount of carbon stored in the boreal forest vary amongst the authors. These various results are summarized in table 1 (not including NPP). Griffiths and Jarvis (2005) analyzed an area of $13.7 \times 10^6 \text{ km}^2$. In this study, the total carbon storage in the boreal forest is 395 Pg. The estimated yearly carbon sink in this area is about 0.47 Pg and the boreal forest has a total NPP of 2.6 Pg C/yr, according to this study. To estimate the carbon budget in the boreal zone, model stimulations of carbon flows were used (Griffiths & Jarvis, 2005., Taylor & Lloyd, 1992). By using the provided information from Griffiths and Jarvis (2005) about the total area of the boreal forest and the yearly carbon uptake, the NEP values were estimated to be 34 g(C) m^{-2} per year. Luysaert et al., (2007) on the other hand showed that the results of carbon uptake in the boreal forest measured in NEP varied from 40 to 178 g(C) m^{-2} per year, covering an area of around 18% of the world forest biomes.

The study by Shvidenko and Apps (2006) shows a boreal forest area of around $11.6 \times 10^6 \text{ km}^2$. According to this study, this area accounts for about 33% of the world's forest areas. In results, the total amount of carbon stored in the boreal forest is around 23% of all the terrestrial carbon, with a total of 559 Pg C stored. 88 Pg C is stored in the biomass of the boreal forest, and the rest, 417 Pg C, is stored in the soils. For these result, inventory data and simple models were used to estimate the carbon fluxes. The NPP in these areas varied from 2.6 Pg C/yr to 3.2 Pg C/yr (Shvidenko & Apps, 2006., IPCC Third Assessment Report, 2001). The results show that the region of the boreal forest was a net carbon sink of 0.6 - 0.7 Pg C/yr. Of this, about 0.21 Pg C/yr was taken up by the biomass and 0.13 Pg C/yr was taken up by the soils. Atmospheric inversion studies for the boreal zone were used to estimate the carbon uptake (Shvidenko & Apps, 2006). The estimated NEP values from the above mentioned results varied from 224 to 276 g(C) m^{-2} per year.

In an area of $15.1 \times 10^6 \text{ km}^2$, the boreal forest contain a total carbon stock of 703 Pg C. Of this, 625 Pg C is in soils and 78 Pg C in the vegetation. Furthermore, the boreal forest is a net carbon sink of 0.54 Pg C/yr and the estimated NEP value is about 36 g(C) m^{-2} per year (Kasischke & Stocks, 2000). The carbon results are based on the models and estimations of average carbon densities (Kasischke & Stocks, 2000., Apps et al, 1993) On the other hand, according to figure 4 (below), the boreal forest region stores around 384.2 Pg carbon. This is shows a lower amount of carbon stored in the boreal forest, than according to Kasischke and Stocks (2000).

In the more recent study by Pan et al. (2011), an area of $11.4 \times 10^6 \text{ km}^2$ was analyzed. By using forest inventory data, the average yearly carbon sink in the boreal forest was estimated to be around 0.5 Pg C/yr during the period of 1990-2007. This results in carbon sink of about 22% of the world's forests sinks. The estimated carbon storage in the boreal forest is around 273 Pg C, with an estimated NEP value of 44 g(C) m^{-2} per year. Here, about 20% of the carbon is stored in the plant biomass, while around 60% is stored in the soils.

Boreal Forest				
Source	Area ($\times 10^6 \text{ Km}^2$)	C stored (PgC)	C uptake (PgC/yr)	NEP($\text{gC/m}^2\text{yr}$)
Kasischke & Stocks (2000)	15.1	703	0.54	36
Griffiths & Jarvis (2005)	13.7	395	0.47	34
Shvidenko & Apps (2006) & IPCC (2001)	11.6	559	2.6 – 3.2	224 – 276
Luyssaert et al. (2007)				40 – 178
UNEP/GRID - Arendal (2009)		384		
Pan et al. (2011)	11.4	273	0.5	44

Table 1. The table shows a summary of the results for the boreal forest given by different sources seen in the first axis. The empty spaces are due to the lack of information. The table shows the total forest area in $\times 10^6 \text{ Km}^2$, the amount of carbon stored (Pg C), the yearly uptake of carbon (Pg C/yr) and the NEP values ($\text{g(C) /m}^2\text{yr}$).

