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Estimation of eucalyptus forest plantations carbon sequestration potential in Uruguay with the CO2fix model

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Tiivistelmä/Referat – Abstract

Purpose of this thesis is to estimate the carbon sequestration potential in eucalyptus plantations in Uruguay. This study also aims to show how beneficial these plantations are for carbon sinks. The aim of this research is calculate total carbon balance in eucalyptus plantations and compare the results to degraded lands. This study is first-of-its-kind study in Uruguay, but not unique globally. The objective was to use a modeling approach to formulate the results.

The methodology of this study is based to the dynamic growth model (CO2fix V3.1). Model is developed to calculate and estimate forest carbon fluxes and stocks. In this study the model was utilized for estimating how much carbon is sequestered in eucalyptus plantations and soils. In this thesis the model was used to simulate eucalyptus forest plantations that stem from numerous studies and different data. Ad hoc Excel model was generated to form calculated results from the simulated data. A separate sensitivity analysis is also formulated to reveal a possible different outcome.

The framework is based on a stand-level inventory data of forestry plantations provided by the Ministry of Uruguay (MGAP) and companies. Also multiple scientific reports and previous studies were used as guidelines for simulations and results. The forest stand, yield, soil and weather data used for this study are from three different departments. There are over 700 000 hectares of different species of eucalyptus plantations in Uruguay.

The theoretical framework was tested computationally with eleven simulations. CO2fix was parameterized for fast-growing eucalyptus species used in different parts of Uruguay. The model gave outputs per hectare and then this result was scaled up to the national level. This study will also estimate how much grassland (Pampa) and former pasture land could sequester carbon. Situation prior to plantation is a baseline scenario and it is compared to the expected carbon sequestration of plantations. The model is also used to calculate the effect of changing rotation length on carbon stocks of forest ecosystem (forest vegetation and soil) and wood products.

The results of this study show that currently the 707,674 hectares of eucalyptus plantations in Uruguay have the potential to sequester 65 million tonnes of carbon and reduce 238 million tonnes of CO_2. The calculated carbon storage is 38 and simulated 25 million tonnes of C, products are deducted from the equation. During 22 years (1990–2012) the annual carbon sequestration benefit (afforestation-baseline) without products is 1 757 847 Mg C.

The results suggest that it is reasonable to establish eucalyptus plantations on degraded, grassland (Pampa) and abandoned pasture land. The implications of the results are that eucalyptus plantations in Uruguay actually enhance carbon sequestration, are carbon sinks and store more carbon than grassland and abandoned pasture land. Plantations have a vast sequestration potential and are important in mitigating of CO_2 emission and effects of the climate change. The findings endorse the significance of plantations to increase carbon sinks and this role will broaden in the future.

The most relevant findings of this study are that afforestation increases the soil carbon in 10-year rotation plantations by 34% (101.1>75.6) and in 12-year rotation 38% (104.4>75.6 Mg Cha^{-1}) in a 60-year simulation. The net (afforestation-baseline) average carbon stock benefit in the soil is 25.5 Mg C ha^{-1} in a 60-year simulation.

The (CO2Fix) model indicate that the total average carbon sequestration for eucalyptus plantations is 92.3 Mg Cha^{-1}. The average total carbon storage ranges from 25.8–138.5 Mg Cha^{-1} during a 60-year simulation. The simulations show that the net annual carbon storage in the living biomass is 29.1, 25.5 (soil) and 37.6 Mg C (products) on the average scenario. There is some fluctuation in the sequestration results in other 10 simulations.

Previous studies have showed that the average carbon stock for eucalyptus plantations varies from 30–60 Mg C ha^{-1}, when soil and products are deducted.

The capacity of forest ecosystems to sequester carbon in the long run could be even more strengthened if a rotation length increases. Extending rotation from 10 to 12 years increased the average soil carbon stock from 25.5 to 28.8 Mg C (by 13%) in 60 year simulation. The results also indicate that mean annual precipitation (MAP) alters the carbon sinks of the forest ecosystem.

There are some limitations in this study and they are clearly explained and analyzed. Hence, most of the results are estimations.

Ministry and companies need to prolong planting of trees and even intensify annual programs in order to achieve carbon sequestration targets. Further research is needed to get an estimate of the total forest ecosystem carbon storages and fluxes.

Avainsanat – Nyckelord – Keywords
CO2fix, Eucalyptus, Uruguay, forest plantations, forest simulation model, forest industry, subtropical forest, afforestation, CDM, Kyoto protocol, carbon accounting, carbon credits, climate change, greenhouse gases (GHG), soil organic carbon (SOC), mean annual precipitation (MAP).

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Tiivistelmä/Referat – Abstract

Opinnäytetyön tarkoituksena on arvioida hiilen sitomisen potentiaalia eukalyptusplantaaseilla Uruguayssa. Tutkimuksessa pyritään osoittamaan miten hyödyllisiä nämä metsät ovat hiilinieluina. Tämän tutkimuksen tavoitteena on laskea kaikkien eukalyptusplantaasien hiilitasapaino ja vertaa tuloksia ruohoalueisiin. Tämä tutkimus on ensimmäinen Uruguayssa toteutettu, mutta ei ainutlaatuinen maailmanlaajuisesti. Tulosten muodostamisessa käytetään mallintamista.

Tutkimus menetelmät perustuvat dynaamisen kasvun malliin. CO2fix V3.1-malli on kehitetty laskemaan ja arvioimaan metsien hiilivirtoja ja -varastoja. Tässä tutkimuksessa mallia käytettiin arvioitaessa, kuinka paljon eukalyptusviljelmät ja maaperän sitovat hiiltä. Tässä kirjoitelmassa mallia käytettiin simuloimaan eukalyptusplantaaseja. Simulaatiot pohjautuvat lukuisiin tutkimuksiin ja erilaisiin tulostietoihin. Tulosten analysointia varten luotiin tarkoitusta varten sovellettu Excel-malli tarjoamaan enemmän tuloksia simuloiduista tiedoista. Erillinen herkkyysanalyysi on myös muotoiltu paljastamaan mahdollisia poikkeavia tuloksia.
Teoreettinen viitekehys perustuu metsäplantaasien leimikkotason inventointitietoihin, jotka on hankittu Uruguayn ministeriöstä (MGAP) ja eri yrityksiltä. Useita tieteellisiä raportteja ja aiempia tutkimuksia on myös käytetty antamaan suuntaviivoja simulaatioille ja tuloksille. Tässä tutkimuksessa käytetyt metsän-, maaperän- sekä puun tuottavuuden tiedot ja sää informaatio ovat kolmesta eri maakunnasta. Teoreettinen viitekehys testattiin empiirisesti yhdentoista simulaation avulla. Uruguayssa on yhteensä yli 700 000 hehtaaria eri eukalyptuslajien viljelmiä. CO2fix parametrisoitiin näiden nopeasti kasvavien puille, joita on istutettu eri puolilla maata. Malli antaa arviota hehtaarille ja sitten tämä tulos yleistetään koko maan tasolle. Tutkimuksessa esitetään myös aluksi arvioita, kuinka paljon niityt (Pampa) ja entiset laidunmaat voivat sitoa hiiltä. Tilanne ennen metsää toimii vertailuna tuloksille. Lähtökohtaa verrataan plantaasien hiilen sidontaan. Mallia käytetään myös laskemaan metsän kiertoajan muutoksen vaikutukset metsäkekosysteemin (kasvillisuus ja maaperä) ja puutuotteiden hiilivarastoihin.

Tämän tutkimuksen tulokset osoittavat, että 707 674 hehtaaria eukalyptusmetsää on mahdollista sitoa 65 miljoonaa tonnia hiiltä ja vähentää 238 miljoonaa tonnia hiilidioksidia (CO2) Uruguayssa. Hiilivarastot ovat yhteensä 38 miljoonaa tonnia hiiltä, kun puutuotteet on vähennetty tuloksista. Vuotuinen hyöty (metsä-lähtötilanne) hiilensidonnasta on 1 757 847 mg C. Tulokset viittaavat siihen, että eukalyptusmetsiä on järkevää perustaa taantuneille ruohoalueille, niityille (Pampa) ja hylätyille laidunmaille. Istutukset sitovat enemmän hiiltä kuin ruohoalueet ja parantavat maaperän hiilivarastoja. Tulokset osoittavat, että eukalyptusviljelmät Uruguayssa todella parantavat, vahvistavat ja lisäävät hiilensidontaa, kun maankäytön muotoa vaihdetaan.
Tämän tutkimuksen olennaisimmat havainnot ovat, että metsitys lisää maaperän hiiltä 34 prosenttia (101.1 > 75.6) 10 vuoden kiertoajan aikana ja 12 vuoden aikana 38 % (104.4 > 75.6 Mg Cha^{-1}) 60 vuoden simuloinnin aikana. Keskimääräinen maaperän nettohiilivarasto (metsä-lähtötilanne) on 25.5 mg C ha^{-1} vuodessa.
CO2fix malli vahvisti, että keskimääräinen eukalyptusviljelmä sitoo vuoden aikana hiilidioksidia 92.3 mg Cha-1. Metsän keskimääräinen hiilivarasto vaihtelee välillä 25.8–138.5 mg Cha-1. Simulaatiot osoittavat, että elävän biomassan nettohiilivarasto on 29.1, maaperän 25.5 ja metsätuotteiden 37.6 mg C keskimääräisessä skenaariossa. 10 eri simulaation hiilensidontatuloksissa on olemassa jonkin verran vaihtelua. Metsäkekosysteemien hiilensidonnan kapasiteetti pitkällä aikavälillä voisi olla vieläkin parempi, jos metsän kiertoaikaa jatketaan. Metsän kasvattamisen jatkaminen 10 vuodesta 12-vuoteen lisää keskimääräisen maaperän hiilivarastoa 25.5 tonnista 28.8 tonniin (13 %) 60 vuoden simuloinnin aikana. Tulokset osoittavat myös, että keskimääräisen vuotuisen sademäärän vaihtelut muuttavat metsän ekosysteemien hiilinieluja.
Tuloksista tehdyt päätelmä ovat, että eukalyptusviljelmät Uruguayssa ovat suuria hiilinieluja ja sitovat enemmän hiiltä kuin ruohoalueet, niityt tai hylätyt laidunmaat. Plantaasit tarjoavat valtavia hiilen varastointi mahdollisuuksia sekä ovat tärkeitä ilmastonmuutoksen torjunnassa ja CO2-päästöjen lieventäjiä. Tulokset tukevat plantaasien tärkeyttä hiilinieluja lisäämisessä ja tämä rooli tulee vielä laajeneman tulevaisuudessa. Tässä tutkimuksessa on joitakin rajoituksia. Ne eritellään, sekä esitetään selkeästi ja analysoidaan tarvittaessa. Muutamien rajoitusten takia useimmat tulokset ovat suuntaa-antavia arvioita. Ministeriöiden ja yritysten pitää jatkaa plantaasien kasvattamista ja jopa tehostettava vuotuisia puiden istutusohjelmia, jotta asetetut hiilivarastojen tavoitteet voidaan saavuttaa. Lisätutkimuksia tarvitaan, jotta saadaan aikaiseksi vielä kattavammat sekä tarkemmat laskelmat eukalyptusplantaasien hiilivarastoista ja -virroista.

Avainsanat – Nyckelord – Keywords CO2fix, eukalyptus, Uruguay, metsäplantaasit, metsän simulointimalli, metsäteollisuus, subtrooppinen metsä, metsien uudistaminen, CDM, Kioton pöytäkirja, hiilen laskenta, hiilidioksidi, ilmastonmuutos, kasvihuonekaasut, maaperän orgaaninen hiili, keskimääräinen vuotuinen sademäärä.

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Foreword/ Acknowledgements

My mother was diagnosed with cancer in the same autumn as I got my enrollment letter to school. She beat it for a while – two years – and finally that gruesome and vigorous monstrosity caught up with her. Mother was too tired to carry on fighting until the end of my studies and passed away in August 2010. It was really painful and arduous autumn. Studies got left behind to some extent, but it was reasonable, taking into account the circumstances. I did not want to leave unfinished the practical training in the summer of 2010, since I was in the other side of the planet (Uruguay). Fortunately, after three months, I managed to saw her before she slept away. She was always very supportive in my studies. She cared a lot about people and everybody liked her–also in the workplace.

I would like to express my gratitude to my supervisor Markku Kanninen and Professor Lauri Valsta for their guidance. I would also like to express my great gratitude to MartJan Schelhaas. You have supported and guided me greatly during practical training and this study. My thanks go also to the University of Wageningen, the research institute Alterra and Trees4Future for making this interesting work possible.

My warmest thanks belong to my father. You have always encouraged me in my studies and motivated to graduate. You have been most inspiring mentor and idol to me. Finally, inordinate thanks to rest of the family for their irreplaceable and priceless support all these years.

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(Dedicated to my mother Birgitta)

‘Facts are stupid things’

– Misquotation by Ronal Reagan

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1. INTRODUCTION

Academic researchers are unanimous that the global climate is really changing more rapidly and to even worse conditions than previous studies has expected. It is clearly evident and has been proven by numerous studies that the climate is warming. This trend of global warming will continue over the next 30 years and beyond. The time span between 2000–2009 was the warmest in records going back to 1850, and 2010 was the warmest year on record. Some scientists argue that the observed warming could also simply be annual variation, but they are a small minority. Global warming is primarily due to the human activities. Effects to the climate are caused by greenhouse gas emissions (GHG) from rising use of fossil fuels, increased agriculture and land-use change. Climate scientists have predicted that extreme weather will occur more frequently as the CO_2 levels rise and the atmosphere continuously warms. According to the different reports, climate change has increased the frequency of heat waves and caused record high temperatures, heavy precipitation and floods in many regions in the past half century. This alteration has already been seen widely in recent years (Stern 2006; IPCC 2007, 2012, 2013; HadCRUT3 2013). Global warming is additionally increasing the deglaciation of glaciers and ice sheets (in Antarctica and Greenland). This process will result in an even greater sea-level rise and changes sea water temperature. Partial melting of the ice sheets could raise the sea-level by 4 to 6 meters or more (NOAA NCDC 2013; NASA GISS 2013; WMO 2013).

Carbon dioxide is stored in sinks in different parts of the world, in the seawater, soils, atmosphere and plant biomass. The ecosystem acts as a net carbon sink from the atmosphere when it accumulates carbon. This sequestration has a cooling effect on the global climate. The releasing of carbon has an opposite reaction to the atmosphere, causing the global climate to become warmer. Oceans store a large amount of carbon than any other pool. Forest ecosystems (trees and soil) constitute the largest terrestrial carbon pool and are likely to have a greater mitigation effect. Significant carbon stocks are stored in plantations in the tropical and temperate regions (Birdsey 1992; Clark 2002; Malhi et al. 2008; Reay et al. 2010).

The global importance of forests and forest plantations

The media have reported on the beleaguered Finnish forest sector over the past few years. Concurrently, forest companies have reported several investments in overseas tree plantations. Pulpwood plantations of eucalyptus and pine trees are booming in Uruguay, Brazil and China. Short-rotation tree plantations grow rapidly, give high yields and are a significant source of raw material for the industry. Fast-growing species yield at least 10 cubic meters per hectare, usually a mean annual increment is between 20 and 30 m3/ha or even more. Plantations make good financial sense, and the returns of investments on eucalyptus plantations are generous (Bauhus et al. 2010; Montes del Plata 2012; Stora Enso 2012).

Forest management has a necessary and prominent role in increasing the mitigation of carbon and alleviating climate change. Forest management practices include irrigation and the maintenance of water levels, and the selection of rotation cycles, tree species and soil types (Evans and Turnbull 2004). These actions in fast-growing plantations contribute to the net impact on carbon sequestration. Short-rotation tree plantations store carbon and also reduce greenhouse gas emissions. Carbon sequestration mitigates CO_2 emissions in the long term, and in this way contributes to reducing the effects of climate change. Intensively managed forest plantations grow faster and simultaneously produce more biomass than many natural forests. Due to this fast growth rate a plantation have better potential for carbon sequestration than a native forest. Plantations also alleviate the pressure on harvesting of natural forests (Evans and Turnbull 2004; Nabuurs et. al. 2007; IPCC 2007; Bauhus 2010; Kaul et al. 2010a,b).

This thesis focuses on intensively managed fast-growing eucalyptus tree plantations in Uruguay. Plantations are a common land-use form in different parts of the tropics and subtropics. Globally, this type of plantation was estimated to cover 10 million hectares in 2000, growing at a rate of 1 (Mha) each year. This 10 (Mha) represented about 10 per cent of the total plantation area in that era (Kanninen et al. 2010). Plantations have considerably expanded in twenty years. Forest plantations currently represent about 5% of the total forest area of 4033 million hectares, covering 201 Mha. Planted forests constitute about 7% (282 Mha). In 2010 there were about 200–264 Mha of different types of plantations in the world, and increasing at rate of 2.5–

4.5 Mha annually. There is some discrepancy in the data, because organizations report different results. Broadening of the definition from forest plantations to planted forest also increase the estimates. In 2001, plantations provided about 35% of the globally harvested wood. By 2020, they could supply about 44% or half of the global industrial round wood supply (IPCC 2007, 2012; FAO 2000; 2011).

There is about one million hectares of fast-growing plantations in different regions of Uruguay, including eucalyptus and pine species. Forest plantations in Uruguay are the case scenario of carbon dynamics (carbon stocks and fluxes). Most of the plantations in Uruguay are established on grassland and degraded land (Montes del Plata 2012). Nowadays, it is also common in other parts of the world to plant fast-growing trees on degraded lands (FAO 2005a, 2005b, 2005c; Lemma et al. 2007; Bauhus et al. 2010; Berthrong et al. 2012)

The aim and purpose of this study was to calculate and estimate carbon storage and fluxes of eucalyptus forest plantations. This thesis estimates with the CO2fix model the forest carbon sinks of these plantations. Study also analyzed how effectively grassland, degraded land and natural forest sequester carbon. The hypothesis is that natural forests, Pampa, agricultural or degraded lands sequester more carbon than fast-growing tree plantations. The purpose is to empirically overrule this assumption. Forest ecosystems sequester CO_2 more and for longer periods of time than many other land use forms. Converting agricultural and degraded land into plantations could increase the amount of carbon sequestered. The potential gain of carbon is calculated in this study as the difference between grassland (the baseline) and the sequestered carbon by a plantation.

Many studies have proved that eucalyptus plantations store more carbon than grassland and abandoned pasture land. It is assumed that plantations in Uruguay also have this property. Plantations will increase the amount of carbon sequestered and mitigate the effects of climate change. The model could also be used to compare different rotation lengths, choose the optimal rotation time that also has the largest carbon stock, and monitor variations in carbon stocks. It is possible that plantations in Uruguay store more carbon than are emissions to the atmosphere. Carbon sequestration and storage figures are important for the country, and can be used in different reports.

Forests are carbon stocks

Globally forest covers 31% of the total land area, and altogether about 4033 million hectares (Mha). Tropical forests comprise 44% (1623.6 Mha) and Boreal forests 34% (1254.6 Mha). The areas of planted forest constitute about 7% (264 Mha) of the total forest area. The total global forest carbon stock was 861 ± 66 Pg C (or Gt C or billion tonnes of C) in 2011. Of this 383, ± 30 Pg C (44%) was stored in the soil (to 1-meter depth), 363 ± 28 Pg C (42%) in live biomass (above and below ground), 73 ± 6 Pg C (8%) in deadwood, and 43 ± 3 Pg C (5%) in litter. Tropical forests store 471 ± 93 Pg C (55%), and 56% of carbon is stored in biomass and 32% in soil. The boreal forest sink is 272 ± 23 Pg C (32%), and only 20% is in biomass, while 60% is in the soil. Terrestrial ecosystems (forest and soil) also provide several other ecosystem services than carbon storage. Natural forests and forest plantations give shelter for countless animal species and space for recreation. For instance, forests filter water, control water runoff, protect the soil, cycle and store nutrients (Watson et al. 2000; FAO 2010; Pan et al. 2011; IEA 2013).

Different studies have estimated that the world's terrestrial ecosystems could mitigate from 1 to 2.3 gigatonnes (Gt) of carbon yearly (or Pg, petagrams), and the total global net forest sink was estimated to vary from 1.1 to 2.7 Gt (or billion metric tonnes) of carbon per year between 1995 and 2050. In other words, forests sequester about 2.4 Gt C (Pg C) or 8.7 Gt CO_2 equivalents ($GtCO_2eq$) per year from the atmosphere. This amount is about 24–28% of current annual fossil fuel emissions in the world. In the 1990s, the carbon stock only increased by 0.7 Pg C per year. Global carbon stocks in the terrestrial ecosystem (plants and soil) is about 2400 Gt (IPCC 2001; FAO 2010; Kaul et al. 2010a,b).

A recent study by Pan et al. (2011) estimated the terrestrial forest carbon uptake had to have been 4 ± 0.4 Pg C during 1990 to 2007 with a net sink of 1.1 ± 0.8 Pg C per year. This was equivalent to 50% of the fossil fuel carbon emissions in 2009 and about 13% of the total global CO_2 emissions. From this 4 Pg C y^{-1}, tropical forests account for 70% (2.9 Pg). During 17 years, net emissions from tropical deforestation doubled from 1.6 to 2.9 Pg C ± 0.5. Harris et al. (2012) estimated that tropical deforestation accounted about 10% of global emissions and 0.81 Gt C per year between 2000 and 2005. Tropical forest regrowth has created a carbon sink of 1.6 ±

0.5 Pg C yearly. Other studies have estimated that the annual storage is ranging from 2.0 to 3.4 Pg C. Terrestrial ecosystems (forest and soils) emit carbon to the atmosphere through deforestation, photosynthesis, the burning of forest lands and decomposition of wood. Deforestation is mainly caused by anthropogenic activities. Annual global land-use change, deforestation and forest degradation emissions totals about 1.6 Gt C or about 5.856 billion metric tonnes. This is approximately 16% of global carbon emissions. Some studies have estimated that greenhouse gas emissions could reach up to 20% and 6.3 GtCO_2eq. Deforestation globally in hectares of forests is around 13 million. The terrestrial ecosystem removes annually more CO_2 that is lost by deforestation. Eucalyptus plantations could mitigate deforestation and sequester carbon about 1–3 million tonnes of carbon annually (Birdsey 1992; IPCC 2007; FAO 2010; REDD 2013a, b).