Tropical Forest				
Source	Area ($\times 10^6 \text{ Km}^2$)	C stored (PgC)	C uptake (PgC/yr)	NEP ($\text{gC/m}^2\text{yr}$)
Kasischke & Stocks (2000)	17.6	375		
IPCC (2001)	17.9	428		
Falge et al. (2002)				608
Griffiths & Jarvis (2005)	17.0	553	0.66	39
Luyssaert et al. (2007)				403 ± 102
UNEP/GRID - Arendal (2009)		548		
Malhi (2010)	18.5		1.09	59
Pan et al. (2011)	19.5	472	4.0	205

Table 2. The table shows a summary of the results for the tropical forest given by different sources seen in the first axis. The empty spaces are due to the lack of information. The table shows the total area ($\times 10^6 \text{ Km}^2$), the amount of carbon stored (Pg C), the yearly uptake of carbon (Pg C/yr) and the NEP values ($\text{g(C) /m}^2\text{yr}$).

Carbon stored by biome
(Gigatonnes of C)

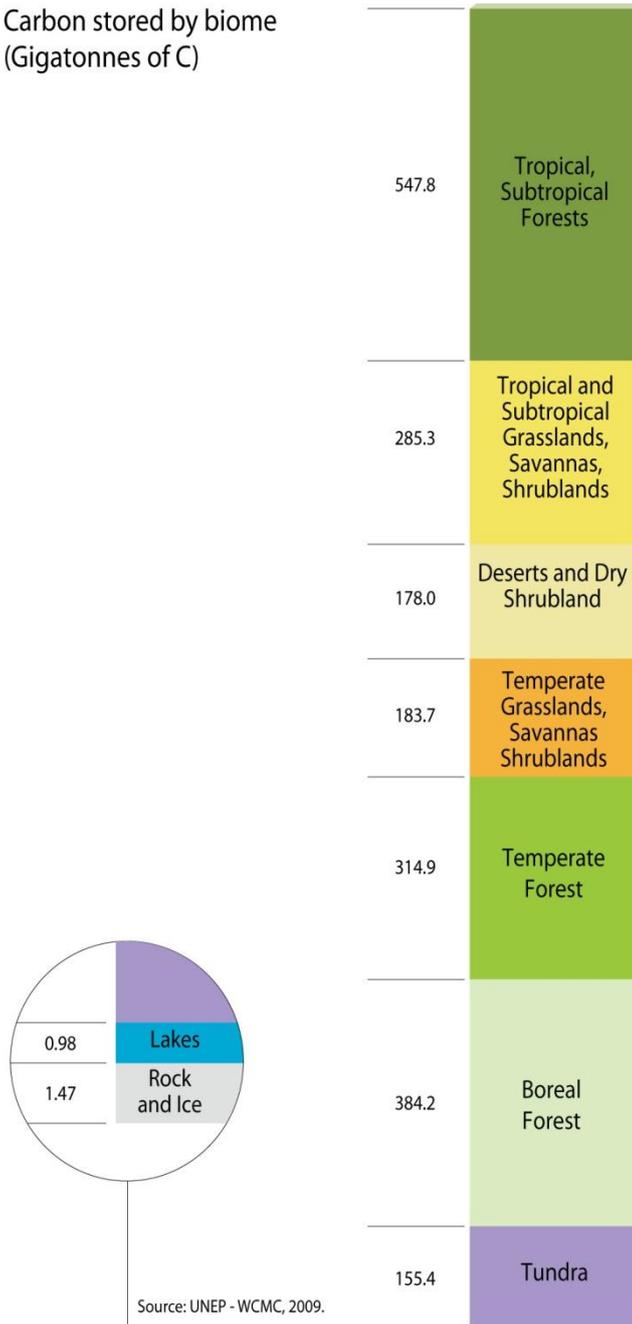


Figure 4. The figure shows the carbon stored in different biomes, measured in Gt of C. The most important is the tropical and subtropical forests and the boreal forest, which store 547.8 Gt C (547.8 Pg) respectively, 384.2 Gt C (384.2 Pg) (UNEP/GRID-Arendal, 2009).

The carbon uptake in the tropical forest

Just like with the boreal forest, the amount of carbon stored in the tropical forest varies amongst different authors and studies. All the results are summarized in table 2 (not including NPP). Over the period between 2000 and 2005, around 12% of the total anthropogenic CO₂ emissions were absorbed by the tropical forests, making the tropical forest areas a land carbon sink of around 47% (Malhi, 2010). In IPCC's third assessment report (2001), a total carbon stock in the tropical forest accounted for about 428 Pg C in an area of 17.6×10^6 km². Here, the carbon stored in the soils is 216 Pg C, and the carbon stored in plant biomass is 212 Pg C. The yearly NPP in these forest varied between 13.7 Pg C/yr and 21.9 Pg C/yr. In the study by Falge et al. (2002) estimated the NEP values, by using EC measurements in the tropical forest, to be around 608 g(C) m⁻² per year. The results by Luysaert et al. (2007) showed lower NEP values with a variation 403 ± 102 g(C) m⁻² per year, covering an area of about 43% of the world's forest biomes.

According to Griffiths and Jarvis (2005), the tropical forest area of 17.0×10^6 km² cycle around 12% of the carbon dioxide held in the atmosphere. This accounts for a carbon storage of 553 Pg, with a yearly sink of 0.66 Pg C. The total NPP in these forests is around 21.9 Pg C/yr and the estimated NEP values from provided information is about 39 g(C) m⁻² per year. In order to investigate the carbon sinks in the tropical forest, model stimulations of carbon fluxes were used (Griffiths & Jarvis, 2005., Taylor & Lloyd, 1992) On the other hand, according to Kasischke and Stocks (2000), the total amount of carbon stored in the tropical forest, in an area of 17.6×10^6 km², is around 375 Pg C. Here, 216 Pg C is stored in the soils, and 159 Pg C is stored in vegetation biomass. The carbon storage results were estimated from basic models of carbon pools and flows (Kasischke & Stocks, 2000., Brown et al., 1993). The total carbon storage is thereby lower compared to the estimations shown by both Griffiths and Jarvis (2005) and IPCC's third assessment report (2001).

Malhi (2010) divided the tropical forest area into three main areas of America (8.02×10^6 km²), Africa (6.61×10^6 km²) and Asia (3.89×10^6 km²), which results in a total area of 18.5×10^6 km². The yearly carbon uptake in these areas was estimated to be around 0.56 Pg C, 0.31 Pg C and 0.22 Pg C respectively. The total carbon uptake being around 1.09 Pg C/yr for these three areas combined, with estimated NEP value of 59 g(C) m⁻² per year. The estimated results were from inventory plots used to evaluate the carbon fluxes (Malhi, 2010., Lewis et al., 2009). On the other hand, figure 4 (above), shows that the amount of carbon stored in the tropical forest (including the subtropical forest) is about 547.8 Pg.

Pan et al (2011) estimated a total carbon storage of about 472 Pg C in the tropical forest, by using forest inventory data. In the tropical forest, most of the carbon is stored in the plant biomass, which is about 56% of the total carbon storage. The carbon stored in the soil about 32%, which is much less than the amount stored in the soils of the boreal forest. In the total area of 19.5×10^6 km², the tropical forest accounts for a yearly carbon sink of about 4.0 Pg. The estimated NEP value from the provided information is 205 g(C) m⁻² per year.

The future climate impact on the forests

Models of coupled carbon and climate suggest that increasing levels of CO₂ in the atmosphere would increase both the above and below ground carbon stocks; resulting in an increase of net terrestrial carbon uptake. Although, with further increasing levels of CO₂ would cause plant photosynthesis to saturate, while soil respiration continues to increase with the increasing temperature. This would cause the terrestrial biosphere, i.e. the forests, to shift from carbon sinks to carbon sources (Stork et al. 2007).