Many carbon models have been developed and used to estimate forest carbon dynamics. These studies have quantified the carbon balance of forest ecosystems. Previous studies have showed that the average carbon stock for eucalyptus plantations varies from 30–60 Mg C ha^{-1}. The long-term (50–300 years) total carbon storage could be from 120 to 300 Mg C ha^{-1}. Studies have proved that carbon content in the soil varies from 70 to 120 Mg C ha^{-1} (Parton et al. 1987; Kurz et al. 1992; Kimmins et al. 1999; Price et al. 1999; Peng et al. 2002; Seely et al. 2002; Masera et al. 2003; Bruijn 2005; Nabuurs et al. 2007, 2008; Kaul et al. 2010 a, b; Berthrong et al. 2012). A few of these studies have tracked the carbon after harvesting in the form of wood products. Carbon stored in the products has varied from 5 to 80 Mg C ha^{-1} (Skog and Nicholson 1998; Liski et al. 2003; Masera et al. 2003; Skog 2008).

1.2 Purpose, aims and implementation of the study

1.2.1 Purpose and aims of the study

The purpose of this thesis is to calculate and estimate carbon sequestration and fluxes of eucalyptus forest plantations in Uruguay. The main research question is to evaluate full carbon cycle and total amount of carbon storage in forest plantations.

These estimates are compared to different land-use forms (Pampa, degraded and pasture land), and emissions produced by the county. It is assumed that eucalyptus store more carbon than abandoned pasture land and other grasslands. Establishing new plantations to grasslands, agricultural and degraded lands could enlarge carbon storage, and increase the amount of CO_2 sequestered. Afforestation and reforestation are efficient forest management practices in reducing emissions and alleviate the global climate change. Reducing deforestation is even more effective in carbon mitigation than afforestation in the short term. The conversion of forests to agricultural land could have more negative effects to greenhouse gas emission. Forest also prevents soil erosion and has wider potential in the aggregate to sequester, and act as a sink for carbon.

This thesis tries to clarify the meaning of carbon sequestration and storage, and how important they are. This study also aims to give calculations of the carbon stocks and fluxes to estimate a future role for plantations in carbon offsets, and potential opportunities for carbon trading. One incentive for this study was to show that plantations could increasingly store carbon and have positive climatic impacts. The results could also justify continuous use of plantations to produce raw material. These facts can be used in different reports published by the companies. The main motivation for this study was that this type of evaluations and calculations has never been conducted in the Uruguay.

The aims of this thesis are: (i) utilize the CO2fix model to simulate and estimate carbon sequestration of eucalyptus forest plantations in Uruguay, and (ii) calculate size of carbon stocks, pools and fluxes, and (iii) estimate benefits of a carbon sequestration.

The specific objectives:

To apply the CO2fix model to simulate eucalyptus plantations and to run the model in the carbon balance assessment based on published data. Important objective is also to employ the model to get estimates and results about total carbon storage of plantations. After that the results are also analyzed and discussion is formed.

1.2.2 Implementation of the study

This study has focus on quantitative approach rather than qualitative. Quantitative research refers to numerical data or a phenomenon that can be converted into numbers. In this thesis numerical data was collected and then information was studied using mathematically based methods (Vogt 2007).

The empirical objective of this study is to examine broad inventory Excel sheets, different published studies and use the data to formulate results with the CO2fix model. Data is collected empirically and then added to the model. Then these results are thoroughly analyzed and presented.

The empirical part of this study tries to answer these main research questions:

How much carbon do eucalyptus plantations sequester?

How much carbon is added to the soil on average in different simulations?

Do fast-growing tree plantations sequester more carbon than grassland?

How does a change in a forest rotation period affect to carbon storage?

How does tree productivity affect carbon storage?

What are the financial benefits of managing plantations for carbon storage?

How large are the carbon stocks and pools in eucalyptus forest plantations?

How important are the carbon pools for Uruguay?

How large are the CO_2 emissions in Uruguay, and how much of that is sequestered by plantations?

Are previous carbon sequestration calculations accurate and future estimates even achievable?

2. BACKGROUND

2.1 Uruguay (República Oriental del Uruguay)

Uruguay (Fig. 1) is located in the temperate zone on the East coast of the Atlantic Ocean (33° 00' S and 56° 00' W). An estimate population of Uruguay is 3.31 million people. Total area is 176220 sq km (68 039 sq miles) that is about half the size of the Finland (337030 sq km) or little smaller than Syria (185180 sq km) or the state of Washington (176617 sq km). Uruguay (Fig. 2) is the second smallest country in South America after Suriname (163270 km^2). Uruguay is an emerging market rather than a developed country. Uruguay's GDP was $53.55 billion and per capita $15.800 in 2012. GDP is about one third compared to Finland's corresponding figure $198.1 billion and per capita $36.500 (Uruguay XXI 2011; World statistics 2012).

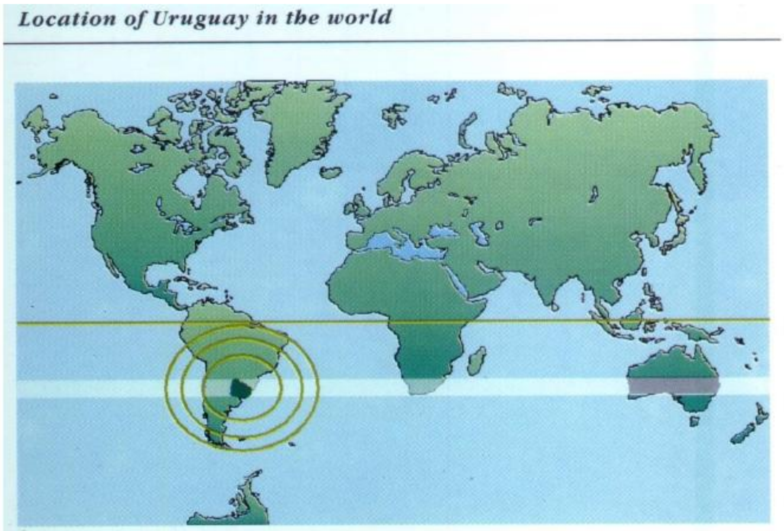

Figure 1. Location of Uruguay (PEFC Uruguay 2009).

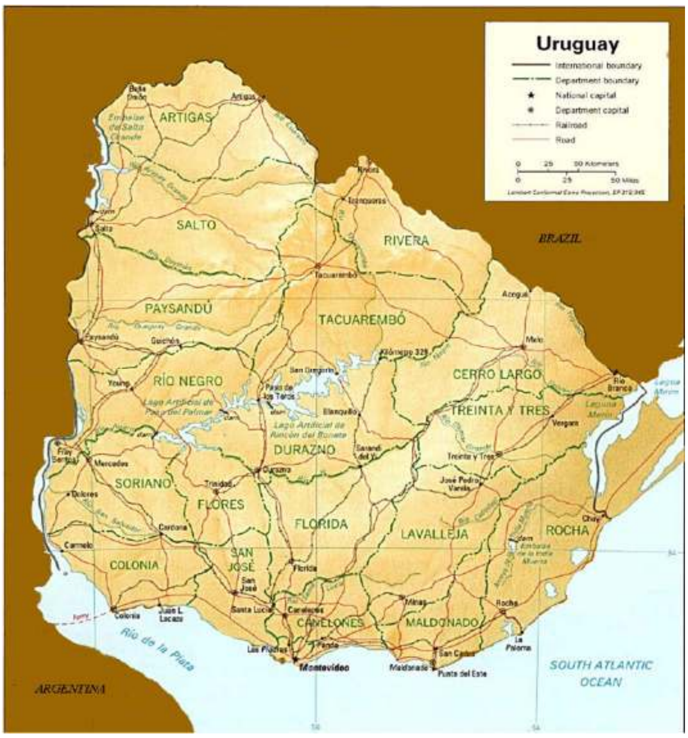

Figure 2. Map of the Oriental Republic of Uruguay (WFI 2013).

The landscape of Uruguay is low hills, plains (Pampa), degraded forests and fertile coastal lowland. The Pampas (The Uruguayan Savanna) prairie ecosystems are a common landscape in the Southern Cone of South America. Lowest elevation point is close to Atlantic Ocean 0 meters, and highest point is the Cerro Catedral 514 meters. Uruguay’s total area is 17.1 million hectares, and about 15.3 million hectares – close to 90% – of that is suitable for agriculture and livestock production. In 2009, the total forested area in Uruguay was 8% of the total land area, and total 1.37 million hectares. Nowadays, figure is close 10% (1.77 million hectares) and 99% privately owned. In 2011, planted forests represent 55% (972,395 ha) and native forests 45% (800,000 ha) of the Uruguay's total area. The total cover of native forest is about 4.5% of the territory. The area of forests could easily be extended to 12–15% (2,160,000 and 2,500,000 ha) of the total area of the country (Eucalyptus 2008; FAO 2013; Eucalyptus 2013; MGAP 2013; Mongabay 2013; WFI 2013).

The first eucalyptus plantations of Australian origin (*E. robusta* and *E. globulus*.) were introduced in 1853 and *Pinus pinaster* in 1890. At the beginning of the 1990's area of forest plantations were about 70 to 80 thousands hectares. In 2004, plantations covered about 413,000 hectares. In eight years (2012) this figure has over doubled close to 1 million hectares with 707,674 hectares of eucalyptus (Fig. 3). It has been estimated that potential area for forest plantations could increase to 3.3 million hectares. The planted areas are located in: Paysandú, Tacuarembó, Rivera, Rio Negro, Durazno, Maldonado, Rocha, Lavalleja, Florida, Soriano and Colonia (Fig. 2). The species that are suitable to the temperate climate conditions and usually planted are: *Eucalyptus globulus, E. grandis, E. maidenii and E. dunnii.* These species are selected based on forestry and commercial consideration. Most of the plantations are on the hands of foreign companies and investors. Native forest surface decreased between 1937 and 1980. Due to Uruguayan forestry policy and prohibition (Forest Act 1987) of harvesting of native forests, such tendency has been reversed. Area of native forests (Fig. 3) has increased from 667,000 ha (1970), to and 752.158 (2010) and to 800,000 ha in 2011 (World Bank 2009; Pou 2011; Grain 2013; MGAP FAO 2010; MGAP 2013; WRM 2013; WFI 2013).

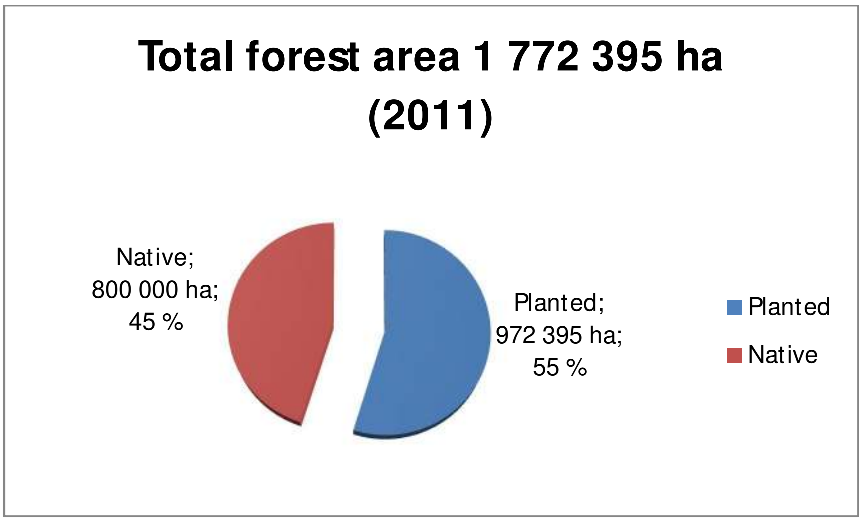

Figure 3. Breakdown of forested area (MGAP 2013).

The State of Uruguay provides an optimal and steady ground for forest plantation development. Year-round temperate climate and its sufficient annual rainfall provide constant growth rates for eucalyptus and pine plantations. Steady annual precipitation also adequately dispenses flows to the ground water. Cheap raw material, availability, and low production costs are the reasons why eucalyptus has become solid foundations to the forestry sector and related businesses in the Uruguay. Other advantages for foreign companies to invest are affordable land prices, tax incentives, currency exchange markets, transportation, educated labor, political reliability and legal framework. There are 97% of privately owned estates and the land registration system is transparent, well-organized and effective. Land prices in Uruguay are naturally increased from 500$ to over 3000$ in thirteen years (2000-2013), due to increased demand. Uruguay is the middle of lucrative South American markets and part of MERCOSUR (free trade area with Argentina, Brazil and Paraguay) (Eucalyptus 2008; Grain 2013; WRM 2013).

Forest sector is one of the most important to the country's economy. Forestry generates job positions 3 to 4 times more than cattle growing. Forestry sector also hires female labor (nurseries, laboratories, office), that is not so common in other rural activities. In 2010 forestry activities accounted for 3.5% Uruguay's GDP ($1.88 billion). Forestry account for 13% of the country's total exports and the value is over 1 billion dollars. In 2010 forestry sector had total number of employees 19000 (sawmills, panels, pulp, cardboard, chips). In 2006 the value of forest products exports was only 250 million dollars. UPM and Stora Enso mills could double the gross value of forest products exports by. Despite the importance of forestry Uruguay's economy rely on the agriculture and livestock sector. 25 percent of the land is used for agriculture, and 90 percent of the territory is grassland, mainly for cattle farming. Agriculture in general contributes to the GDP only 9% ($4.81 billion). Agricultural products and manufactured goods constitute about 65% and 85% of the value of the total exports, respectively. Third important direct contributor to GDP that Uruguay's economy depends to is the service sector, which includes trade, tourism, real estates, financial and insurance services (OECD 2004; Uruguay XXI 2011; Grain 2013; WRM 2013).

Uruguay has ratified Kyoto Protocol since 5 February 2001. Therefore it will voluntarily participate in greenhouse gases reduction through increasing carbon sinks, and decreasing carbon sources. Uruguay's forests store annually one million metric tonne of carbon (Mt C) or 0.001 gigatonne or 1 million megagrams (Mg) in living forest ecosystem (Mongabay 2013). Other estimate from World Bank (2009) is 1.6 million Mg C annually. In 2011, total forest carbon was 83 million metric tons (0.083 Gt C) and average carbon density 28 Mg C ha (Mongabay 2013), other estimate is about 90 Mg C (World Bank 2009). In 1998, the third national inventory of greenhouse gases calculated that annual CO_2 emissions were only 1.96 Mt

(0.00196 Gt CO2eq). Land use change and forestry mitigated carbon by 3.95 Mt. FCPF in Uruguay (2013) estimated in 2004 that total annual carbon sequestration (forests, grasslands and agricultural soils) is estimated to be about 0.01 Gt CO_2 (0.00273 Gt C), which is about 20% greater than total CO_2 emissions in the country. Annual CO_2 emissions in Uruguay were 8 300 000 metric tons (0.0083Gt) in 2010. Mitigation has increased enormously in 13 years due to planting of new forests. Fossil-fuel combustion is more than half of the sequestration capacity of forests. Mainly, because landscape is grassland and forest cover is only 10% of total land area. There is also pumped other greenhouse gases (GHG) into the atmosphere by the agriculture and waste sector, mainly methane (CH_4) and nitrous oxide (N_2O). Thus forest ecosystem sinks offset about 50% of the total emissions. In 2004 the forestry sector, agriculture and livestock were responsible for about 80% of total GHG emissions in Uruguay. It is estimated that plantation forests could sequester carbon 280 Mt CO_2 (76.44 Mt C or 0.076 Gt C) in 2030. This would mean 2.54 million tons of carbon annually, more than double compared to current estimates. This would also require about million hectares of new plantations. Sequestration could offset 23% of total GHG emissions in Uruguay, meaning that emissions would have to be four times bigger. There are definitely some discrepancies on previous carbon sequestration figures and they are scrutinized in the conclusions chapter (World Bank 2009; FCPF Uruguay 2013; Mongabay 2013).

All new plantations are established on grasslands, cleared agricultural lands (pasture) or degraded lands. At the same time, native forest area has increased. Deforestation is not a problem in Uruguay. Forest degradation problems are related to loss of biodiversity, landscape, invasive alien species and changes in rural land use. Other causes of forest degradation in recent years are illegal logging and pressure from intensive agriculture crops (FCPF Uruguay 2013; Mongabay 2013). Forest degradation problem in Uruguay needs to be addressed and implemented with different paths. Capacity building programs, training and strengthening of civil society sectors and government. Policies need to be updated, especially those, which are related to the degradation of native forests. Protecting forests will be beneficial to climate change mitigation, and can provide incentives to rural population (World Bank 2009; Berthrong et al. 2012; Montes del Plata 2012).

2.2 A cursory glance at assets of forestry companies

Several foreign forestry companies have invested to Uruguay in past 20 years. Most of them have acquired land for plantations and few have established pulp mills and sawmills.

Montes del Plata is the biggest player amidst the industry in Uruguay. MdP is a joint venture of Chilean Arauco and Swedish-Finnish Stora Enso. 250 people receive income from the company and over 1000 people manage the growing, harvesting and transportation of raw material for the pulp mills. The firm has currently about 180 000 hectares of different species of eucalyptus and pine forests. 77 per cent consists of *Eucalyptus globulus* (Blue Gum), *dunnii and grandis* plantations. 23% of planted trees are different pine species (*Pinus taeda, radiate, pinaster*). Plantations are established to the departments of Tacuarembó, Soriano, Rivera, Río Negro, Paysandú, Florida, Flores, Durazno and Colonia. Company has altogether 246 732 properties, of which 102 833 ha are native forests, conservation areas and other land. MdP has still 11 081 ha available for plantations and it plans to acquire even more estates in the future. Company also has its own seedling production, and at the moment produces about 20 million seedlings annually in Fray Bentos. Montes del Plata manage and supervise almost entire value chain. Only the transportation services are outsourced. Company is founded in 2009 when it bought the majority of prior owner Ence`s assets. 2011 MdP informed via press release that constructions of the pulp mill will start on beginning of 2012. Start-up should be in the first half of 2014. Capacity of the pulp mill is reported to be 1.3 million tonnes annually and consumes about 3–6 million m^3 yearly. Plant will rise alongside the Río de la Plata (River Plate, Silver River) in Punta Pereira (department of Colonia). The total investment of the pulp mill is estimated cost approximately EUR 1.4 billion. Project will also be funded by Finnish Export Credit (FEC), Finnvera, Swedish Export Credit (SEK), the Inter-American Development Bank (IDB) and different financing institutions. Finnish company Pöyry was selected after a bidding process (tendering) to manage and consult the project (World Bank 2009; Carrau 2010: Montes del Plata 2012; Stora Enso 2012).

The biggest competitor is Finnish UPM, which also manages over 150,000 hectares of plantations and has an outsourced 19 million annual seedling production.

Subsequent rivals are Weyerhaeuser and Global Forest Partners (GFP). They both own about 50 000–100 000 hectares of different plantations (World Bank 2009)

When a eucalyptus tree reaches its economically optimal rotation age, about 8–10 years, it will be harvested. No thinning is carried out during that time period. After felling, within six months, another tree will be planted in the site (replanting). The slash (harvest residue) from the short-rotation plantations is left to the site after harvest and not transported to energy production. The slash biomass will provide nutrition to plants and increase carbon stock. Company uses herbicides to alleviate competition, and fertilization for providing optimal growth environment to the next generation. All of this information are also included in the simulations and noticed in the results (Carrau 2010; Montes del Plata 2012; Stora Enso 2012).

3. THEORETICAL AND CONCEPTUAL BACKGROUND OF THE STUDY

3.1. Literature review. CO2fix studies and results

There have been published several studies about the carbon storage and sequestration in different plantations around the world, but there has never been conducted this type of study in Uruguay. Also in department of forest sciences at University of Helsinki, can be found numerous studies and master´s theses. To my knowledge, none of them are CO2fix studies or calculated CO_2 sequestration of eucalyptus plantations. So this thesis is first-of-its-kind study that estimates eucalyptus forest plantation carbon storages and fluxes in Uruguay.

In several other countries have been estimated carbon sequestration and fluxes of different forest plantations. Few studies have analyzed short-rotation hardwood trees such as eucalyptus. Most of the researches have estimated teak, sal or other long rotation plantations. The lack of previous studies about this specific issue has been on key motivation in undertaking the thesis.

Several studies suggest that different species sequester different amounts of carbon; hence a specie selection is significant in the plantations. Hardwood species grow faster than softwood (conifers) and aggregate bigger carbon storage. Consequently, eucalyptus plantations store more carbon per hectare. Many studies have showed that soil carbon is smaller in tropical sites than in the temperate and boreal conditions, because of continuous logging. Rapid rotation periods could deplete soil nutrients, alter soil chemistry and hydrology. Frequent harvests lead to lower values in living biomass and carbon storage. Longer rotations in plantations could improve soil organic carbon (SOC) pools. Several studies have proved that conversion of pasture land to short rotation plantations and afforestation projects will increase carbon storage. Trees sequester carbon much higher rates than grassland or degraded land (Alig et al. 1997; Adams et al. 1999; Stavins 1999; FAO 2003; Masera et al. 2003; Nabuurs et al. 2007, 2008; Kaul et al., 2010a, b; Sumawinata et al. 2011; Berthrong et al. 2012). In most of the studies Mg (megagram) is used to avoid the confusion. 1 Mg C ha^{-1} (megagrams per hectare) is same as 1 ton C ha^{-1}.