Under the effects of doubling CO₂ concentrations in the atmosphere, the temperature, the precipitation and the water availability in the boreal forest (and also the tropical forest) is expected to undergo significant changes. The rate of photosynthesis is expected to grow, thus affecting the growth rate of trees. These results vary amongst different field conditions. Changes in climate will also affect the frequency of fire in the boreal forests. According to different models, an increase in temperature will increase the fire frequency. An example is the potential for fire in Canada will rise with about 40% (Pan et al., 2011., Brey Meyer, 1996). Increasing temperature, thus warmer winters in these regions will in turn not only lead to increased frequency of fires in the boreal regions, but also increase damages caused by increasing insect outbreaks (Pan et al., 2011). Furthermore, the warming effect of climate change will also affect carbon stored in the soil in the boreal region, causing losses of carbon from the terrestrial biosphere (Davidson & Janssens, 2006).

In the regions of the tropical forest, these areas have experienced a high rate of temperature warming of about 0.26°C per decade since the 1970s. In the Northern Hemisphere, there has also been a decline in precipitation. These factors have led to the migration of species and disturbance in reproduction and abundance in plant and animal species, due to the changing climate in these areas (Stork et al. 2007).

Increasing temperature caused by increasing levels of CO₂ into the atmosphere will cause drought frequencies to increase in the tropical forest areas. This is also due to the decrease of rainfall in these regions, which was mentioned above. As a result, these factors will turn the areas which are affected into carbon sources instead of carbon sinks. Thereby causing a further increase in climate changes in the future (Malhi, 2010., Stork et al. 2007., Cramer et al., 2004., IPCC Third Assessment Report, 2001).

Discussion

The amount of carbon taken up by the forests varies amongst the authors and their studies. According to the more recent studies (Pan et al., 2011., UNEP/GRID-Arendal, 2009), the tropics seem to be the major forest carbon sinks. Even though these forests account for most of the carbon storage, the carbon emissions due to deforestation of these areas are very significant. In the period 2000 to 2007, the yearly carbon source due to deforestation was about 2.9 Pg C. These emissions were though neglected due to regrowth of some areas in the tropical forest, leading to an uptake of carbon (Pan et al., 2011).

NEP for the tropical forest seems to be around the same levels as in the boreal, this is because of the fact that the total area in the tropical forest is estimated to be bigger than that measured for the boreal forest. Although some studies show very high NEP values for the tropical forest, e.g. Falge et al. (2002), which estimates the high value of 608 g(C) m⁻² per year (table 2). Still, the high NEP in the tropical forest can be explained by the higher biodiversity and the higher rates of NPP in these forests, compared with the boreal forest (Griffiths & Jarvis, 2005., IPCC Third Assessment Report, 2001). Also, the total area covered by the tropical forest is estimations between 17.0 and 19.5 x 10⁶ Km² amongst the different sources (table 2), which is a greater total area than for the boreal forest; which vary from 11.4 to 15.1 x 10⁶ Km² (table 1). The different methods used for estimating the carbon also affects the results of the total carbon uptake by the boreal and the tropical forests.

Higher NEP values may in areas which are undergoing forest management, due to the fact that the main point of forest management is to increase the biomass productivity in the forests. Although EC measurement results show that even unmanaged forests are carbon sinks, making forests in general carbon sinks. Climate and weather conditions seem to have a small influence in the NEP values, as precipitation and temperature only explains about 5% of the variability of the NEP in different forest types (Luyssaert et al., 2007., Griffiths & Jarvis, 2005).

Furthermore, the net uptake in the tropical forest varies from 0.66 to 4.0 Pg C/yr (table 2), while the net uptake for the boreal forest varies from 0.47 to 3.2 Pg C/yr (table 1). The differences between these values are quite that big, although, the tropical forest seems to stand for a bit more of the carbon uptake than the boreal forest, according to the sources seen in table 1 and 2. This may be due to the fact that, as mentioned, the total area for the tropical forest is greater than the total area for the boreal forest, leading to a greater uptake of carbon by the tropical forest than by the boreal forest. Also, as mentioned above, the higher NPP values for the tropical forest may play a role in this, since the higher values of NPP results in a greater uptake of carbon, due to the higher amount of biomass in the tropical forest (Griffiths & Jarvis, 2005., IPCC Third Assessment Report, 2001).