Berthrong et al. (2012) estimated that variation from 900–1100mm in mean annual precipitation (MAP) could change total soil carbon with about 60–100%. Precipitation alter significantly SOC pools in afforestation sites, up to 1012 kg $Cha^{-1}yr^{-1}$ in 60-year rotation.

Pérez-Cruzado et al. (2012) study estimated that the average annual SOC in pasture was 82.3 Mg Cha^{-1}. Afforestation changed average biomass C stock to 38.8–42 and soil to 82.9–92.0 Mg Cha^{-1}. Study also demonstrated that bioenergy and carbon sequestration are the best options for mitigating CO_2 emissions. Simulation period was set to 100 years for all alternatives.

Kaul et al. (2010a) indicated that in India the long-term total carbon storage varied between 101 to 156 Mg C ha^{-1}. Average carbon stocks for eucalyptus (*Eucalyptus tereticornis Sm.*) was 41 Mg ha^{-1}, poplar (*Populus deltoides Marsh*) was 55 Mg C ha^{-1}, teak (*Tectona grandis Linn. f.*) 50 Mg C ha^{-1} and sal forests (*Shorea robusta Gaertn. f.*) 82 Mg C ha^{-1}. The soil carbon pool was 75 for eucalyptus and 67 Mg C ha^{-1} for poplar. Carbon content in the soil increased at the end of the first rotation to 85 and 102 Mg C ha^{-1}. The long-term period was set to 300 years in this simulation. The CO2fix model calculated net annual carbon sequestration for eucalyptus and poplar plantations was 6 and 8 Mg $Cha^{-1}yr^{-1}$, respectively. Simulation included forest biomass and also wood products, such as logwood, pulpwood and slash. So these numbers are not directly comparable to this thesis, because only the pulpwood and slash is taken into account. Study also showed that the intensity of thinning changes the carbon stock of an ecosystem and products. The biomass, and at the same time, certainly carbon stocks in plantations are the highest, when no thinning is applied. Study proved that in the regime where no thinning was conducted had the highest carbon stock (143 Mg Cha^{-1}). Longer rotation periods also ensure bigger sequestration and growth of more valuable saw logs (Kaipainen et al. 2004; Kaul et al. 2010a & b).

Kaul et. al. (2010b) calculated with the model that in the long term (100 years) long rotation species stored 141 Mg Cha^{-1} and non-forest lands (106 Mg Cha^{-1}). This study also showed, undisputedly, that long rotation forests sequester more carbon than short-rotation plantations. However, a short rotation plantation gives higher yields (MAI values). Kaul et al. (2010a) also found out that the fluctuation carbon stock in products was less sensitive than of trees to the change in rotation period. Kaipainen et al. (2004) found a decrease in soil carbon stocks when rotation length was increased for some study cases in Europe using the CO2fix model, indicating that soil carbon must be measured.

Bruijn (2005) studied carbon dynamics (carbon-cycle) of The Malinau Research Forest (MRF) in Indonesia. The MRF covers 300,000 ha of total Borneo forests. Thesis estimated carbon stock from the Landsat 5 images on a landscape level. A simulation length was 30 years. The results gave an estimate that The Malinau Research Forests sequester carbon 19 100 000 Mg or 0.019 gigatons (Gt) CO_2 and this amount will decrease 4.4% in 30 years. Simulations proved that protecting 50,000 ha of primary forest and planting 5000 ha teak (*Tectona grandis*) plantation on swidden cultivation fields will lead to 1 Tg (0.001 Gt) carbon stock. Stand based simulations were calculated with CO2fix V3.1 and a simulation length was 50 years. Simulations showed that turning swidden cultivations to a teak plantations leads to a sink of 1.0 Tg C. The result showed also that it is not recommended to turn a primary forest to a palm oil plantation. Establishment would generate a net carbon source of 0.0011 gigatons.

Masera et al. (2003) showed that long-rotation of 300-years total carbon storage varies from 141 to 271 Mg C ha^{-1}. Carbon sequestration in soils varied from 63 to 168 Mg C ha^{-1}, in products 5 to 37 t C ha^{-1} and in living biomass 62 to 103 t C ha^{-1}. In that study long term simulation period was 300-year, mid-rotations 200-year and for short-rotations (agroforestry) 100-year period.

Nabuurs and Schelhaas (2002) used data from 16 different forest types in the Europe and calculated with the model that the total long-term (200 years) mean carbon stock varied from 52 to 196 and the average was 114 Mg Cha^{-1}. After this period of time the net carbon storage decreases. The net annual carbon sequestration average was 2.98 and the variation was from 1 to 4 Mg Cha^{-1} per year.

Ma and Wang (2010) studied the capacity of provincial forest ecosystems carbon sinks in Chinese mainland. Researchers estimated that carbon sequestration could be 8.4 gigatonnes (Gt C) of carbon between 2005 and 2050. In the same period of time original forest and new afforestation projects are capable of absorbing 4.9 and 3.5 Gt

C, respectively. In China, it has been realized after studies, that planting new forests (replanting) and concurrently carbon sinks, it is possible to reduce carbon emissions.

Pérez-Cruzado et al. (2012) calculated that use of slash for bioenergy led to a decrease in soil carbon. It is worth pointing out that net CO_2 emissions from use of bioenergy are zero if harvested forest is followed by replanting. It is also always better to substitute fossil fuels by biomass, and that way mitigate greenhouse gases permanently (Kaul et al. 2010b).

3.2. The carbon sequestration and storage results obtained with other methods

Many studies and publications have showed that plantations have greater carbon storage and tree aboveground biomass (AGB) distribution than natural forests. Tropical rain forests have higher potential of sequester carbon than temperate forests (Evans and Turnbull 2004; Terakunpisut et al., 2007; Baishya et. al., 2009).

Sumawinata et al. (2011) used airborne and spatial radar technology to estimate the impact of plantations on the reduction of greenhouse gas (GHG) emissions. Study concluded that pulpwood plantations are not carbon emitters, they act as carbon sinks. Results proved that afforestation and reforestation provide the foundation for the land to sustainably recover. Pulpwood plantations increased carbon absorption when established on a degraded peat land and are more effective managing CO_2 emissions. Research also showed that greenhouse gas emissions are not caused from the management of the plantations. Instead, emissions arise from the decomposition of fallen leaves, bark, needles and twigs (litter). Summary of the study was that degraded peat land must never be left unmanaged. Sustainable alternative for ecosystem services is to always establish a new forest.

Liski et al. (2011) calculated with Yasso07 model the climate impacts of forest biomass use for energy in Finland. The use of forest biomass for energy creates emissions and increases the amount of atmospheric carbon. As a result of this, also carbon stock decreases. The amount of carbon stored in the forest is reduced as much as collected biomass would store carbon, if it had been left to rot in the woods.

Collected forest biomass reduced Finland's stored carbon 2–6 million tonnes between 2005 and 2025. Use of forest biomass for energy or increased use of them could not reduce emissions from energy production very quickly.

Piao et al. (2005) developed a satellite-based model from a field data to estimate China's forest total biomass carbon stocks. During last two decades an averaged forest biomass of China was 5.79 Gt C (billion metric tonnes) and an average biomass density of 45.31 Mg C ha^{-1} or 45 metric tonnes. Fang et al. (2005) recorder slightly different estimates: total Pg C was 4.5- 4.6 and carbon density 42.6–43.5 Mg ha^{-1} during 1988–1993.

Xu et al. (2010) estimated that China's carbon stock could increase to 7.23 Pg C in 2050 and annually 0.14 Pg C, if forests grow naturally. Estimates were derived from national forest inventory data, published literature and field measurement data. In comparison to other forest carbon storage values in the Northern Hemisphere, storage in the Europe was 7.3 (1990), U.S 14 Pg (2010) and Canada 14.5 petagrams (Pg C) (1989). 1 petagram is 1 Gt (10^{15} grams, 10^{12} kilograms), so 14.5 petagrams is 14.5 billion metric tonnes (Fang et al. 2005; EPA 2012).

Fang et al. (2005) reviewed recent publications and used inventory data. Study was based on slightly inconsistent recent inventory data and field observations. Study showed that forest carbon stocks are in a range of 36–56 Mg and the area-weighted mean is 43.6 Mg C ha^{-1} in the middle and high latitudes in the Northern Hemisphere. Previous calculations of balancing the global carbon budget were 61–108 Mg Cha^{-1}. In North America forests had a weighted average carbon stock of 117.8 Mg C ha^{-1}, Central America had 179.2 Mg C ha^{-1}, and in South America comparable amount was 194.6 Mg C ha^{-1} per year (FAO 2006a).

Houghton et al. (2001) showed that total forest biomass varied from 39 (1983) to 93 (1997) Pg C (petagrams) in Brazil's Amazonian forests. The average biomass in the Amazonian forest region was 177 Mg C ha^{-1}. Mean biomass of deforested areas was 156 Mg C ha^{-1}. In this study the biomass consisted dead and material, belowground biomass, but did not include soil. So it is not directly comparable to this study, since also a soil biomass is also calculated. Houghton et al. (2001) study was conducted through field measurements, satellite-based data and modeling. Baccini et al. (2012) used multi-sensor satellite data and reported bigger total carbon amount storage of

228.7 Pg C in the tropical forests. Researchers estimated aboveground live woody vegetation carbon storage.

2.5 billion ha (6.2 billion acres) of tropical forests in Latin America, Africa, and Southeast Asia store 247 gigatonnes (247 billion metric tonnes) of carbon. Aboveground forest carbon is 193 Gt (193 billion metric tonnes of carbon) and belowground forest (roots) carbon is 54 Gt (54 billion metric tonnes) of CO_2 (Saatchi et al. 2011). Pan et al. (2011) estimated that 471 ± 93 Pg C (55%) is stored in tropical, 119 ± 6 Pg C (13%) in temperate and 272 ± 23 Pg C (32%) in boreal forests.

Kauppi (2003) showed that 300 Pg C (300 billion metric tonnes, or 300 gigatonnes) is more accurate estimate of the global forest C pool. Pan et al. (2011) estimated that the total forest carbon stock could be 860 Pg C. Pidwirny (2006) study showed 540 to 610 Gt C and FAO (2011) has estimated 638 Gt C forest sinks. Total amount of carbon dioxide 1500 to 1600 Pg C (petagrams= gigatonnes) is stored to a soil organic matter. The biggest sinks on the planet are oceans; they contribute 38 000–40 000 Pg C each year (Pidwirny 2006).

When these amounts are placed in some kind of perspective; respiration, both on land and in the sea emits about 173 Pg C (173 Gt) to the atmosphere each year. Though, currently photosynthesis removes more CO_2 from the atmosphere annually. Energy sectors carbon dioxide emissions are 6.5 Pg C each year and transport-related emissions are 6.63 (2007) Gt C. Transport-sector emissions could increase to over 9 Gt by 2030. Total global fossil fuel-related CO_2 emissions could increase to 28.8 Gt and 40 Gt by 2030 (Pidwirny 2006; IPCC 2007).

Usually from the media one could get the impression that aviation industry is the biggest polluter, but the facts prove otherwise. Outgoing, incoming and overflying aircraft emissions inside EU are only 162 million metric tons annually (0.162 Gt C). 180 million passenger cars produce 1 Pg C annually, and there are about 800 million cars in the world (4.4 Pg C emissions). In Finland transport related CO_2 Emissions in 2007 was per capita 2.6 tonnes ($2e^{-9}$ Pg) and total CO_2 emissions per capita 12.8 metric tonnes ($12.8e^{-9}$ Pg). The forestry sector contributes through deforestation annually about 5.86 Gt (billion metric tonnes) of CO_2 equivalent of global carbon emissions, which is almost equal to the global transport or energy sector (IPCC 2007; Reay et al. 2010; CDM 2012).

In 2012, total United States greenhouse gas emissions were 5600 Tg (5.6 GtCO_2eq) or 5.6 billion metric tonnes CO_2 equivalent. So U.S emissions are close to worldwide energy and transport sector emissions. Coal-fired power plants produces yearly about 1.5 billion tons (1.5 Gt) in U.S. 500 megawatt (MW) coal-burning power plant produces emissions annually 3 million tons (0.003 Gt) of CO_2. One ton of CO_2 is emitted by running the average coal power plant about 9 seconds or powering the average house for one month. Coal plants generates about 45–50% of the electricity in the U.S, and in 2010 the total nominal capacity was 338 GW (338 000 MW). In 2008 U.S carbon dioxide emissions per capita were 18 metric tonnes yearly, this makes about 5.4 billion metric tonnes (5.4 Gt) nationwide emissions. In Uruguay 2008 CO_2 emissions were 2.5 metric tonnes per capita that is 7.5 million tonnes (0.0075 gigatonne) yearly. In Finland amount was 10.6 metric tonnes and 56 million tonnes (0.056 Gt) per annum and total GHG emissions were 73 million tonnes or 0.073 gigatonnes (Gt). Finland's per capita emissions are same amount that the average coal power plant emits when running only 2 minutes or powering the average home for 2.5 month (EPA 2012; Greeneru 2012; CDIAC 2013; EIA 2013; IEA 2013).

Forestry activities and land-use in U.S. sequestered a net carbon of 784 million metric tonnes (Mt CO_2eq) or 0.784 Gt CO_2 equivalents annually. This is about 14 per cent of total cumulated greenhouse gas emissions in 2011. U.S. forestry sinks sequester every year about 784 times more carbon than in Uruguay (EPA 2012; Greeneru 2012; World Bank 2009). Woodbury et al. (2006) estimated that during 1990 to 2005 the U.S forest sector (forests and products) sequestered an average 162 Tg C $year^{-1}$ (0.162 Gt) or 0.583 Gt CO_2 equivalents. Forest sector's carbon sequestration offset 10% (0.56 Gt) of U.S. CO_2 emissions (5.6 Gt CO_2eq).

3.3 CONCEPTUAL BACKGROUND

3.3.1 Framework of the study

Framework and outline of this study is presented in the Figure 4. Framework presents the elements that affect to the study. Framework explains how the research questions in this study is evaluated; estimation of intensively managed eucalyptus forest plantations fluxes and carbon storage capacities in Uruguay with CO2fix model. Affecting phenomenon's are presented more thoroughly in the subsequent chapters.

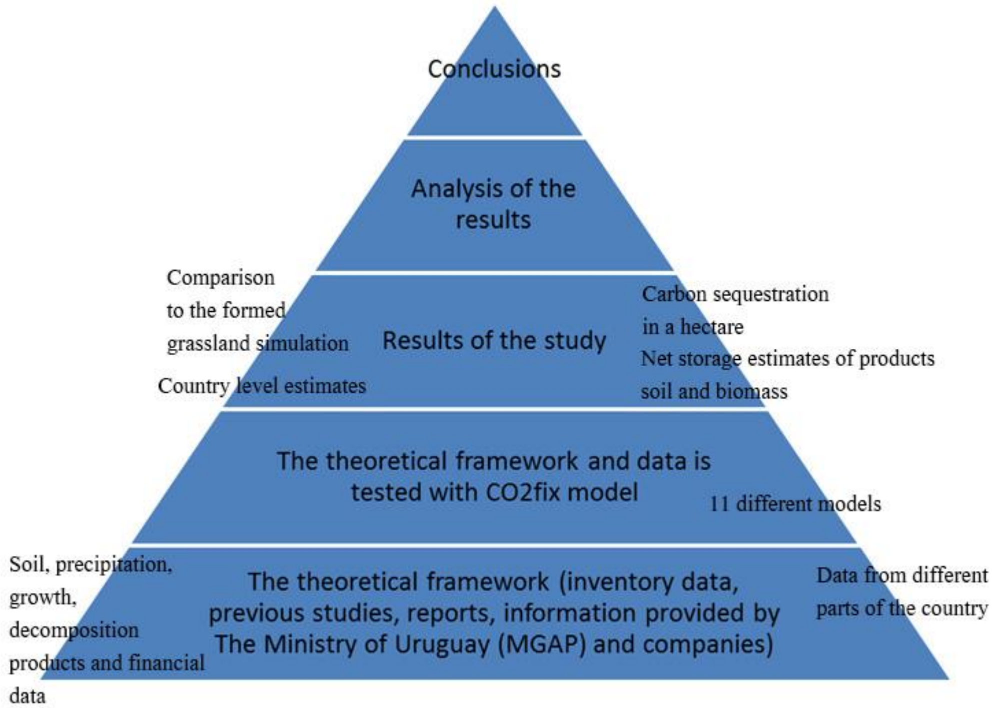

Figure 4. Framework of the study.

3.3.2 Carbon sequestration, storages, sinks and pools

Climate is warming and temperatures could be dramatically higher decades after due to climate change. Large part of this warming is caused by the greenhouse effect and different gases.

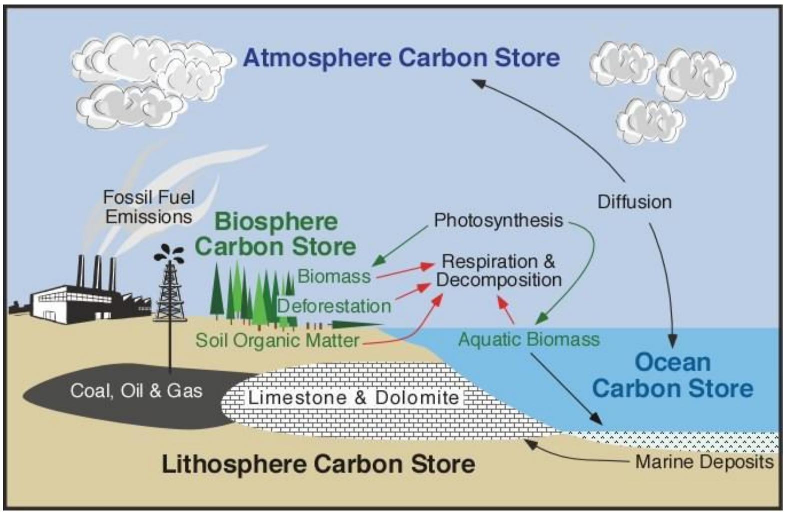

Figure 5. The carbon cycle. Carbon is stored in different parts of the world in the major sinks (Pidwirny 2006).

Human activities produce carbon dioxide (CO_2) into the Earth's atmosphere (Fig. 5). CO_2 is also the most important greenhouse gas (GHG). Currently in the world, total emissions from fossil fuels are over 8 Pg C per year (8 billion metric tonnes). In 2000, CO_2 equivalent emissions accounted 77% and methane (CH_4) 14% of CO_2 equivalent emissions (Karl and Trenberth 2003; Pidwirny 2006; Botzen et al. 2008). It is important to understand that these human-emitted (cumulative anthropogenic) carbon emissions from fossil fuels are a major driver of global warming. Carbon dioxide lingers 50–200 years in the atmosphere. Other primary greenhouse gases are nitrous oxide (N_2O), water vapour and ozone. Methane is a 21 times more influential, and N_2O is 310 times more significant greenhouse gas than CO_2. CO_2 has a long lifetime, but methane stays only a 10-years in the atmosphere (Stern 2006; Nasa 2010; Reay et al. 2010; EOE 2013; IPCC 2013).

Carbon dioxide is cycling (Fig. 6) – organic and inorganic forms – in the hydrosphere (oceans), terrestrial biosphere, atmosphere and lithosphere. Carbon is in continuous circle between different storages, such as the living organisms, soils (organic and rocks), oceans and atmosphere. These all are vast carbon fluxes and sinks (table 1) for sequestration of carbon. During 2002–2011 oceans sequestered on average about 2.7 Pg C (28% of total) and terrestrial biosphere 2.4 Pg C (27% of total) yearly. Soil organic carbon (SOC) is the largest terrestrial carbon pool. It can be either a source or sink of greenhouse gases (CO_2, CH_4 and N_2O). It depends how land is managed and used (Jonas et al. 1999; UNFCCC 1997; GCP 2012; EOE 2013).

Table 1. Estimated sinks of carbon on the Earth (Pidwirny 2006).

Sink	Amount in billions of metric tons or Gt
Atmosphere	578 (1700)–766 (1999)
Soil Organic Matter	1500 to 1600
Ocean	38 000 to 40 000
Marine Sediments and Sedimentary Rocks	66,000,000 to 100,000,000
Terrestrial Plants	540 to 610
Fossil Fuel Deposits	4000

Carbon is essential element to the Earth and can be found in different forms throughout the globe. Carbon sequestration means that CO_2 is removed from the atmosphere and transformed to C. Then carbon is stored in a sink for a long period of time. UNFCCC (1992) describes that storage is a: “Reservoir”, which "means a component or components of the climate system where a greenhouse gas or a precursor of a greenhouse gas is stored". Carbon sinks are "any process, activity or mechanism which removes a greenhouse gas, an aerosol or a precursor of a greenhouse gas from the atmosphere”. Sink is place of the storage of some material (UNFCCC 1992).

Terrestrial ecosystems (forest vegetation and soil) sequester and store carbon dioxide (CO_2) from the atmosphere. Forests, in every part of the world, have an enormous and important role in CO_2 fixation. Forests ability and capability is one way to slow the accumulation of CO_2 in the earth's atmosphere. Trees store CO_2 through photosynthesis and the rest is returned to the atmosphere by autotrophic respiration. Transformed carbon in the tree is afterwards distributed to the living plants, plant detritus (decomposing dead plants) and soil. (Pidwirny 2006; Bravo et al. 2008; Kaul et al. 2010a, b; EOE 2013).