The difference in total area affects the amount of carbon taken up by the two forest biomes in different ways. In a larger area there is more space for vegetation, leading to a greater ability

to take up carbon. Although, as seen in the case of the boreal forest, it is not only the vegetation that can store the greatest amount of carbon, it is also the soil below the forest which can contribute in the carbon uptake from the atmosphere. This is because of the formation of the permafrost during the cold weather seasons which are longer than the growing seasons (Kasischke & Stocks, 2000). The amount of carbon stored in soils is about 60%, whereas the amount of carbon stored in the plant biomass is about 20% (Pan et al., 2011). The tropical forest on the other hand stores most of its carbon in the vegetation, which accounts for about 56%. The amount of carbon stored in soils is slightly lower, about 32% (Pan et al., 2011). Although, according to Kasischke and Stocks (2000), the tropical forest stores a larger amount of carbon in the soil than in the plant biomass, which is seen in the result section. This means that there are still some uncertainties to whether the tropical forest stores most of its carbon in the soil or in the plant biomass.

The main factors which have an effect on the tropical forest and its carbon budget are deforestation and degradation of the forests, regrowth of the forest and increasing biomass. The degradation of the forest and deforestation are the main factors which contribute to carbon emissions, while regrowth of the forest and increasing biomass increases the amount of carbon taken up by the forest (Pan et al., 2011). Deforestation most certainly seems to be one of the main factors which will lead to great losses of carbon if it continues in the same rate in the future. Other factor which affects the tropical regions is drought, which is expected to increase with future climate changes. This is mainly due to higher temperature levels and a decrease in precipitation caused by the increase of CO₂ levels in the atmosphere. The increase in drought frequency in the tropical forest areas might therefore cause these areas to shift from carbon sinks to carbon sources, thus affecting the climate even more (Pan et al., 2011., Cramer et al., 2004., IPCC Third Assessment Report, 2001).

According to the study of Malhi (2010), the results show that there is almost a net balance between the carbon sink and the carbon source in the tropical forest. Deforestation, due to increase in world population, causes more removal of tropical forest. One example is the area of the Brazilian Amazon rainforest, where the deforestation is increasing in the areas with higher biomass. This in turn alters the carbon budgets, again, causing these areas to become carbon sources because of the decrease in biomass and the impact on the photosynthesis processes which decreases with decreasing biomass (Pan et al., 2011., UNEP/GRID-Arendal, 2011).

The deforestation mostly affects the tropical forest because of two main reasons; firstly, the deforestation rates in these regions are higher than in the boreal regions. Secondly, the amount of carbon stored in the plant biomass is higher in the tropical forest than in the boreal forest. Therefore, reducing the area of trees in the tropical forest causes a higher release of carbon due to the carbon storage of about 56% in the vegetation (Pan et al., 2011., UNEP/GRID-Arendal, 2011). The higher NPP values, between 13.7 Pg C/yr and 21.9 Pg C/yr, for the tropical forest than the total NPP of 2.6 Pg C/yr in boreal forest, emphasizes the fact that

deforestation of the tropical forest plays a more significant role in the carbon balance (Griffiths & Jarvis, 2005., IPCC Third Assessment Report, 2001).

Due to climate change, there is a possibility that there will be an increase in the frequency of the El Nino events. This also affects the tropical forest areas, making some parts especially vulnerable. Increasing El Nino events would result in a decrease of precipitation and an increase of cyclones. The decrease in precipitation might then, as mentioned above, result in increasing drought frequency, thus, resulting in an alteration of the carbon budget in the tropical forest regions (Pan et al., 2011., Stork et al. 2007).

Even though studies show expected results of the impact of future climate, there are still a lot of uncertainties when it comes to how the tropical forests (or forests in general) will respond to the increasing levels of CO₂, and how these responds will interact with the future changes in climate. Where water is available the responses to the increasing levels of CO₂ may be positive. The responses may also vary between species, and from region to region according to changes in moisture regime. The decrease in the amount of rainfall which could result in drought conditions may cause some areas of the tropical forest to become carbon sources instead of carbon sinks (Stork et al. 2007).