Fast-growing species in tropical and temperate forest plantations could store carbon rapidly, mitigate the effects of deforestation, act as a carbon sink, and this way reduce greenhouse gas emissions. Due to these reasons plantations are an important factor of the global carbon cycle. The carbon sequestration and stocks varies from the tree species, site properties, spacing, climate conditions, size and age of forest etc. (Houghton et al. 1983; Birdsey 1992; Vucetich et al. 2000; Pussinen et al. 2002; Terakunpisut et al. 2007; Kaul et al. 2010a, b).

Forest soils – 44% of total – are one of the most important forest carbon stocks. Forest soil carbon stocks could be equal or even in some cases a double compared to forest vegetation. Carbon stocks at site include the crops and soils as a dynamic ecosystem (dead wood, litter and soil organic matter), above – and below – ground biomass, and their changes. The aboveground biomass consist of all woody stems, branches, and leaves of living trees, creepers, climbers, and epiphytes, herbaceous undergrowth, dead fallen trees and other coarse woody debris, as well as the litter layer. Standing aboveground woody biomass is the most easily measurable pool. The below-ground biomass is versatile mix of living and dead roots, the microbial community and soil mesofauna. And also various forms of soil humus (soil organic carbon, SOC), charcoal from fires and iron-humus pans. Forest products (timber, pulp products, non-timber forest products such as fruits and latex) and agricultural crops (food, fiber, forage, and biofuels) are also major pool of carbon and most of these are taken off the site. These pools have to be included to the estimate when calculating net carbon flux and storage in forest ecosystem. These all are included in biomass module (chapter 4.2.2) and are estimates of carbon pool (Noble et al. 2000; Watson et al. 2000; Woodbury et al. 2006; Mäkipää et al. 2012).

3.3.3 Deforestation, afforestation, mitigation and adaptation

Close to 27 per cent of the planet's land area is covered by forests. The area of global forests is 4 billion hectares (3 952 million ha or 40 million square kilometers). About 20% (31 Mha) are protective plantations. The global forest plantations, which consist of exotic monocultures, covered about 150 million hectares (Mha) in year 2006 and 200 Mha worldwide in 2011. These areas are about 5% of the global forests. Planted forests account for 7%, which is an entirely broader concept, covered about 260 million hectares (Mha). Planted forests are also established by seeding or planting. Planted forests are semi-natural forests and consist of native or introduced species. In 1980 there was only 18 Mha, in 1990 100 Mha and 1995 124 Mha plantations in the world. In 2007, global annual planting rate was 4.5 million ha. Asia and South America accounted for 89 percent (FAO 2000, 2006c, 2010, 2011; Fang et al. 2007; Nabuurs et al. 2007).

Deforestation means cutting, clearance or clearing of indigenous forests and woodlands. Then land is subsequently converted to another land-use form. Forests are being cleared for livelihoods, farms, profit, pastures, survival or urban use. Deforestation does not mean cutting down of industrial forests such as plantations. Deforestation leads to a decrease in the world's stored carbon. Anthropogenic degradation of the forests also increases soil erosion and loss of soil nutrients (IPCC 2007; FAO 2011).

Afforestation means converting other land-use forms to forests, such as developed, degraded or abandoned agricultural land. Forests sequester more CO^2 and for longer periods of time. Fast-growing trees species are an efficient method of replanting degraded lands. Reforestation is replanting of trees on previous forestland where trees has been in the last 50 years, but then converted to other land-use form and maintaining areas as forest. Forest mitigation activities include developing new forests and avoiding deforestation. New forests also provide wood fuels, which could substitute fossil fuels. These measures will reduce carbon emissions, enhance the sequestration rate and mitigate climate change. Reducing deforestation produces better carbon mitigation benefits than afforestation in the short term. Forest plantations are afforestation and reforestation, they are considered for mitigation of greenhouse gas emissions. The global afforestation and reforestation activities could sequester carbon between 1.1 and 1.6 Pg C (1.1–1.6 million Gt C) annually. “Reduced Emissions from Deforestation and forest Degradation” (REDD) is a mechanism to aid developing countries to increase the carbon stored in forests, reduce emissions and get financial subsidies for replanting and protection. With the REDD program it is possible to create a financial aid and be rewarded for the carbon stored in forests. When a forest is harnessed to grow carbon pools there is same time an opportunity forgone, pulp or saw wood. This creates an opportunity cost between profits from logging, fuel wood and pasture sites or conservation. Adaptation is adapting to climate change and there is wide array of options in different sectors (transportation, industry, agriculture etc.). Adaptation forestry is combination of management of forests, soil, land, water and planting. Improvement of tree species increase biomass productivity and carbon sequestration (IPCC 2001, 2007; Kaul et al. 2010a; REDD 2013a, b).

Deforestation – mainly caused by anthropogenic activities – is one of the largest contributors to climate change. Forest soils are also a large storage of carbon and deforestation releases carbon from this pool. These emissions will significantly increase the concentration of greenhouse gases in the atmosphere. Avoiding deforestation is essential to mitigate additional emissions of CO_2 in the atmosphere. About 300–800 Mg CO_2 ha emissions can be prevented through avoided deforestation. Forest ecosystems sequester CO_2 more and for longer periods of time than many other land uses. Establishing new plantations to agricultural and degraded lands can increase the amount of carbon sequestered. In other words, afforestation is an effective convention in reducing emissions and mitigates the global climate change. Avoided deforestation and forest degradation could also control erosion, conserve water resources, prevent flooding and reduce run-off. The undesirable side of afforestation is that intensively managed forests to grasslands may decrease water flow into rivers and other ecosystems. The positive effects of afforestation will off-set negative sides and costs (FAO 2011; IPCC 2001, 2007, 2011; Kanninen et al. 2010; Berthrong et al. 2012; EOE 2013; NRS 2013).

United Nations Food and Agriculture Organization (FAO) estimated in 2005 that forest area continues to decrease every year about 13 million hectares and 6 million of that are classified as primary or old growth forests (FAO 2006a). This rate of deforestation has recently been slowing. Regrowth figure is about 2.8 million hectares per year, so the net forest loss is 10 million hectares. Deforestation, forest degradation, and land-use change causes almost one fifth of global CO_2 emissions (6 Gt CO_2eq) (IPCC 2007; Kanninen et al. 2010; Pan et al. 2011).

Climate change has the greatest effect to the poorest people in the world. People living below the poverty threshold ($1 a day) have increasing burdens and often hardest hit by weather catastrophes, desertification, deforestation and rising sea levels. It is tragically ironic that people living in the developing countries have contributed the least to the problem of global warming. But they do have a irrefutable role in deforestation and in that way to rising CO_2 levels (FAO 2013).

In some developing countries climate change has in recent years worsened food security, contributed to the spread of diseases, and reduced the availability of fresh water and water for the plants. Adaptation to climate change and reducing emissions requires significant resources and help from the developed countries. So it is place for intervention from the international community and provides some possibilities to the most vulnerable countries. The Adaptation fund and FCPF cooperation are ways to at least reduce to some extent emissions from deforestation and forest degradation (IPCC 2007, 2012).

The impacts of deforestation (FAO 2013; Pou 2011):

- Negative effect to the carbon and water cycle (increased GHG emissions),
- drought (poor soils do not support agriculture)
- extinction of species
- desertification
- reduced biodiversity
- degradation of livelihoods (people are often forced to move)

3.3.4 Global carbon-dioxide (CO_2) emissions

Carbon dioxide (CO_2) is a naturally occurring gas and also released into the atmosphere by burning of the fossil fuels, land-use changes, other industrial processes and other human activities. During the last 800 000 years CO_2 levels have been between 180 ppm and 280 ppm. In 18th century the global average was about 280 ppm and figures have climbed an accelerating rate in recent decades. Current daily mean concentration of CO_2 in the atmosphere are close to 390 parts per million (ppm). Considered safety limit is 350 ppm, last time the CO_2 levels were that low was in early 1988. Carbon levels transcended to the limit of 400 parts per million (ppm) in May 2013, that was the first time in the records history since 1958 (CDIAC 2013; NOAA NCDC 2013).

Global carbon dioxide emissions reached of 8.63 million metric tons of carbon or 31.6 gigatonnes (billion metric tonnes) of carbon dioxide equivalents (Gt CO_2eq) in 2012. This is more CO_2 that fossil-fuel combustion has emitted into our atmosphere than any time in human history. If nothing is done then the global emissions will be at 58 Gt (billion metric tonnes) by 2020. From 2010 levels the global CO_2 emissions increased 3.2% (1.0 Gt) and China made the largest contribution with 0.7 Gt CO2eq (720 million tonnes). China's total carbon dioxide emissions were 8.72 Gt CO_2eq (billion metric tonnes) in 2011. U.S. CO_2 emissions in 2011 were 5.6 billion metric tonnes CO_2eq (5.6 Gt). Finland's and Uruguay's comparable figures were 54.1 (0.0541 Gt) and 8.3 (0.0083 Gt) million metric tonnes CO_2eq. China, USA, Finland and Uruguay per capita fossil-fuel CO_2 emissions in 2010 are 1.68, 4.71, 3.14 and 0.54 metric tons of carbon, respectively (IPCC 2007; EPA 2012; CDIAC 2013; EIA 2013; IEA 2013).

Deforestation, forest degradation, and land-use change are man-made disturbances to the earth's climate. This anthropogenic degradation of the environment contributed 18.54% of total carbon emissions in 2012. It is 1.6 billion metric tonnes of carbon or 5.86 Gt CO_2 equivalents. In 2007, emissions were 17% (5.0 Gt) from 29.7, and in 2004, 17% (4.6 Gt) from total 27.1 Gt CO_2eq (Kanninen et al. 2010; EIA 2013; EOE 2013). Pan et al. (2011) estimated that tropical land-use change emissions were 1.3 Pg C year^{-1} (Gt C) or 4.7 billion tonnes CO_2 equivalent (Gt CO_2eq). Deforestation emissions contributed 2.9 Gt minus tropical carbon sink 1.6 Gt C year $^{-1}$.

3.3.4 Kyoto Protocol

Annex 1 countries include all the OECD countries and economies in transition. Other countries are referred to as Non-Annex I countries. Annex I countries has promised to lower greenhouse gas (GHG) emission levels to their 1990 status by the year 2000. This goal can be obtained individually or jointly. Kyoto obligate actions only from 30 industrialized countries. International climate agreement covers the emissions of a mere 15 per cent. Russia, Japan, Canada and New Zealand didn't agree for a second term (2013–2020) of Kyoto. The United States have never even joined to the Protocol (UNFCCC 1992; Bauhus et al. 2010)

38 developed nations out of 191 countries have agreed to cut carbon emission by 5.2% of 1990 levels between and 2008–2012. 191 states have signed and ratified the protocol, but only these 38 Annex I countries have committed to reduce four (carbon dioxide CO_2, nitrous oxide N_2O, methane CH_4, sulphur hexafluoride SF_6) greenhouse gases (GHG). Other two gases that are reported in the United Nations Framework Convention on Climate Change (UNFCCC) are hydrofluorocarbons (HFCs) and perfluorocarbons (PFCs). Uruguay is Part of UNFCCC since 1994 November. The Kyoto 2 protocol allows some of these emission cuts compensated through land-use change projects, which aim to sequester atmospheric carbon. Some of these projects can be part of Clean Development Mechanism (CDM) projects and get economic benefits through carbon trade. In developing nations of these 38 participants land-use change can affect the world’s terrestrial carbon stock (UNFCCC 1997; Nabuurs et al. 2000; Bruijn 2005).

3.3.5 CDM other carbon credit mechanisms

Three market-based mechanisms included in the protocol to help countries meet their emission reductions: The Clean Development Mechanism (CDM), Emissions Trading (cap and trade) and Joint Implementation (JI). These mechanisms promote Annex I of UNFCCC (1997) countries to reduce the costs of meeting carbon emission targets. CDM is the second-largest carbon trading scheme that operates in the world. The largest is European emission trading system (EU ETS). The EU ETS issues EU allowances (EUAs) and they covers about 60% of the total volume of carbon credits, and 80% of the value of credits traded worldwide. The main goal of the EU ETS is reduce industrial greenhouse gas emissions cost-effectively. Factories have a limit of the total amount of emissions. Companies receive or have to buy emission allowances or international credits from different projects (CDM 2012; EU ETS 2013).

One important factor of the Clean Development Mechanism is that it aims to more sustainable development in developing countries. CDM is for countries that aren't listed in Annex I and the main idea is emission reduction. The emission-reduction projects in developing countries can earn tradable certified emission reduction (CER) credits, which each are equivalent to one tonne of CO_2. Industrialized countries could buy and trade these CERs and compensate emissions and meet their Kyoto Protocol reduction limitation targets. The CDM is a project-based mechanism. It is recommended to initiate projects that reduce emissions of production. Other approach to create emission cuts is through afforestation and reforestation projects. Reductions, which are created with carbon capture and storage, are subtracted by a "baseline" of emissions without the CDM project. With the CDM projects in developing countries industrialized countries and companies could achieve credits and meet the Kyoto Protocol emission reduction targets. Projects need to establish “additionality” and be measurable, and create long-term emission reductions. "Additionality” is a lever to ensure emissions reduction results are real and increase the carbon stocks. Reduction has to be prominent, and proved that would have occurred without the project. Additionality ensures that credits ate not issued to "freeriders". A company also have to create a baseline where the recent and future emissions can be compared. 4500 organizations and 161 countries are involved. Currently, in the South America there are 422 on-going CDM projects in the pipeline and number of all projects in the world is close to 9000. In 50 countries projects have earned certified emission reduction (CER) credits. Several projects registered under the Clean Development Mechanism use fast-growing trees species. Forest plantations provide opportunity to achieve maximum carbon sequestration and achieve credits

(UNFCCC 1992; 1997; 2013; Klepper and Peterson 2004; Klepper 2010; UNEP 2010; CDM 2012).

In 2010, CDM projects between seller from the developing and a buyer from an industrialized country contracted 463 Mt CO_2 (0.463 Pg) of emissions. CDM projects have managed to offset totally 1 billion metric tonnes (1 Pg) of CO_2 equivalents since the start in 2004. 1 billion megagrams is more than emissions that Germany (810 million tons) or 180 million passenger cars produce annually. The UNEP Risoe center (2010) that is responsible for the book keeping of CDM projects have estimated that the overall amount of CDM projects could increase to 7.9 billion metric tonnes CO_2 by 2020. Annex I and Annex B countries have committed to reduce emissions roughly about 15 billion metric tonnes (15 Pg) of CO_2. About one third of this reduction amount could be supplied by CDM credits (Klepper and Peterson 2004, 2010; UNEP 2010; CDM 2012).

In 2003 Uruguay started negotiations and assessment of potential CDM projects. There were several potential projects also in agriculture, forestry and forestry for wood industry. In 2009, there were still zero registered CDM projects in agriculture or forestry. Since 2005, UPM has used CDM carbon finance and generated profits through selling electricity to the power grid. In 2010 June, started first afforestation project in Uruguay. Plantation was established on degraded grazing land in Cerro Largo. The project area is total of 820 ha and planted trees are eucalyptus grandis and dunnii. Rotation period in plantations is 30 year and emission reduction 21.957 metric tonnes CO_2eq annually (World Bank 2009; CDM 2010).

Klepper (2010) showed that it is not possible to exactly demonstrate that CDM projects have actually reduced global emissions. Hagem and Holtsmark (2009) criticised the CDM that participants from developed world countries does not have to take on binding agreements to reduce emissions. They just have to buy emissions rights from developing countries. Hence, it could be an obstacle to a global climate agreement.

3.3.6 Ecosystem services

"Ecosystem services are the benefits people obtain from ecosystems" (MA 2005). Forests and also plantations provide several other ecosystem services than carbon storage. These services are divided into four (Fig. 6) categories: regulating, provisioning, supporting and cultural. These all are essential to the survival of human beings. Regulating services contribute to the control of climate (carbon sequestration), pollination of plants, diseases, floods, drought and waste. Forests also affect to purification of water and water quality. Forests provide raw material, firewood, food, medicines, fodder, cosmetics and fibers (provisioning services or ecosystem goods). Proximately 1 billion people depend on forest goods. Cultural services include recreational use and aesthetic, heritage, religious value and spiritual benefits. Fourth category is necessary for the production of others, supporting services. Such as photosynthesis, primary production, nutrient cycling, soil formation and biodiversity (MA 2005).

Intensively managed forest plantations provide also other goods and services, such as renewable energy, non-wood forest goods and offsetting logging pressure on natural forests. Forests also affect to purification of water and water quality in general. Plantations also create employment and development to the communities. Use of one ecosystem good or service will hinder, influence and depend on others. In plantations, timber production will affect the availability of other services. So there is some trade-offs. Ecosystems have three types of values: economical, ecological and socio-cultural. Should reviewed and evaluated separately but they are always linked together. Total economic value (TEV) is useful for quantifying the value of ecosystems. TEV consist use values and non-use values. Almost all of the values can be quantified in monetary terms, although, supporting services are difficult to measure. There are several methods for evaluating, such as survey-based valuation, direct market valuation and indirect market valuation. Plantation forests will increase ecological values (naturalness, diversity, rarity etc.) if planted on former agricultural land and decrease if native forest is cleared. Social values (heritage, spiritual, cultural diversity, identity etc.) could decrease or be lost when a native forest is replaced by a plantation (MA 2005; Bauhus et al. 2010).

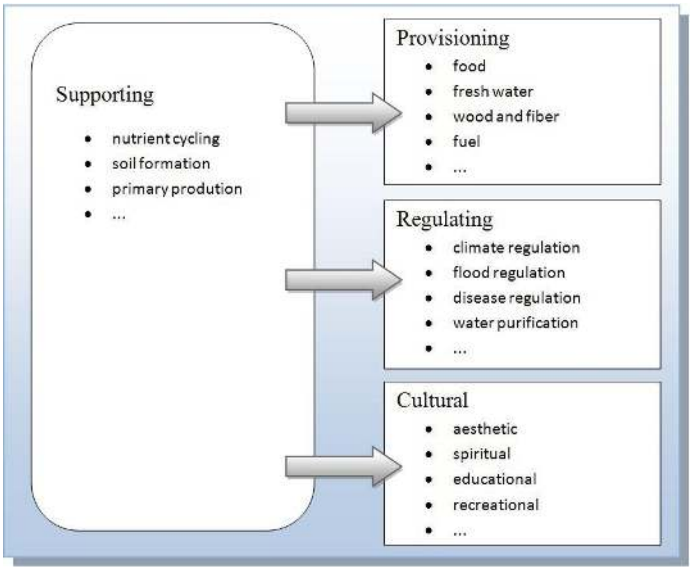

Figure 6. Ecosystem services (MA 2005).

3.3.7 External benefits and cost, environmental externalities

A positive externality is a benefit that affects an entity who did not participate in production of that benefit. Producer of externality does not get the full benefit, is less than the benefit to society. Sequestration of carbon is beneficial for every citizen in the globe, but the firm or individual does not get full compensation of providing this positive externality. Carbon storages and other ecosystem services are uncompensated environmental effects of production. The producer could however monetize the benefit with different carbon credits (Varian 2010).

Positive externalities should be encouraged and negative discouraged. Governments should implement more policies that decrease GHG emissions. Different parties should also provide more grants, subsidies to producers and promote ways to storage carbon. These actions – among others – will reduce cost of production and encourage more supply. Subsidies and lower production cost will reduce the market price paid by consumers. Hence, storage of carbon and decreasing fluxes becomes more viable options (Varian 2010).

Companies' production around the world generates emissions of GHG (greenhouse gas), which are a negative externality – also called "external cost". The Kyoto Protocol is designed to tackle the emission of the greenhouse gases. Despite the efforts emissions are still a negative externality. It is scientifically proven fact by

Intergovernmental Panel on Climate Change (IPCC 2007) that these emissions impact the world climate negatively. The Climate change is a negative externality and its mitigation would ease in pursuit to remain the world viable. Externalities could lead to inefficiency when companies do not equalize marginal costs and benefits. Mitigation of global warming would correct this externality. In order to achieve the true cost and benefits, the economic equilibrium, GHG emissions have to be internalized by some instrument (cap-and-trade permits, Pigouvian taxes or direct regulation). Eucalyptus plantations mitigate GHGs (CO_2) and that way equalizing marginal costs and benefits. Forest companies also reduce production-related emissions through intensive recycling and usually producing the necessary electricity (Stern et al. 2006; Rezai et al. 2011).

4. METHODS AND MATERIAL OF THE STUDY

4.1 CO2fix V3.1

Previous versions of the model have been in service throughout the world and the two earlier versions have over 2000 users. It has been widely applied in different types of forest ecosystems. It was programmed with C++ and for the CASFOR (Carbon sequestration in afforestation and sustainable forest management) project. The new models CO2fix V 3.1 and 3.2 were programmed for CASFOR II project. The CO2fix model is available from the web at http://www.efi.int/projects/casfor. It is free version and includes examples and case studies.

The model (Fig. 7) calculates the carbon storage and fluxes (carbon dynamics) of the forest ecosystem (trees, soil and products) at the stand level. In figure 8 boxes represent stocks and arrows are produced fluxes in a forest.

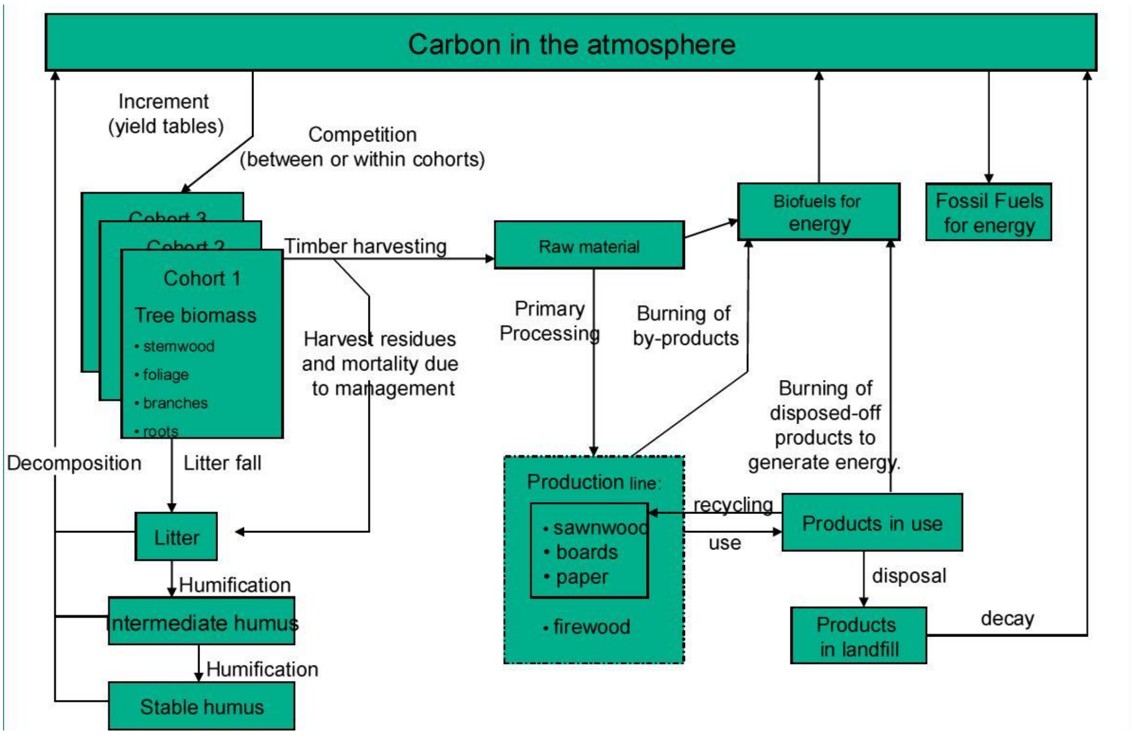

Figure 7. Carbon fluxes and stocks in the CO2fix model (Masera et al. 2003; Schelhaas et al. 2004).

The CO2fix V3.1 model calculates the carbon stocks and fluxes (carbon balance) of forest ecosystem. The multi-cohort model converts different ecosystem data to annual carbon stocks and fluxes (carbon dynamics). The program quantifies fluxes in the soil organic matter, the forest biomass and the wood products chain. These data is more profoundly described in the module chapters. The model is divided to six modules (Fig. 8): soil carbon, biomass, products, bioenergy, carbon and financial accounting. Model calculates changes in carbon stocks and gives results of carbon sequestration over time and at the hectare scale. Usually time period is one year. These numbers are derived from inventory data and more specifically, from current annual increment figures (CAI). Current annual increment figures are well documented and known in different sites in the country. This approach is also called a full carbon accounting approach. The term "full carbon accounting" means accounting of stock changes in all carbon pools (e.g., forest products) in a given time period and set of landscape. It is not possible to calculate photosynthesis and respiration rates with the model. The model is really versatile and can be used as a basis for many different cases: afforestation projects, agroforestry systems, and selective logging systems. Therefore it has been proved applicable also to temperate and tropical conditions. Fire and storm damages can also be simulated in the model. In this study it is used to modelling carbon sequestration and fluxes of tree plantations. The model was also used to estimate total carbon balance of alternative ecosystems; both even and uneven-aged natural forest and grassland (Noble et al. 2000; Nabuurs & Schelhaas 2002; Masera et al. 2003; Schelhaas et al. 2004; Groen et al. 2006).

The CO2fix carbon accounting module calculates only CO_2 and does not take into account leakage and greenhouse gas emissions. In the module it is possible to get an estimate of the amount of carbon credits that can be generated. Different types of crediting systems give background support for the calculation of the project (The stock change method for other projects, tCERs and lCERs for CDM-AR projects). In this study stock change approach is used to get an estimate (Schelhaas et al. 2004).

In this study the model is used to eleven individual cases: Eucalyptus plantations, grassland (Pampa)/ degraded land and future estimates (2050). The model was also used to analyse how do different rotation lengths and parameters, and tree productivity (MAI) effects to carbon pools. More detailed version of the model and the parameters of the modules can be found on the articles (Nabuurs and Mohren 1993; Masera et al. 2003; Schelhaas et al. 2004).

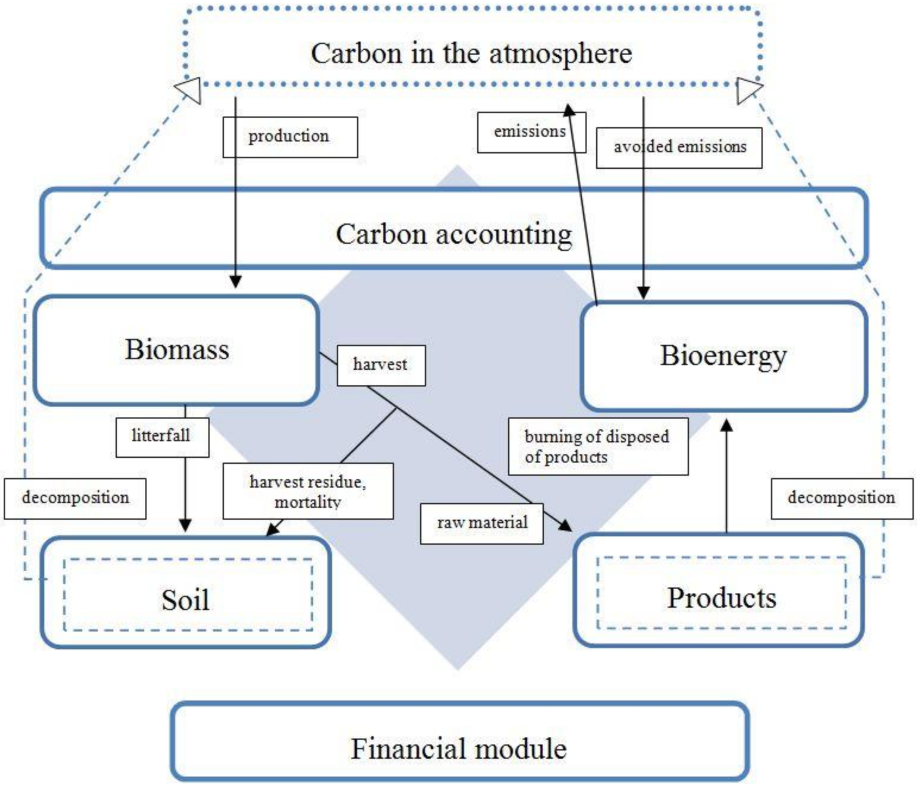

Figure 8. The CO2fix model is divided to six main modules (Masera et al. 2003; Schelhaas et al. 2004).

A broad ad hoc model was also developed with Excel to form and analyze results. That model also assisted to fully understand correlations and develop meaningful figures. The data was exported from the CO2fix to numerous Excel sheets and then model was formulated. A sensitivity analysis is also carried out, for the purpose of seeing the different outcome. Few results that CO2fix simulated are applied for sensitivity analysis.

4.2.2 Biomass module and parametrization

Biomass, in this study consists of the total live tree material above ground. The carbon stocks and flows in the above ground (forests' living biomass) is calculated estimated using a 'cohort model'. In this thesis growth of the cohorts (trees) is described by a function of tree or stand age (Reed 1980; Masera et al. 2003; Schelhaas et al. 2004).

Uruguay's Ministry of agriculture, livestock and fishery (MGAP FAO 2010) has an exceptionally well documented forestry and plot data. The age of the stands, the growth of trees, biomass and stem wood volume current annual increment (CAI) (Eq. 2) can be obtained from the yield tables. The inventory data and reports consist – among other information – stem volume increment data in m^3/ha^{-1} per year. That data is used in the model to calculate to the biomass growth. Basic wood densities and carbon contents of dry weight are detailed in table 2. Dry matter in live biomass is set a default 50%. Used parameters are weighted averages and estimates of stem wood yield at the stand level, and used as an average for the department and the national level. The growth rates of roots and branches can also be calculated in this module. The mean annual increment (MAI) (Eq. 1) is simply the average volume production or wood yield per year, divided at any point by a forest total age. Current annual increment (CAI) (Eq. 2) is the increment in volume over a period of one year at a particular age in the tree's history. Figure 9 demonstrate that in the crossing of these curves is the optimal age at which the tree should be harvested (Gill & Jackson 2000; Carrau 2010; MGAP FAO 2010; Kaul et al. 2010; Varmola et al. 2010; Pérez-Cruzado et al. 2012; MGAP 2013).

MAI and CAI mathematically:

MAI: Volume of stand/age of stand= m^3/ha^{-1} per year Equation 1.

CAI at age 8: Volume at age 9 - volume at age 8 $m^3/ha^{-1}/y$ Equation 2.

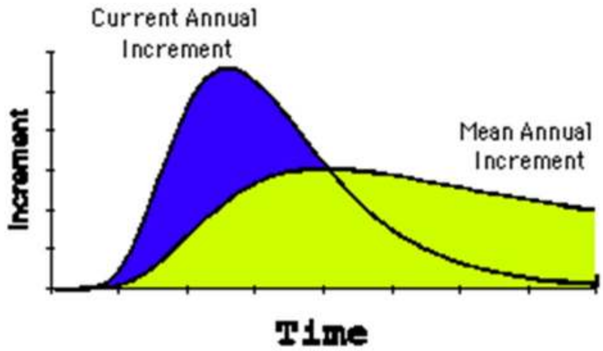

Figure 9. Current annual volume increment (CAI) and mean annual increment (MAI) of a forest stand as a function of age (Fennerschool 2013).

Usually in plantations fraction of trees dies every year and some competition between cohorts appears. Data on natural mortality was found from inventory studies and previous studies. Trees are usually planted spacing 1666 (3m x 2m) trees per hectare, with a remaining tree density of 800–1200 stems ha^{-1} before a clear-cut (MGAP FAO 2010; Pérez-Cruzado et al. 2012; MGAP 2013).

Management related mortality is excluded from the simulations, because there is no damage to forests during rotation and final harvest is the only operation. Eucalyptus forest plantations are properly managed and according to the national forest policies. No thinning is carried out during rotation period and a clear-cutting is conducted when forest reach a loggable state after 8 to 12 years. Harvest residues are left out to soil as nutrition and carbon stock. Harvested biomasses have to be added to the products and soil modules and subtracted from the existing carbon stock (Schelhaas et al. 2004; Carrau 2010; MGAP FAO 2010; MGAP 2013).

4.2.3 Soil module and parametrization

Soil consists of litter, humus, small twigs, coarse woody debris (CWD). Soil includes all dead organic matter one meter above the mineral soil horizons. Soil module is based on the Yasso model (the dynamic soil carbon model). The model gives specific data of decomposition and soil carbon, carbon in soil 0–100-cm depth. It has been used in different forest types around the world. The module is divided into three litter compartments: foliage and fine roots (non-woody litter), branches and coarse roots (fine woody litter) and stems and stumps (coarse woody litter). Then litter diverges yet another five decomposition compartments: Extractives, celluloses and humus. All of them becomes dead organic matter and decompose to the soil in a different rate. Values for decomposition rates, dead wood, litter, and soil humus were based on previous literature. Root, foliage and branch turnover rates are weighted averages (Table 2). Yasso also requires some climate information: Mean annual temperature, precipitation and potential evapotranspiration values. Trees cool the air and lower temperatures through an evapotranspiration (Fig. 10) process. Eucalyptus plantations need more water than grassland and fewer resources are available for other land-use forms. Forests could also have 30–50% greater evapotranspiration level than grassland and abandoned pasture land (Liski and Westman, 1997a, b; Liski et al., 1998; Tolbert et al. 2000; Liski et al. 2003b, c; Masera et al. 2003; Schelhaas et al. 2004; Pérez-Cruzado et al. 2012; EOE 2013).

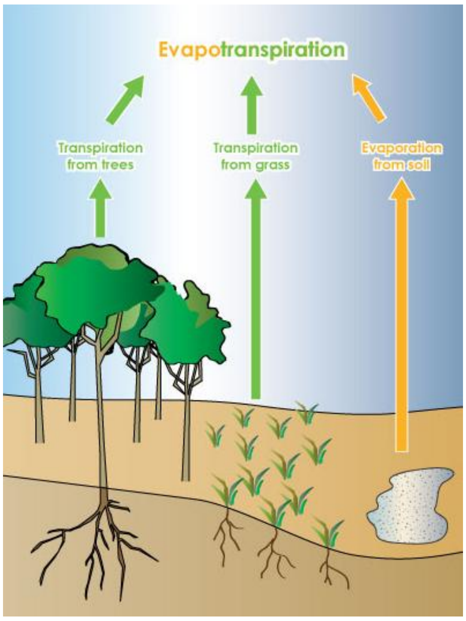

Figure 10. Evapotranspiration (EOE 2013).

For the soil module of CO2fix used data was mostly from Worldclimate (2013); precipitation, average monthly temperatures and growth seasons. Average rainfall in different cases: 130mm (Artigas), 119mm (Paysandú) and 125mm (Tacuarembó). After entering the data the model will calculate degree days above zero (6516.8) and potential evapotranspiration (733.4mm) (Meteorología 2012; WWCI 2012; Mongabay 2013; Worldclimate 2013).

All forest plantations are afforestation on grassland and degraded land. Therefore, the initial values for soil stable humus represent grassland and degraded land. The model calculated initial carbon (Mg Cha^{-1}) levels when roots, branches and foliage figures were derived from the grassland simulation (Table 6). In this study grassland is the baseline scenario and shows how much carbon is in soil compartments without a plantation. The soil is parametrized with 78 Mg Cha^{-1}, of which 27.8 Mg C is fine, coarse and non-woody litter from harvest slash. (Kaul et al. 2010; MGAP FAO. 2010; Berthrong et al. 2012**;** Pérez-Cruzado et al. 2012; MGAP 2013).

4.2.4 Products module

The end use of forests is necessary to understand in estimating the magnitude of forestry to the global carbon cycle. Large portion of the carbon that is stored in the harvested trees continues to stay captured in products. After the harvesting of forest the carbon is transferred and stored into furniture, houses and timber bridges etc. for a long time – years to many decades. Pulp and paper are short-term goods and discarded to decay or recycled. This also means that the carbon is released sooner to the atmosphere. Forest biomass could be substitute for fossil fuels, if burned for energy, and decrease use fossil fuels, which emits more carbon. In this study, the end use of timber is estimated to be pulp production. One simulation is set for 70% of tree is going to products and the rest to pulp and recycling. In the results chapter can be found comparison between these two end uses. Products and forests could sequester more than companies emit carbon dioxide through manufacturing facilities or country produces (Birdsey 1992; Masera et al. 2003; Schelhaas et al. 2004; IPCC 2007).

4.2.5 Bioenergy module

The bioenergy module calculates percentage how much it is possible to utilize biomass instead of fossil fuels. Usage of a bioenergy decrease greenhouse gas emissions. It is also noteworthy to mention that the bioenergy has a minor influence to increases the amount of the atmospheric carbon. At the moment Montes del Plata does not use bioenergy, but this grievance will be fixed when the new mill in the Punta Perreira begins operations. Since usually a pulp mill can use industrial residues (bleach, water and discarded products) again in the pulp process. Most of the waste generated in wood cooking process can reused. Pulp process residues are later burned to produce energy and then transformed to electricity. In this thesis bioenergy is excluded, because the companies do not use biomass fuels in a large scale (Carrau 2010; Naqvi et al. 2010; Montes del Plata 2012; Stora Enso 2012).

4.2.6 Financial module and parametrization

The financial module creates an estimation of the financial profitability of a plantation. Profitability is derived from the net present value (NPV) of a plantation, where costs and revenues are discounted to the beginning of the project (Masera et al. 2003; Schelhaas et al. 2004). Fixed annual cost from different management actions are estimated to be 46$/yr., no fixed annual returns.

4.2.7 Carbon accounting module

In this study stock change approaches is applied for carbon accounting. The other method would be merchantable certified emission reductions (CER) and it is used for trading between different countries (Groen et al., 2006).

CO2fix carbon accounting module calculates only CO_2 and does not take into account leakage and greenhouse gas emissions. In the module it is possible to get an estimate of the amount of credits that can be generated. Different types of crediting systems give background support for the calculation of the project (The stock change method for other projects, tCERs and lCERs for CDM-AR projects) (Schelhaas et al. 2004).

5. SIMULATIONS

In this study the model was used and calibrated to eleven individual scenarios that stem from the data provided by the Ministry of agriculture, livestock and fishery (MGAP), multiple reports and studies (Table 2–11). The simulations were parametrized for eucalyptus plantations in different parts of Uruguay. The average grassland simulation was also formed to get a baseline. The net carbon sequestration (carbon benefit) is the difference between the average carbon stock and the initial grassland (baseline) carbon stock in each scenario. Natural forests were left out from simulations due to limited availability of information and inventory data. Comparison to natural forests would have given a meaningful reference level. Planted areas formerly been grassland for decades or used for agriculture or replanted after clear-cut.

In this study, simulations 1–7 The long-term period was set to 60 years in all simulations. Simulation 8 is future estimate of carbon stocks in year 2050. Rotation periods of forest plantations varied from 10 and 12 years; 10-year rotation period in Paysandú and Tacuarembó (scenarios 1 & 6). In simulation 2 rotation period is altered from 10 to 12 years to see how it will effect to the total carbon storage. In scenario 7 (Artigas) rotation period is prolonged with two years because soil is less fertile.

Scenarios were calibrated with different regional climatic data (Table 4). Simulations included the mean monthly precipitation and temperature, growing season (September–May), degree days above zero and potential evapotranspiration. The current annual increment (CAI) and mean annual increment (MAI) figures were derived from different articles, studies and yield tables. The weighted average increment figures are from local growth and yield tables and from same type of climate and soil conditions. Mortality is taken into account every year until end of rotation period (Skolmen 1983; Gill & Jackson 2000; Masera et al. 2002; Lemma 2005; Olmos 2007; Terakunpisut et al. 2007; Law et al. 2008; Nabuurs et al. 2008; Kaul et al. 2010; Varmola et al. 2010; Uruguay XXI 2011; Ma, X. & Wang 2011; Pérez-Cruzado et al. 2012). After tree harvest 90 per cent of wood is removed and the rest 10% is slash, and left to the site (Carrau 2010).

CO2fix V.3.1 is applicable to many sites, management systems, and therefore many simulations. CO2fix can be used to different land-use forms, and it is possible to represent grassland or cropland systems. Grass (or crop) has to be parameterized as a 'tree'. Stem volume has to be very small, no branches, foliage or roots are included. The carbon content of grass is set to the model default value of 0.48 Mg C/ Mg DM and MAI is 0.01 m3/$ha^{-1}year^{-1}$. The versatility of the model can be seen in the results. In this study the model was also applied to grasslands, which is expected to continue to degrade without a plantation. Grassland defines how much carbon is in the soil compartments if a eucalyptus plantation was not initiated. This act as a baseline for the C pool and consists of degrading grassland. The baseline for simulations is 92.3 ton of carbon and 5.2 ton of grass dry matter ha^{-1}. After the initial carbon, comparison between different land use forms was plausible and sufficient. Weather and environmental data is same as in simulation 1, the average scenario. (Reich et al. 2002; Masera et al. 2003; Stolpe et al. 2010; Berthrong et al. 2012).

The simulation 7 describes estimates of changes to carbon pools when end-use is different. Scenario 7 estimate results when 70% of raw material goes to products, remaining 30% to pulp and energy production. Products are considered as a long-term use and result in larger carbon storage.

6. DATA ANALYSIS

6.1 Data of the study

Data of the study is from multiple sources: research publications, previous studies, inventory data provided by companies and Ministerio de Ganadería, Agricultura y Pesca (MGAP). Data used in the simulations are presented in tables 3–9 (Skolmen 1983; Gill & Jackson 2000; Masera et al. 2003; Lemma 2005; Olmos 2007; Terakunpisut et al. 2007; Law et al. 2008; Nabuurs et al. 2008; Carrau 2010; Kaul et al. 2010; Stolpe et al. 2010; Varmola et al. 2010; Uruguay XXI 2011; Ma, X. & Wang 2011; Pérez-Cruzado et al. 2012).

In table 2 is presented the mean annual increment (MAI) of an average eucalyptus plantation in Uruguay. These figures (Table 2) are weighted averages and estimates of the potential of eucalyptus plantations to sequester carbon (Concalves et al. 2004; Kaul et al. 2010; Pérez-Cruzado et al. 2012; etc...).

Table 2. MAI averages in Uruguay.

MAI (m3/ha^{-1}year^{-1}) of the trees, average figures of the country.				
age	**10 years Rotation period**	**12 years rotation period**	**low productivity**	**hybrid**
1	5	5	3	7
2	10	10	4	20
3	15	12	5	25
4	18	15	7	27
5	22	17	8	30
6	24	20	9	31
7	26	23	10	32
8	28	25	10.5	35
9	30	27	10.5	37
10	32	28	11	40
11		30	11.5	
12		32	12	

Table 3 shows used average parameters for first nine simulations. Used carbon content in previous studies is 50% (0.5). Wood density was set to 0.525 Mg per m^3 of wood. Turnover rate means (foliage, branches, roots) the annual rate of mortality. Foliage turnover rate of 0.324 means that 32% of the total biomass is converted to litter every year. Turnover of all biomass and slash is added to the soil compartments. Carbon fluxes into roots, branches and foliage and their carbon contents are determined by their growth. Relative growth is relative to the stemwood production (Masera et al. 2003; Schelhaas et al. 2004).