The factors which mainly affect the boreal forest, and its role in the global carbon budget, are changes in harvest pattern, regrowth of the forests and increasing disturbance in these areas due to changing climate (Pan et al., 2011., IPCC Fourth Assessment Report, 2007). With an increase of CO₂ into the atmosphere, the ability for plant and soils to take up carbon will increase in the forest areas. Although, if the level of CO₂ released into the atmosphere continues to increase, the ability for the vegetation to take up carbon will decrease, thus, switching the terrestrial biosphere from carbon sinks to carbon sources. This is due to the fact that increasing temperature caused by climate changes and the release of CO₂, would cause plant photosynthesis to be saturated, while soil respiration on the other hand would continue with increasing temperature levels (Stork et al., 2007). This would mostly affect the boreal regions, since most of the carbon storage occurs in the soils and not in the biomass (Pan et al., 2011., Kasischke & Stocks, 2000). Also, with warmer temperatures, the decomposition rate in the soils may be enhanced, causing less carbon do be stored in the soil in the boreal regions (Davidson & Janssens, 2006).

According to Kasischke and Stocks (2000), the tropical forest is probably going to remain a carbon sink of atmospheric CO₂, mainly due to reforestation. The boreal forest on the other hand is likely to shift from a net carbon sink to a net carbon source. This is due to human activities such as deforestation, which is expected to increase mostly in Russia. Climate changes will also affect the boreal forests by an increase of disturbances. Both fire and insect outbreaks are, as mentioned above, expected to increase. This may therefore lead to a shift these from carbon sinks to carbon sources. Although there still remain some uncertainties to if the increasing fire frequencies may be due to the changes in climate, caused by increasing CO₂ concentrations, or if it is natural variability of fire frequency (Pan et al., 2011., Brey Meyer, 1996).

Ecosystem shifts caused by changes in future climate may alter the distribution of carbon between the land-surface and the atmosphere. Warmer climate can lead to migration of the boreal forest from taiga regions into the tundra, thus, leading to an increasing carbon sink in this forest belt, since the larger biomass of trees can take up more carbon than the herbs and shrubs which currently grow in the tundra regions. On the other hand, an ecosystem shift from tropical forest to savannah would result in a carbon source out to the atmosphere (IPCC Fourth Assessment Report, 2007).

Finally, there are a number of uncertainties when it comes to the comparison between the amounts of carbon taken up in the two different forest biomes, mainly the fact that different authors have used different boundaries for the forest types, hence leading to difference in the total forest areas. Also, the estimation of the NEP values for IPCC (2001), Griffiths and Jarvis (2005), Shvidenko and Apps (2006), Malhi (2010) and Pan et al., (2011) may have been incorrect since they were only calculated through the information about the areas and the yearly carbon uptake provided by these authors, and not by direct EC measurements. Furthermore, the question of which of these forest biomes take up most of the carbon still remains uncertain, due to the great variation of total forest extent amongst the different researchers and also the total carbon that these forest take up. Although according to most recent studies (e.g. Pan et al., 2011, table 1 and 2), the tropical forest is the forest which accounts for most of the carbon uptake.

Conclusion

In conclusion, there are a lot of variations of the total extent of the boreal respectively the tropical forests amongst the different researchers and their studies. This leads great variations in the carbon uptake in the two different forest biomes. The factors which influences the total carbon stored by each forest are, as mentioned, total extent of the forests, their plant biomass and their soils. The boreal forest, which has lower species diversity than the tropical forest, still manages to store about the same level of carbon as the tropical forest. This is because the boreal forest stores about 60% of its carbon in the soil, due to the formation of permafrost. The tropical forest, on the other hand, stores most of its carbon in the plant biomass, which is about 56% of its total carbon storage.

The future climate caused by increasing levels of CO₂ in the atmosphere will mostly affect the boreal forest by increasing the frequency of natural disturbances, such as, fire and insect outbreaks. This is mainly due to the increasing levels of the global temperature. Natural disturbances such as fire and drought, caused by the changing climate, will also affect the tropical forest. The main factor affecting the ability for the tropical forest to store carbon seems to be anthropogenic disturbances, such as deforestation, which stand for most of the carbon losses by these forests.

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