Table 3. Parameters used in the simulations.

Parameters	E. grandis	E. globulus	average	hybrid
Wood density, kg m^{-3}	480 (0.48)	570 (0.57)	525 (0.525)	500 (0.5)
Carbon content (g-C/g-DM)				
Foliage			0.52	
Branch			0.455	
Stem			0.5	
Root			0.452	
Turnover rates, $year^{-1}$				
Foliage			0.324	
Branch			0.0303	
Root			0.047	

Average relative growth Ratio of dry weight increase relative to stem increase, 10 years rotation period	Foliage %	Branch %	Root %	Hybrid
1	0.16	0.25	0.25	N/A
2	0.25	0.22	0.28	N/A
3	0.19	0.22	0.28	N/A
4	0.2	0.24	0.27	N/A
5	0.29	0.24	0.25	N/A
6	0.3	0.25	0.24	N/A
7	0.31	0.26	0.25	N/A
8	0.32	0.28	0.27	N/A
9	0.33	0.29	0.29	N/A
10	0.3	0.3	0.3	N/A

Average relative growth, 12 years rotation period	Foliage %	Branch %	Root %	Hybrid
1	0.16	0.25	0.25	N/A
2	0.18	0.22	0.28	N/A
3	0.19	0.22	0.28	N/A
4	0.2	0.24	0.27	N/A
5	0.29	0.24	0.25	N/A
6	0.3	0.25	0.24	N/A
7	0.31	0.26	0.25	N/A
8	0.32	0.28	0.27	N/A
9	0.33	0.29	0.29	N/A
10	0.3	0.3	0.3	N/A
11	0.3	0.3	0.3	N/A
12	0.3	0.3	0.3	N/A

Table 4. General parameters use in the soil module (Meteorología 2012; WWCI 2012; Mongabay 2013; Worldclimate 2013).

Soil module parameters	**Paysandú** 10 years	**Different** turnover rates	**Arti-gas** 12 years	**Tacua-rembó** 10 years	**Hybrid** (MAI 40)	**12 years** (12 MAI)	**2050 MGAP** estimate
mean monthly precipitation mm	119	119	130	125	120	119	119
Degree days above zero	6516.8	6516.8	7081.4	6784	3802	6516.8	6516.8
potential evapotranspiration mm	733.4	733.4	801	766.3	628.4	733.4	733.4

Table 5. The soil module. Cohort parameters initial carbon (baseline), scenario 1. (Reich et al. 2002; Kaul et al. 2010; Stolpe et al. 2010; Berthrong et al. 2012; Pérez-Cruzado et al. 2012).

Initial carbon, Paysandú	**Mg Cha**
non woody litter	2.42
fine woody litter	0
coarse woody litter	0.37
soluble compounds	1.29
holocellulose	3.28
lignin-like compounds	5.04
humus stock 1	17.64
humus stock 2	34.35

Table 6. The soil module. Parameters for Tacuarembó, initial carbon, scenario 6.

Initial carbon, Tacuarembó	**Mg Cha**
non woody litter	2.42
fine woody litter	0
coarse woody litter	0.37
soluble compounds	0.37
holocellulose	3.22
lignin-like compounds	4.95
humus stock 1	17.46
humus stock 2	34.14

Table 7. The soil module. Parameters for Artigas, initial carbon, scenario 7.

Initial carbon, Artigas	Mg Cha
non woody litter	2.24
fine woody litter	0
coarse woody litter	0.36
soluble compounds	1.24
holocellulose	3.15
lignin-like compounds	4.85
humus stock 1	17.26
humus stock 2	33.90

Table 8. Parameters of the wood products module, the pulp scenario (1).

Wood products	short term 1 years	medium term 5 years	long term 10 year
production line			
raw material allocation	pulp	paper	
process loss	10%		
end products			
paper	89%	10%	1%
recycling	80%	80%	80%
energy	15%	15%	15%
landfill	5%	5%	5%

Table 9. Parameters of the wood products module, 70% of the timber go to boards and logwood, scenario 5.

Wood products	short term 1 years	medium term 15 years	long term 30 year
production line			
raw material allocation			
process loss	10%		
logwood			50%
boards			50%
end products			
logwood			100%
boards			100%
paper			
recycling	90%	90%	90%
energy	5%	5%	5%
landfill	5%	5%	5%

Table 10. Financial parameters, the average scenario (1) (Olmos 2007; Schäfer & Ponce 2007; MGAP FAO 2010).

Financial parameters, 10-years	$/ha	$/M^3
Costs		
thinning	0	
Planting	1000	
harvest	2502	
other	400	
Total	3902	
recurring costs, annual	46	
price of stumpage logs		39.2
harvest returns	6059	

Table 11. Financial parameters for 12-year rotation period, scenario 2 (Olmos 2007; Schäfer & Ponce 2007; MGAP FAO 2010).

Financial parameters, 12-years	$/ha	$/M3
costs		
thinning	0	
Planting	1000	
harvest	2502	
other	400	
total	3902	
recurring costs, annual	46	
price of stumpage logs		39.2
harvest returns	6957	

6.2 Study areas and the soil attributes

The study areas are in the different departments of Uruguay (Fig. 11), such as Paysandú, Tacuarembó and Artigas. The sites are located between 32.33°S 58.00°W and 30.38°S 56.50°W. Areas consist of different soils and types of vegetation. The average values for a department is used in estimating the value for the area and scaled up to the national level. There are permanent forest inventory plots in every department, but that data could not be founded and the cooperative company declared them as confidential. Also information and inventory data about natural forests were limited. The topography in Uruguay is low hills and plains (Pampa) and fertile coastal lowland (Uruguay XXI 2011; MGAP 2013; FAO 2013).

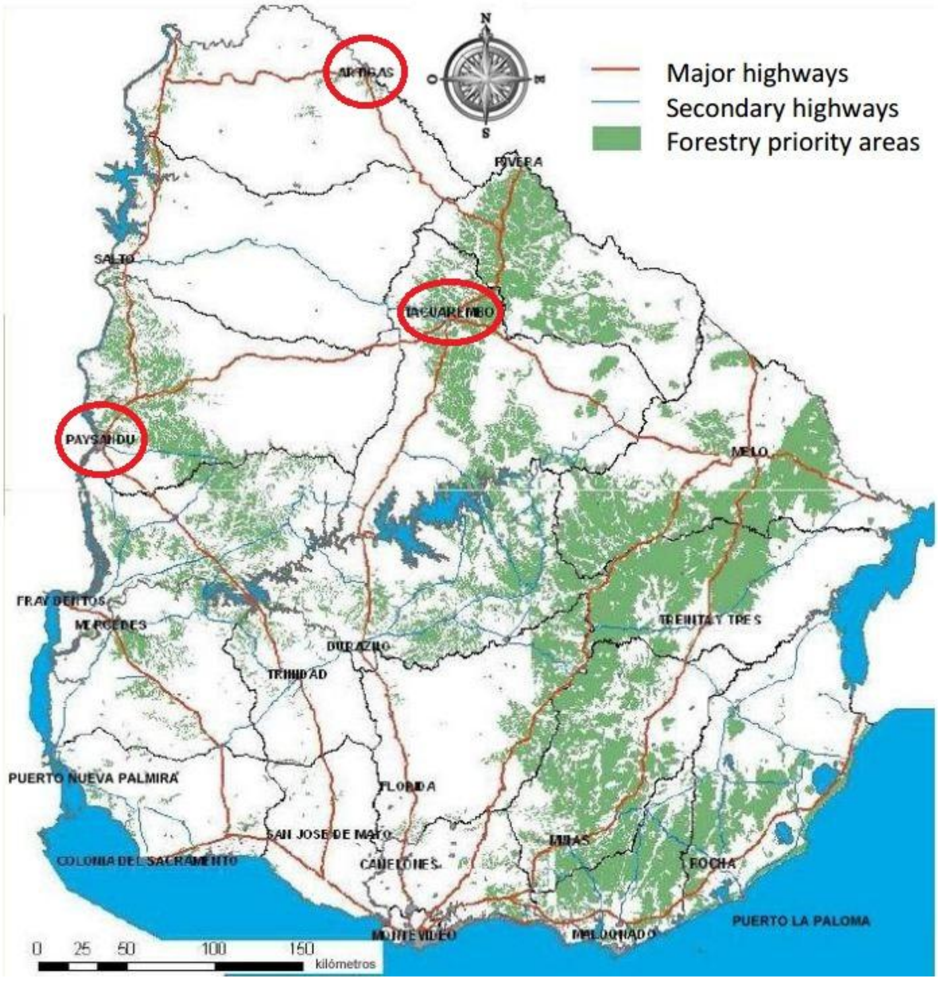

Figure 11. Location of study areas (Uruguay XXI 2011).

The erosion observed in few sampling points of planted forest was slight (63%) or moderate (25%), showing some erosion in most of plantations. Study areas and plantations in general are located on soils that are characterized by good drainage. The rotation age and planting density varies between site and species. Rotation age in eucalyptus plantations varies from 7–16 and no commercial thinning. The stands had an initial planting density of about 1600 trees per hectare and the final clear cut age were 8–14 years. The harvest densities were 800 to 1200 trees ha, variability is due to fluctuation in mortality. Mean annual increment varies from 5–40 m^3/ha^{-1} $year^{-1}$. In this study the average stem volume (m^3/ha) varies from 37–77.63 in a 60-year simulation (6x10-year rotation) and highest is 191.6 m3/ha (Carrau 2010; MGAP FAO 2010; Montes del Plata 2012; MGAP 2013).

6.3 Climate and Precipitation

Uruguay is located in the temperate zone. The climate is humid subtropical, which is part of subtropical climate zone and fairly uniform nationwide. There are seasonal variations and distinct winter and summer. The study areas don't have significant meteorological differences. The average temperature of 24ºC and the average minimum temperature were of 8ºC in May and September. Freezing temperatures and weather extremes are almost unknown or rarely fall below zero degrees. The average annual temperatures 19.5 ºC (Artigas Uruguay, 30.38°S 56.50°W), 18.0ºC (Paysandú, 32.33°S 58.00°W), 18.6ºC (Tacuarembó), 17 ºC (San Jose, 34.40°S 56.70°W) and 16.5ºC (Carrasco, 34.83°S 56.00°W). The average maximum temperature of 29ºC was recorded in January (Montevideo, 34.87°S 56.17°W). The climate attributes data for the model, and more specific to the soil module were acquired from internet sites (Meteorología 2012; WWCI 2012; Mongabay 2013; Worldclimate 2013).

Oceans are surrounding Uruguay and rivers pass through the different parts of the country, so there sufficient water available to the plants. There is no specific rainy season and the rainfall distributes almost evenly to different months. Annual precipitation tends to increase from southeast to northwest and in the summer rains more than in the winter. Between 1961 and 1970 (120 months) the total average annual rainfall in San Jose (34.40°S 56.70°W) was 1 131.5 mm and in Carrasco (34.83°S 56.00°W) 1 059.6 mm. Rainiest months on average are March 133.3 mm and December 125.9 mm (San Jose) and 110.7 mm and 84.0 mm (Carrasco). Based on the last 8 years of historical weather data Montevideo receives rain 950 millimetres annually, so the mean monthly precipitation is below 100 mm. In Artigas (30.38°S, 56.50°W, and 123 meters above sea level) average annual rainfall is 1 235 mm and in Melo (32.36°S, 54.18°W, and 100 meters above sea level) 1 160 mm (Meteorología 2012; WWCI 2012; Mongabay 2013; Worldclimate 2013).

6.4 Reliability and limitations of the model and study

The model is applied to eleven simulations that stem from the data provided by the Uruguay's Ministry of agriculture, livestock and fishery (MGAP), multiple reports and studies (tables 2–11). Most of the data are from local studies and from similar climate and soil conditions.

The multi-cohort model groups individual trees or a group of species. These groups are assumed to show similar growth, stem wood production, mortality, turnover rates and final harvest in the model. Every stand or plot is not – certainly – similar and the results are estimates. There is also variation between different eucalyptus species. Study areas were chosen to be relatively representative. There are some divergences on local silviculture, weather and overall conditions. In order to achieve more accurate, generalizable results and better comparability, inventory and stand level data would be required (Masera et al. 2003; Schelhaas et al. 2004).

The model and the results depend on the mean annual increment data. The (MAI) figures are weighted averages and estimates from different articles, studies and yield tables. The local average values were compared to relevant studies and to same type of climate and soil conditions. The results are then estimates and averages in general level and they will try to show the potential of eucalyptus plantations to sequester carbon and increase the total carbon stock. Field studies and plot data from different sites would have provided more accurate data and results (Skolmen 1983; Gill & Jackson 2000; Masera et al. 2002; Lemma 2005; Olmos 2007; Terakunpisut et al. 2007; Law et al. 2008; Nabuurs et al. 2008; Carrau 2010; Kaul et al. 2010; Varmola et al. 2010; Uruguay XXI 2011; Ma, X. & Wang 2011; Pérez-Cruzado et al. 2012).

The weather data for different departments are also averages and demonstrate situation in some part of the country. Precipitation in department level in Uruguay could vary about 200mm in month (Worldclimate 2013). Climate and microclimatic conditions in departments affect the cumulative carbon storage in soil. Variations in precipitation and temperature will affect carbon sequestration potential (Lemma 2006; Ma and Wang 2011).

7. RESULTS OF THE STUDY

The CO2fix model rigorously simulated the carbon contents in soil, biomass and products. Carbon sequestration in grasslands (Table 12 & Fig. 12) was the baseline for simulations with the 60 years average soil carbon of 75.6 ton $ha^{-1}yr^{-1}$ and average of 1.26 ton $ha^{-1}yr^{-1}$. The results of this study show that in scenario 1 (simulation 1) carbon stored in the soil after afforestation varies from 64.38 to 147.93 with the average of 101 Mg Cha^{-1} (Table 12). Carbon in living biomass ranges from 2.13 to 68.73 mg Cha $^{-1}$ and the average was 31.6 Mg Cha^{-1} carbon in products from 39.34 to 88.23 Mg Cha $^{-1}$ with the average of 37.6 (Table 12.). After a rotation period more carbon is added to the soil and the total carbon is increasing constantly in the forest ecosystem. The 60-year average increase to the soil carbon in eucalyptus plantations is 34%. Also in other six simulations (Table 12.) carbon content in the soil compartment grow over 30% due to afforestation. The increase to the soil is 23.6 to 28.8 tons of carbon in a hectare. Table 12 shows the estimated accumulation of the average carbon stocks in time in each simulation.

Table 12. Total accumulated carbon per hectare (Mg Cha^{-1}) in eucalyptus plantations, average in 60 years.

Results, Average in 60 years	grassland Mg C ha^{-1}	pulp scenario	carbon benefit	% change
Paysandú (west) 10 year rotation, simulation 1	Mg Cha^{-1}	Mg Cha^{-1}	Mg Cha^{-1}	
MAI		32		
biomass	2,4	31,6	29,1	
soil	75,6	101,1	25,5	34 %
products	0,0	37,6	37,6	
total	78,0	170,2	92,2	118 %
Paysandú (west) 12y, simulation2				
MAI		32		
biomass	2,4	35,7	33,3	
soil	75,6	104,4	28,8	38 %
products	0,0	33,7	33,7	
total	78,0	173,8	95,8	123 %
Paysandú, low productivity, 12y, simulation 3				
MAI		12		
biomass	2,4	15,4	13,0	
soil	75,6	74,5	-1,1	-1,4 %
products	0,0	13,9	13,9	
total	78,0	103,8	25,8	33 %
High productivity, clones, simulation 4				
MAI		40		
biomass	2,4	45,2	42,8	
soil	75,6	121,0	45,4	60 %
products	0,0	50,3	50,3	
total	78,0	266,4	138,5	242 %
70 % products, 12y, simulation 5				
MAI		32		
biomass	2,4	31,6	29,1	
soil	75,6	101,1	25,5	34 %
products	0,0	107,2	107,2	
total	78,0	239,8	161,8	208 %
Tacuarembó (center) 10y, simulation 6				
MAI		32		
biomass	2,4	31,5	29,1	
soil	74,9	103,3	28,5	38 %
products	0,0	36,3	36,3	
total	77,3	171,1	93,8	121 %
Artigas (north) 12y, simulation 7				
MAI		32		
biomass	2,4	36,0	33,6	
soil	74,1	97,7	23,6	32 %
products	0,0	35,1	35,1	
total	76,6	168,9	92,3	121 %

The net carbon sequestration (afforestation stock- grassland baseline) varies between 25.8 and 161.8 Mg Cha^{-1} (Table 12.) during the simulations of 60 years. In this study the term "carbon benefit" (Table 12.) is used to describe the remainder of the baseline (grassland) and simulation. The average net sequestration is 92.2 Mg Cha^{-1}. The highest average net carbon storage in the plantation at rotation period 12 reached 95.8 Mg Cha^{-1} and 1.6 Mg $Cha^{-1}yr^{-1}$. Calculations include biomass, soils and products. The annual carbon storage and biomass production increment will change depending on mortality and initial planting density. The planting density is usually 1400–1666 stems ha^{-1} and reducing to about 800–1200 before harvest, due to mortality.

In the simulation 3, poor site index, there is a decrease in soil carbon in first eight years and after that more carbon is added to the soil. Simulations do not include grass biomass and carbon, also non woody litter carbon is about 3 tons bigger in the beginning. The result is that after 5 rotations the average soil carbon seems to decrease; stored carbon varies from 64.38 to 90.77 Mg Cha^{-1}. After 60 years the net carbon storage is larger than in grassland, biomass adds more C to the soil compartments.

High productivity species with 40 MAI almost double the carbon content in the soil compartments from 25.5 to 45.4 Mg Cha^{-1} compared to the average scenario (simulation 1). The implication from this is that companies should continue to plant more hybrids and other productive species in order to ensure extensive wood volumes and carbon sequestration. The conversion of grassland to high productivity plantation leads to an increase in soil carbon of 45 metric tonnes of carbon per hectare.

Products simulation (5) estimated the effect of changing the end use from pulp to sawn wood and boards. After the harvest the carbon continues to stay captured in products longer time period than in pulp, which is short-term good and decay faster. The products simulation calculated that the soil carbon change from 37.6 to 107.2, hence the total carbon storage climb from 92.3 to 161.8 Mg Cha^{-1}.

The comparison of different areas of the country provided more evidence of climate and soil significance to the carbon sequestration. In simulation 6 (Tacuarembó) soil carbon content increased compared to the first simulation by 10%. Products sinks are decreasing by -4% and biomass pools remain the same. Mean annual precipitation and soil conditions alter the results. In Artigas (simulation 7) biomass carbon stocks are increasing by 4.5 tons per hectare. Changes in soil and product C stocks are negative by 1.9 and 2.5 tons per hectare, respectively.

Figures 12 and 13 show the long-term (60 years) estimated carbon sequestration hectare scale values in eucalyptus plantations, as simulated by the model. Figure 13 shows comparison of two scenarios; the annual soil carbon stock with afforestation and difference to the baseline scenario. From the figures it can be concluded that intensively managed fast-growing eucalyptus plantations have a great impact on carbon stocks.

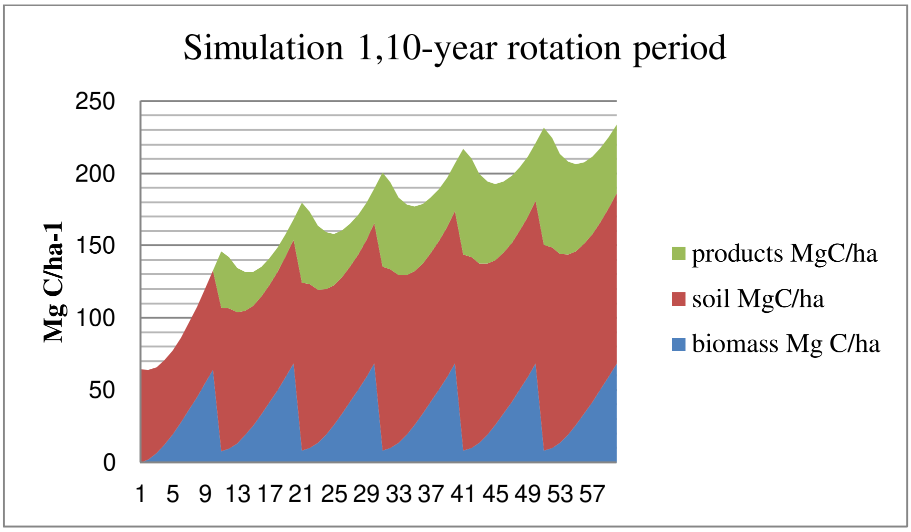

Figure 12. The average carbon sequestration potential of carbon stocks in 60 years (simulation 1).

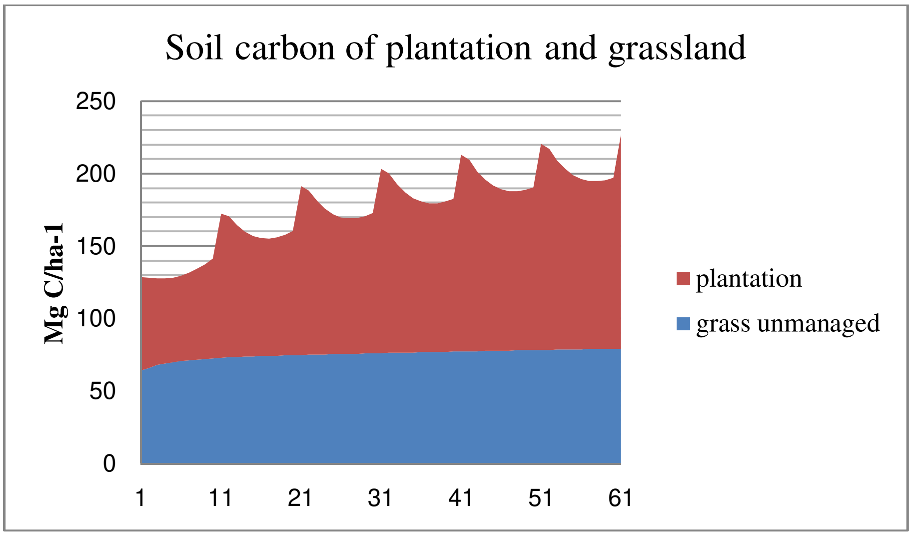

Figure 13. Model simulations for afforestation and grassland scenarios.

The CO2fix model was also used to estimate the effect of changing rotation length (Table 12 & Fig. 15). The rotation length was increased by 2 years. The model confirmed that extending rotation length from 10 to 12 years accumulated the average carbon stock of soil by 3.9% in a hectare. This study also showed – among numerous others – that long rotation forests enhance the total carbon stock and sequester more carbon than short-rotation plantations. Shorter growth could produce better yields (MAI) and are more lucrative than alternative investments.

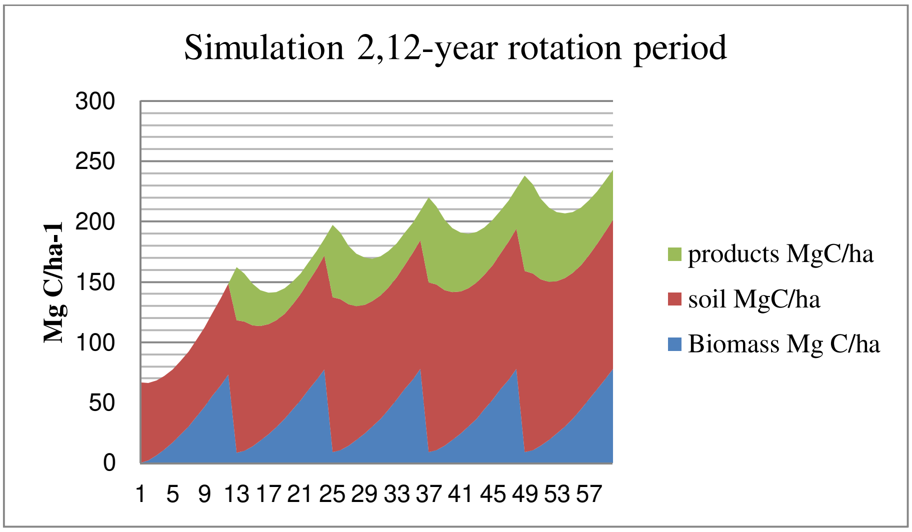

Figure 14. Accumulation of carbon stocks in 60 years.

Figure 14 shows calculated 22 years (1990–2012) average carbon derived from the simulation figures in all plantations. The average total annual carbon benefit is calculated with 707 674 hectare, multiplied with the average benefit figure (soil, biomass, products), and the sum is then divided with 22 years. During past 22 years plantations has added averagely carbon to the soil compartments 937 146 Mg C.

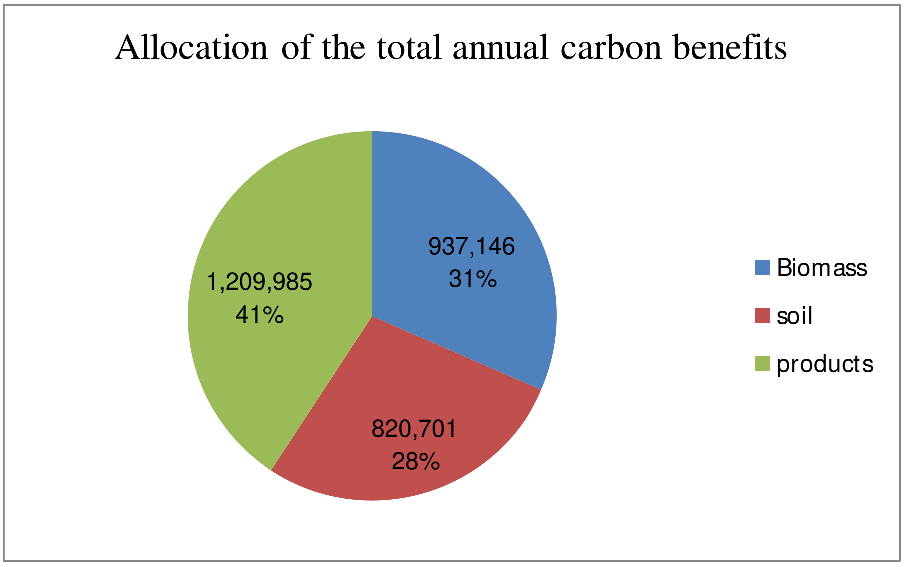

Figure 15. Breakdown of the calculated carbon in different sinks in 1990–2012.

The financial module showed that returns surmount all costs. The module used increment data from the soil module and calculated the results. The average stem volume in simulation 1 was (m^3/ha) 77.63 in a 60-year simulation (6x10-year rotation) and highest was 168.61 m^3/ha. The outputs of the model are that harvest returns totals $6059/ha after first rotation, when stumpage pulp logs cost $39.2 M^3. Volume (m^3/ha) and net present value (NPV) are about 15% larger in harvest age of 12 than 10. The increase in the total carbon content is 2%. Calculations include cost of capital 3.1%, harvest $3902 and recurring costs $46. 2 percentage point change in the used interest rate to 5% alters the NPV by 17%. Figures 16–17 show the annual growth of the trees. MAI values (averages) are calculated estimates from different departments.

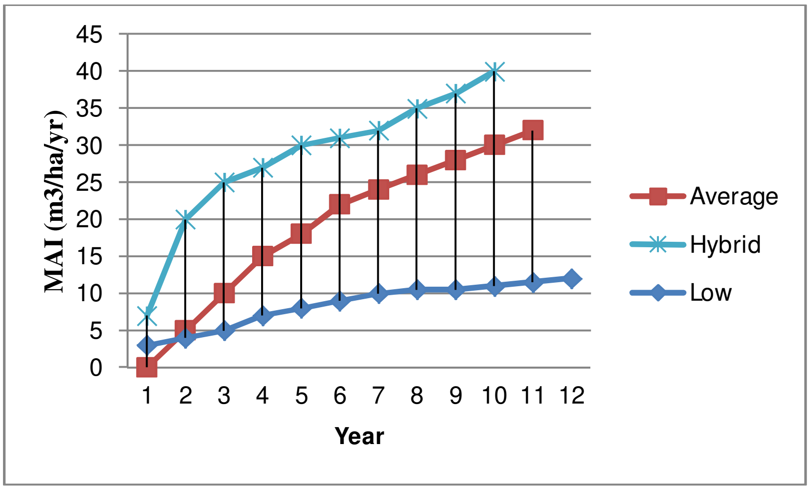

Figure 16. Mean annual increment curves per hectare on average.

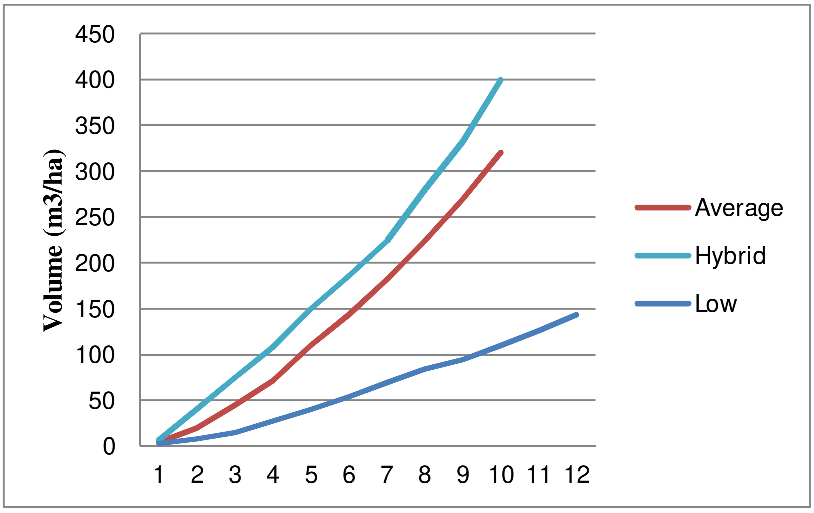

Figure 17. Annual growth of stem volume (m^3/ha) from age 1to 12 on average.

Variation in mean annual precipitation (MAP) affected the accumulation of carbon to soil pools (Berthrong et al. 2012). In this study MAP varies from 1131.5 to 1059.6mm and monthly precipitation from 119mm to 130mm (Table 5.) in different departments. The findings (Table 12.) of this study show also that soil carbon decreases when MAP increases – Ceteris Paribus –. In Paysandú (119mm) the soil carbon sequestration is 75.6 in Tacuarembó (125mm) 74.9 and in Artigas (130mm) 74.1 Mg. Increased precipitation is altering soil composition and nutrients. The net total carbon storage 92.3 in Paysandú is smaller than in Tacuarembó 93.8 Mg Cha^{-1}. Biomass is growing faster due to increased annual rainfall. In Artigas (130mm) the net storage is 92.6 Mg Cha^{-1}. In this simulation (8) the lower results is also due to the poor site index; the northern part of the country is less fertile. The findings of this study suggest also that 125mm average precipitation is optimal for carbon sequestration in eucalyptus plantations. Afforestation increases the soil organic carbon (SOC) most in Tacuarembó (38%). The climate change could mean fluctuation in MAP and alter the results. Some departments could receive more monthly rainfalls and decrease carbon sequestration. Though, it is really difficult to predict exact rainfall levels.

Carbon credits were simulated with the model. Potential credits are hypothetical at this point, because intensively managed fast-growing plantations are not compensated. Most of eucalyptus plantations are for industrial use, mainly for pulp production, not for solely carbon storage. The CDM stands for emission reduction and these reductions are subtracted against emissions. These emissions are estimated to occur in the absence of a project. Eucalyptus plantations would generate carbon credits if managed for wood products instead of pulp (Fig 18.).

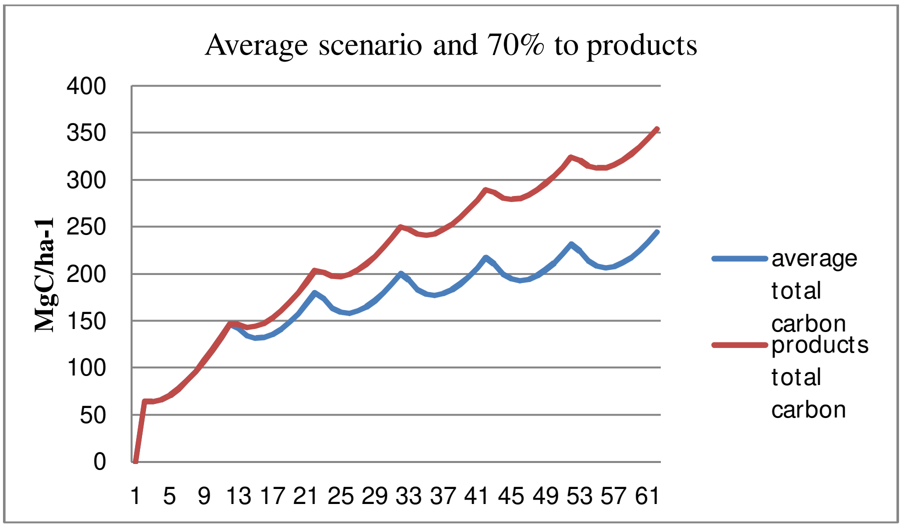

Figure 18. Baseline vs. products (possible credits).

This study suggests that efforts to expand forest carbon stocks need to be strengthened in order to achieve carbon dioxide emissions reductions. MGAP has estimated that there are about 2 million hectares available for eucalyptus and 3 million for total forest plantations. This 2 million ha would be reached in 2050, if an average 34000 seed are planted annually. Alternatively, in 2027 if 85000 seeds are planted averagely in a year, as in 1998. Table 13 shows the 60 years average stocks in the soil, tree biomass and products as simulated by the CO2fix model. 707 674 hectares of eucalyptus plantations have the potential to sequester 65 million tonnes of carbon and reduce 238 million tonnes of CO_2. The annual calculated average sequestration benefit is 1 757 847 and the simulated 1 136 768 Mg C. In 2050 the same figures are 2 876 186 and 1 676 359 Mg C. Storage potential of eucalyptus plantations could be equivalent to offset annual CO_2 emissions produced in the country.

Table 13. Estimated values for carbon pools in the future (year 2050).

dry weight (525)	2012	2012 carbon	annual average	1990 hectares	2 million ha (year 2050)	2050 carbon	60 years annual average	CO2 equivalents
turnover rates (0.324, 0.0303, 0.047)	707674 ha	benefit	increment, Mg C	25000	MGAP estimate, Mg C	benefit	increment (1990-2050)	in Gt
	Mg C	Mg C	22 years	Mg C	2000000 ha	Mg C	Mg C	3,66
PAYSANDU (west) 10y								
Biomass	22 337 092	20 617 212	937 146	728 344	63 128 197	58 267 541	1 533 356	0,0056
soil	71 521 015	18 055 432	820 701	637 844	202 129 836	51 027 541	1 342 830	0,0049
products	26 619 680	26 619 680	1 209 985	940 393	75 231 475	75 231 475	1 979 776	0,0072
total	120 477 786	65 292 323	2 967 833	2 306 582	340 489 508	184 526 557	4 855 962	0,0178
without products	93 858 107	38 672 644	1 757 847		265 258 033	109 295 082	2 876 186	0,0105
simulated C biomass	22 606 200	20 886 320	949 378	53 250	63 861 840	59 001 184	1 064 364	0,0039
simulated C soil	57 588 160	4 122 577	187 390	1 700 000	155 802 750	4 700 455	2 596 713	0,0095
simulated C products	12 754 270	12 754 270	579 740	0	87 125 210	87 125 210	1 452 087	0,0053
total simulated	92 948 630	37 763 167	1 716 508		306 789 800	150 826 849	5 113 163	0,0187
without products	80 194 360	25 008 897	1 136 768	1 753 250	219 664 590	63 701 639	1 676 359	0,0061

Fig. 19 shows that the simulated 60-year average total annual carbon increment is 5.1 and without products 3.67 million tons of carbon.

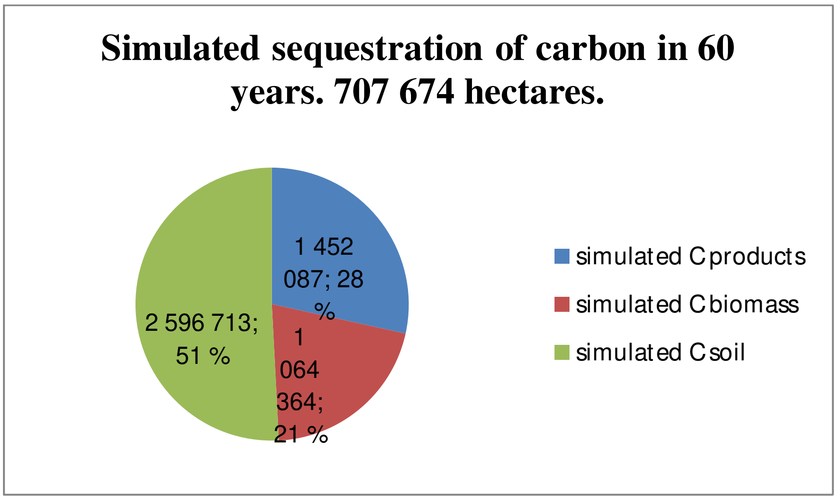

Figure 19. Breakdown of the simulated carbon in different sinks.

Results suggest that the value of eucalyptus plantations as a carbon sequestration tool is important and should be noticed. The eucalyptus plantations actually improve and enhance carbon sequestration if planted to grasslands. More carbon is accumulated to the soil and biomass. The findings of the study endorse the fact that forest plantations increase the total carbon stocks and sequestration capacity is more cumulative than in former pasture land and grassland.

7.1 Sensitivity analysis

With a sensitivity analysis, it is possible to determine how different values will impact to the results. Technique is a way to see the possible different outcome and whether the results turn out to be different than expected.

In the first five simulations the carbon content in the biomass was set to average 0.5 mg carbon per mg dry matter (Mg $CMgDM^{-1}$). Wood density was 0.525 (525 kg/m^3) and turnover rates were same in all five simulations.

In scenarios 9–11 the variables were changed to determine how this alters the outcome. All other variables were same but wood density and turnovers were changed to get a comparison and deviant estimate (table 14). These values were found from several studies and used as an average to formulate estimates (Skolmen 1983; Gill & Jackson 2000; Masera et al. 2002; Lemma 2005; Olmos 2007; Terakunpisut et al. 2007; Law et al. 2008; Nabuurs et al. 2008; Carrau 2010; Kaul et al. 2010; Stolpe et al. 2010; Varmola et al. 2010; Uruguay XXI 2011; Ma, X. & Wang 2011; Pérez-Cruzado et al. 2012).

Table 14. Sensitivity analysis. Different parameters.

Parameters, average, simulation 1	**E. grandis**	**E. globulus**	**average**	**hybrid**
Wood density, kg m^{-3}			525 (0.525)	
Carbon content (g-C/g-DM)				
Foliage			0.52	
Branch			0.455	
Stem			0.5	
Root			0.452	
Turnover rates, $year^{-1}$				
Foliage			0.324	
Branch			0.0303	
Root			0.047	
Simulation 9, different density	**E. grandis**	**E. globulus**	**average**	**hybrid**
Wood density, kg m^{-3}	480 (0.48)			
Carbon content (g-C/g-DM)				
Foliage			0.52	
Branch			0.45	
Stem			0.5	
Root			0.45	
Turnover rates, $year^{-1}$				
Foliage	0.324			
Branch	0.0303			
Root	0.047			
Simulation 10, different turnover rates	**E. grandis**	**E. globulus**	**average**	**hybrid**
Wood density, kg m^{-3}			0.525	
Carbon content (g-C/g-DM)				
Foliage			0.52	
Branch			0.455	
Stem			0.5	
Root			0.452	
Turnover rates, $year^{-1}$				
Foliage	0.25			
Branch	0.03			
Root	0.03			
Simulation 11, different turnover rates	**E. grandis**	**E. globulus**	**average**	**hybrid**

Wood density			0.525	
Carbon content (g-C/g-DM)				
Foliage			0.52	
Branch			0.455	
Stem			0.5	
Root			0.452	
Turnover rates, year^{-1}				
Foliage		0.6		
Branch		0.02		
Root		0.04		

The results of the sensitivity analysis are presented in the table 15. Change in turnover rates of roots, branches and foliage does not have significant effect to the outcome. Turnover rate means (foliage, branches, roots) the annual rate of mortality. root turnover rate of 0.047 means that 4.7% of the total biomass is converted to litter every year.

The model demonstrated higher sensitivity to root and foliage turnovers than to branch turnover. Same tendency can be seen in the study conducted by Pérez-Cruzado et al. (2012). Increase in the foliage turnover rate seems to affect most to the outcome.

In simulation 9 the figures are 0.6, 0.02, 0.05 and in simulation 10 0.25, 0.03, 0.03. The analysis showed that bigger turnover rates increase carbon content in the soil 3.1 tons (by 12%), but in biomass the change is negative by 800kg (-3%). Total carbon benefit increased almost one per cent. Lower turnover rates decreased carbon content in the soil only 0.37% and the biomass changed from 29.1 to 29.7 Mg Cha^{-1}.

The results (Table 15) are that total annual carbon benefit increase from 92.3 to 93.2 (simulation 9) and in to 92.7 Mg Cha^{-1} (simulation 10). Carbon benefit in the soil increases from 25.5 to 28.6 and in scenario 10 decreases from 25.4 Mg Cha^{-1}. Initial carbon (75.6) in the soil is deducted from the soil benefit.

Results also imply that different eucalyptus species sequester more carbon than other, because species have different wood densities, turnover and growth rates. Consequently, E. *globulus* and hybrids accumulate more carbon from the atmosphere than E. *grandis*. Changing wood density from 525 (average) to 480 (E.*grandis*) kg/m^{-}

^{3} alter the results drastically, as expected.. The soil carbon content decreases over 17% in hectare (4.4 Mg Cha^{-1}). The total carbon benefit in the forest biomass changes by 11.3% from 92.2 to 81.9 Mg Cha^{-1} (-10.3).

Table 15. Sensitivity analysis with 3 scenarios (simulations 9–11) and compared to the average scenario.

Simulation, average 60 years	grassland	pulp 10 years	carbon	percentage
average scenario	Mg Cha^{-1}	Mg Cha^{-1}	benefit	change
simulation 1			Mg Cha^{-1}	
biomass	2.4	31.6	29.1	
soil	75.6	101.1	25.5	33.8%
products	0.0	37.6	37.6	
total	78.0	170.2	92.2	118.3%
dry weight (525)				
turnover rates (0.6, 0.02, 0.04)				
simulation 9				
Biomass	2.4	30.7	28.3	
soil	75.6	104.2	28.6	37.9%
products	0.0	36.3	36.3	
total	78.0	171.2	93.2	119.5%
dry weight (525)				
turnover rates (0.25, 0.03, 0.03)				
simulation 10				
Biomass	2.4	32.1	29.7	
soil	75.6	101.0	25.4	33.6%
products	0.0	37.6	37.6	
total	78.0	170.7	92.7	118.9%
dry weight (480)				
turnover rates (0.324, 0.0303, 0.047)				
simulation 11				
Biomass	2.4	28.9	26.4	
soil	75.6	96.6	21.1	27.9%
products	0.0	34.4	34.4	
total	78.0	159.9	81.9	105.0%

Figure 20 shows four scenarios with different turnover rates and one with different wood density compared to the average scenario (simulation 1).

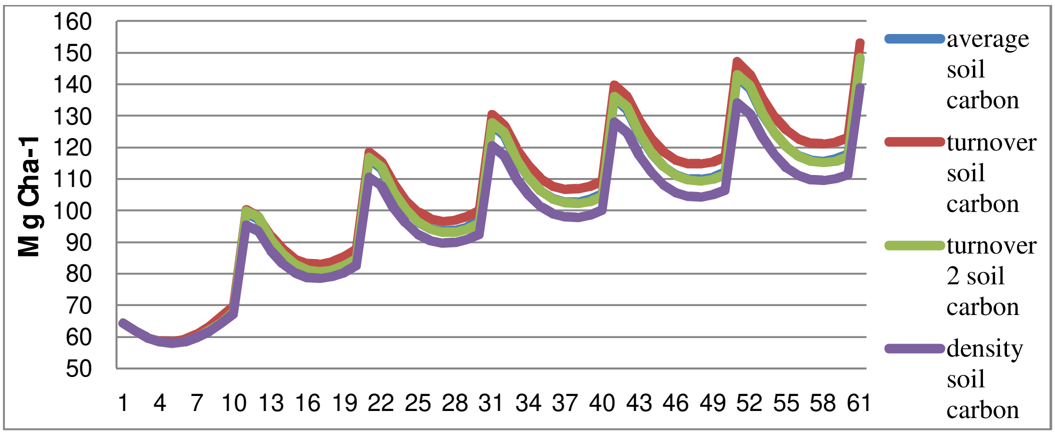

Figure 20. Sensitivity analysis with different parameters, 4 scenarios.

7.2 Reliability and analysis of the results

Somewhat higher values are from the fact that this study included carbon in the soil and products. Also used data was more recent and accurate. Results are reliable and comparable to previous studies. Deviations will occur when results are scaled up to 700000 hectares; hence the outcomes are more or less indicative. Nevertheless, estimates seem considerable precise.

MAI values are averages and estimates from different departments. Pérez-Cruzado et al. (2012) have indicated that site index have an effective impact to soil C stock. To achieve reliable and accurate results more detailed plot data is needed in following studies. Cost of wood products, or demand and prices of the end products are left out from the simulations. Harvest returns are sensitive to changes in price of capital, land prices and different costs. Emissions from transportation of roundwood are not discounted.

In the simulations 1–8 the carbon content in the stem was set to 0.5 mg carbon per mg dry matter (Mg C $MgDM^{-1}$) (0.4–0.56). Wood density was 0.48 Mg DM/m^3 and turnover rates were same in all eight simulations. Relative growth of foliage, branches and roots are also compared to percentage figures found from previous studies. Kaul et al. (2010) showed that the relative distribution of dry matter is 8% in leaf, 15% in branch and root in Eucalyptus forest. Cohort parameters (Table 5) are same in 1–5 and 8–11 simulations to understand more accurately other correlations. This would not be a case in an every department and plot. In the simulations 6 and 7 cohort parameters are adjusted to better correlate with the department level climate variables. In the simulations 9–11 the carbon content was same but the wood density and turnovers were changed to get a comparison and deviant estimate. These value were find from several studies and used as an average to get the estimates.

The carbon pool in plantations was simulated for the changed rotation of 10 to 12 years. Ten year rotation period is estimated to be optimal for eucalyptus plantation in Uruguay. There can be seen shorter rotations in different departments, but they do not necessarily provide higher volumes.

Variation in mean annual precipitation (MAP) is changing – to some extent – accumulation of carbon to soil pools (Berthrong et al. 2012). In this study similar tendency in SOC and forest biomass can be seen. In Uruguay there are planted several species and they all have different wood densities. The results showed that carbon stocks are highly sensitive to changes in wood density. C stocks could vary several tons in a hectare.

2050 simulated estimates are obtained by using 34 000 average annual planting and multiplied by annual volumes. The used average is from the last 22 years. 2050 calculated results are derived from annual carbon benefits and total eucalyptus plantations. It is worth talking into consideration that more accurate plot data would provide more detailed results.

8. SUMMARY OF THE RESULTS

The results were calculated with the CO2fix model and the data of the study were derived from different reports, studies and the inventory tables. The model give estimates of forest total carbon stocks and fluxes. Forest biomass is divided in the model to different compartments: the forest biomass, wood products and soil organic matter.

Empirical part of this study succeeded to refute the hypothesis that natural forests, agricultural, grasslands or degraded lands sequester more carbon than fast growing tree plantations. The results of this study suggest that eucalyptus plantations sequester and add more carbon to soil, than without forest.

Table 16 shows percentage change in carbon stock, compared to grassland scenario, products are not included. Increase in the soil carbon is over 30%, in the first eight scenarios. The total (biomass + soil) increase in the soil carbon is over 70%, in nine scenarios. The most significant increase is in 12-year rotation period; increment in the forest ecosystems carbon storage is 62.1 Mg Cha^{-1} (tons of C). The results suggest that carbon storage potential was highest for high productive species.

Table 16. Summary of the results.

Results	**scenario 1**	**sc. 2, 12-years rotation period**	**sc. 3, poor site**	**high productivity**
Rotation period	10	12	12	10
Precipitation, mm	119	119	119	119
Carbon pool. Mg Cha^{-1}.				
Total in forest ecosystem	170,2	173,8	103,8	266,4
Total carbon benefit in forest	92,2	95,8	25,8	138,5
soil	101,1	104,4	74,5	121,0
living biomass	31,6	35,7	35,7	45,2
products	37,6	33,7	33,7	50,3
Total in all plantations (707 674 ha)	65 292 323	67 819 068	0	N/A
Change in C stock, compared to grassland scenario	70 %	80 %	41 %	113 %
	sc. 5, products	**sc. 6, Tacuarembó**	**sc. 7, Artigas**	**sc. 8, 2050**
rotation period	10	10	12	10
Precipitation, mm	119	125	130	119
Carbon pool. Mg Cha^{-1}				
Total in forest ecosystem	239,8	171,1	168,9	
Total carbon benefit in forest	161,8	93,8	92,3	92
soil	101,1	103,3	97,7	N/A
living biomass	31,6	31,5	36,0	N/A
products	107,2	36,3	35,1	N/A
Total in all plantations (700 000 ha)	N/A	N/A	N/A	184 526 557
Change in C stock, compared to grassland scenario	70 %	74 %	75 %	
	sc. 9, turnover	**sc. 10, turnover**	**sc. 11, density**	
rotation period	10	10	10	
Precipitation, mm	119	119	119	
Carbon pool. Mg Cha-1				
Total in forest ecosystem	171,2	170,7	159,9	
Total carbon benefit in forest	93,2	92,7	81,9	
soil	104,2	101,0	96,6	
living biomass	30,7	32,1	28,9	
products	36,3	37,6	34,4	
Total in all plantations (700 000 ha)	N/A	N/A	N/A	
Change in C stock, compared to grassland scenario	73 %	71 %	61 %	

This study estimated that eucalyptus plantation would have a total carbon sequestration capacity 92.2 Mg Cha^{-1} on average. Results in this study demonstrate that the estimated average biomass carbon density is 29.1 and in soil 25.5 Mg Cha^{-1}. The baseline (grassland) is deducted, so these are net results.

Eucalyptus plantations have the potential to sequester 1.14–1.76 million tonnes of carbon annually. The estimates vary because the first is calculated from annual planting figures and the latter from total plantation area. In 2050 there could be over 2 million hectares of eucalyptus plantations and the annual sequestration is estimated to be 1.7–2.9 million Mg C.

Carbon sequestration is also sensitive to mean annual precipitation. The average monthly rainfall varies between 119–130mm in simulations. The findings of this study suggest that 125mm rainfall (Tacuarembó) provides steady increase in the soil compartments. 119mm and 130mm resulted in the same total soil C stock of 92.3 Mg Cha^{-1}. The financial module proved that eucalyptus plantations in Uruguay are economically feasible. Usually investments to plantations are economically reasonable.

Sensitivity analysis showed that bigger turnover rates increase carbon content in the soil 3.1 tons (by 12%), but in biomass the change is negative 800kg (by -3%). Total carbon benefit increased almost one per cent. Lower turnover rates decreased carbon content in the soil only 0.37% and the biomass changed from 29.1 to 29.7 Mg Cha^{-1}. The wood density of the tree changes the results far more distinctly, as expected. Altering the dry weight from 525 to 480 kg/m^3 lowers the total carbon benefit in the forest biomass by 11.3% (10.4 Mg Cha^{-1}).

9. Discussion

9.1 Answers to main research questions

In this chapter the empirical questions presented in 1.2.2 implementation of the study are answered.

Fast-growing eucalyptus plantations have the potential to sequester more carbon than grassland or abandoned pasture sites. More carbon is also added to the soil in every simulation compared to grassland, which serve as a baseline. The results show that the eucalyptus plantations in Uruguay sequester total (soil + biomass + products) of carbon of 92.2 Mg Cha^{-1} and 1.54 Mg $Cha^{-1}yr^{-1}$. Soils store on average 25.5 Mg Cha^{-1}, after every rotation averagely 34% more carbon is added to soil compartments compared to grassland C stock.

Sufficient evidence was found to demonstrate the link between change in the forest rotation period and carbon storage. 12-year rotation is more profitable and store more carbon to the biomass and soil than 10-year rotation period. Increased rotation periods also ensure growth of more valuable saw logs. Longer intervals between harvests could strengthen the capacity of forest ecosystems (trees and soil) to sequester carbon in the long run. Results in this study also verify this hypothesis; the soil sink increases from 25.5 to 28.8 Mg C (13%). Plantations are also more profitable investments if longer rotation continue to increase yield (CAI).

The growth in volume of wood changes drastically carbon storage in plantations. Variation of the average MAI of 32 to 40 (simulation 4) resulted in 50% increase in the net carbon storage (92.2 to 138.5 Mg C ha^{-1}). It seems also that E. grandis, E. globulus and different hybrids are most productive and could store carbon most efficiently (FAO 2003; Masera et al. 2003; Nabuurs et al. 2007, 2008; Kaul et al., 2010a, b; Berthrong et al. 2012).

Different forest management practices, reduced deforestation, degradation and afforestation are expected to increase in the future. Forest plantations (deforestation, afforestation) prevent further land degradation, reduce carbon emissions, sequester more CO_2 and for longer time. Eucalyptus plantations mitigate efficiently greenhouse gas (GHG) emissions and will take away pressure of harvesting from natural forests.

These factors could be essential in the climate change mitigation. Agro-forestry and bio-energy are also crucial and necessary factors to climate change mitigation and sustainable development management practices, such as fertilization, also enhance carbon sequestration. Fertilizer increase N_2O emissions and reduces benefits of carbon sequestration (Koskela et al. 2000).

It is important for the forest companies to select suitable species to different sites, if the concern is to increase carbon stocks in the future. The forest companies in Uruguay should also leave harvest residue to logging site in the future as well, and not start to produce the energy from the biomass. Since the slash increase the soil carbon and dispense nutrition to the next seedlings (IPCC 2007; Pérez-Cruzado et al. 2012). It is worth mentioning that regrowth of the trees could sequester the carbon emission from burning of these biomass fuels (Koskela et al. 2000).

The simulated results verify previous studies that carbon sequestration is also sensitive to mean annual precipitation. The total net carbon is 2% bigger when precipitation increases from 119mm to 125mm. The result is same with the average scenario (119mm) and scenario 7 (130mm, Artigas). The key finding is that the soil carbon decrease from 25.5 to 23.6 Mg C, when monthly precipitation is 130mm.

Eucalyptus plantations in Uruguay are financially beneficial; returns from logging surpass all costs during the rotation period. Land prices have increased in twenty years about 50% due to powerful demand from different foreign companies. Financial module showed that eucalyptus plantations in Uruguay are economically feasible. A plantation project will be worth an amount greater than the cost to plant it, estimated cost are compared against estimated value. 12-year rotation period increased volume (m^3/ha) and net present value with about 15% – ceteris paribus.

Kaul et al. (2010) and Klepper (2010) have pointed out that it is not necessarily proven fact that implemented CDM projects create additional emissions reductions. A monocultural eucalyptus tree plantation may not even be sufficient and reasonable for CDM projects. Industrial tree plantations are usually temporary and managed for raw material to a pulp mill. At this moment eucalyptus plantations in Uruguay are not viable CDM projects and could not receive carbon credits, because forests do not create additionality. Companies are compelled to prove that the carbon project would not be established anyway. The main purpose of the plantations is to provide raw materials for companies not to sequester carbon. This study showed that forestry CDM projects could be considered in Uruguay, but then plantations end-use have to be changed. Companies would benefit if forests are managed to some other use and get carbon credits if the raw material is changed from pulp to products. Then projects would be additional and increase carbon stocks. Baseline scenario of 78.0 (simulation 1) compared to the total carbon storage result with products (simulation 5) 170.2 Mg Cha^{-1} is the amount that can be seen additional and could get credits. 92.2 tons of carbon would generate in 10-year rotation period about $1300–1845 in a hectare.

There are about million hectares of eucalyptus and pine plantations, and 800 000 ha native forest in Uruguay. It will take 37 years to reach estimated 2 million eucalyptus hectares, amount available for plantations, and area needed for trees is also two times bigger. Year 2027 would be achievable if 85000 trees are planted in a year like in 1998, but that would cost over a double compared to the average annual planting (34000) (MGAP FAO 2010; MGAP 2013). Discounted harvest revenues would exceed all discounted costs, so investment will be profitable and there for viable. The results of the simulations could assist in guiding future planting programs.

There are some limitations and uncertainties in this study, since averages are used in simulations. Precipitation, tree growth figures, soil data and turnover rates are averages and generalized cases from different parts of Uruguay. The results are estimates on a plot and country level. Specific inventory data from field studies could provide more accurate results. But considering the time and the cost needed to carry out extensive measurements is probably not worthwhile.

9.2 Comparison to previous studies

The results of this study seem to be comparable with previous similar studies and calculations. The annual sequestration results of this study are higher than other reported figures 1–2.7 million tons of carbon (World Bank 2010; FCPF 2013; Mongabay 2013). In 2011, the total forest carbon in Uruguay was 83 million metric tons and average carbon density was 28 Mg Cha^{-1} (World Bank 2010). The results of this study estimate 93 million tons of total carbon in eucalyptus plantations, and with forest products 120 million tons. The simulated corresponding results are 92 and 80 million tons of carbon. The total forest carbon figure would be even higher, close to 200 million tons of carbon, if natural forests and pine plantations are included (Carrau 2010; Montes del Plata 2013).

The mean carbon benefits in different sinks are 29.1 (biomass), 25.5 (soil) and 37.6 (products) Mg Cha^{-1}. So the total carbon density is 54.6 Mg Cha^{-1} and 0.91 Mg $Cha^{-1}yr^{-1}$, without products. The total (afforestation-baseline) annual carbon sequestration of 707 674 hectares is 1.76 million and 2.97 tons of carbon with products (1–2.7<1.76–2.97 Mg C). Pérez-Cruzado et al. (2012) estimated that the average biomass carbon was 34.2–42 and in soil 73.4–92 Mg Cha^{-1} in eucalyptus globulus plantation in Spain. The average SOC of the pasture was 82.3 and in this study the baseline for estimations is 75.6 Mg Cha^{-1}. In the research of Kaul et al. (2010a) the average soil carbon pool was 75 Mg Cha^{-1} in India.

The OECD on climate change in Uruguay and the agriculture and forestry sector estimated that plantation forest could sequester carbon 280 Mt CO or 76.4 Mt C (0.0764 Gt C) in 2030. These sinks would offset about 23% of total GHG emissions. This study estimated that eucalyptus plantation have sequestration potential of 150–184 and simulated 90–109 Mt C in 2050. The simulated results are from the CO2fix model and calculated from the ad hoc Excel model. The average annual benefit could be double to current estimates 1.68–2.88 Mg C.

In 2011, Uruguay's total annual carbon dioxide emissions were 8.3 million metric tons of carbon dioxide equivalents (0.0083 Gt CO_2eq), which is 2.27 million Mg C. In 2012, the simulated annual sequestration capacity of eucalyptus plantations was 1.14–1.76 million Mg C (Table 13.). Annual emissions 2.27 million Mg C is about twice than eucalyptus plantation could sequester. In the future – if planting is continued as scheduled – conditions become more favorable to controlling of local CO_2 emissions and climate. The annual sequestration capacity of 0.006–0.011 Gt CO_2 (1.68–2.88 Mg C) would offset annual emissions of 0.0083 Gt CO_2eq (2.27 Mg C) in 2050. Although, CO_2 emissions must remain the same in 37 years.

The findings of the study are similar to the results of Berthrong et al. (2012); carbon sequestration is sensitive to mean annual precipitation (MAP). Berthrong et al.

(2012) estimated that MAP alters the total soil carbon remarkably. The results calculated and simulated in this study demonstrate the antipodean tendency. In Paysandú, where the mean monthly precipitation is 119mm, plantation increases the annual soil carbon by 34% in hectare, in Tacuarembó 38% (125mm), in Artigas 32% (130mm).

This thesis also proved that eucalyptus plantations in Uruguay are economically beneficial in overall and for the forest companies. Sensitivity analysis showed that alteration of turnover rates and wood density parameters changes the results to some extent. Grater turnover rates result in 3.1 ton increase in the soil carbon. Minor wood density reduces carbon sinks. Average figures for analysis were derived from other studies. These results are similar that other studies have published (Masera et al. 2002; Nabuurs et al. 2008; Kaul et al. 2010; Stolpe et al. 2010; Pérez-Cruzado et al. 2012).

Previous studies have showed that forests plantations are significant carbon sinks and have prominent role in the future. The results in this study correspond to these findings. Uruguay's plantations have high potential to sequester carbon and will continue to be a significant carbon sinks in the future. It is a fair assumption from different studies that forests plantations are important in mitigation of carbon dioxide and the climate change.

10. Conclusions

The purpose of this study was to estimate carbon sequestration potential of intensively managed eucalyptus forest plantations in Uruguay. The aim of this research was to calculate carbon stocks and fluxes in the eucalyptus forest ecosystem and show benefits of a carbon sequestration. The used method for calculations and estimations was CO2fix model and ad hoc Excel model. The CO2fix model proved its versatility and wide applicability.

Calculations of the CO2fix and Excel models indicate that eucalyptus plantations are carbon sinks not carbon emitters. In conclusion, the results of this study suggest that plantations in Uruguay store more carbon than grassland and abandoned pasture land. Plantations have a vast sequestration potential already and their importance will increase in the future. There are about 3 million hectare available for different forests; providing a significant opportunities for carbon and pulp plantations for several decades. This study also find answers to the question, whether it is reasonable in case of carbon sequestration to prolong rotation period. Compared to the 10-year rotation, 12-year rotation period increases returns and carbon stocks. The financial module and calculations show elevation of harvest returns by 15% after first rotation.

The simulation results presented in this study show that the 60 years (10 years rotation period) total (afforestation-baseline) average carbon storage benefit is 92.2 Mg Cha^{-1} and in 12 years rotation period corresponding figure is 95.8 Mg Cha^{-1}. Meaning 118% and 123% increase compared to grassland scenario, respectively. Afforestation with eucalyptus increases soil carbon content in 10-year rotation period by 34% (101.1>75.6) and in 12-year rotation 38% (104.4>75.6) (60 years simulation). Estimated average increase in biomass and products carbon accumulation is 25.5 and 37.6 Mg Cha^{-1}, respectively.

In poor site quality areas carbon stocks decrease to 28.8, whereas high productivity totals 138.5 Mg Cha^{-1}. The average total carbon stock in Tacuarembó (10-year rotation) is 171.1 and the hectare scale benefit is 93.8 Mg Cha^{-1}. In Artigas (12-year rotation) the total result is 168.9 and benefit is the same as in Paysandú 92.3 Mg Cha^{-1}, but biomass carbon is grater (33.6>29.1) than soil (23.6<25.5), because of increased precipitation. The results of this study also proved that mean annual precipitation (MAP) alters carbon sequestration. Figures from different departments are averages and indicative, but compared to other studies the results seem reliable and valid. The conclusion is also that it is advisable to plant more productive species to provide increased yields and carbon sequestration in subsequent decades. The alteration in branch and root turnover rates does not change the outcome significantly; the total carbon benefit results changed by 0.4–0.9 tons in a hectare. Foliage turnover rates alter soil carbon results more visibly, because more leafs are flowing to the ground. Sensitivity analysis shows that turnover rates have a minor effect to the results in a hectare scale.

The average net carbon sequestration of 92.2 Mg Cha^{-1} (337 tCO_2) is equivalent to offset emissions produced by heating of about 330 average houses. Heating a typical home for a whole year in the EU generates ton of carbon dioxide, about the same amount of emissions than does a round trip flight from London to New York. One metric ton of CO_2 is also produced to the meet the average monthly energy demand of the typical American household or a car doing the average annual mileage. One hectare (1.54 Mg $Cha^{-1}yr^{-1}$, 5.64 tCO_2) of eucalyptus plantation in Uruguay sequester about the average annual energy related CO^2 emissions of one typical American household or the emissions heating a typical home for a whole year.

707 674 hectares of eucalyptus plantations in Uruguay have the net potential to sequester 38.5 million tonnes of carbon and to reduce 140 million tonnes of CO_2. The total carbon storage is 65 million tonnes if forest products are included. In comparison, combined emissions from flights to and from Europe and overflying aircraft are 162 million tonnes of CO_2. Eucalyptus plantations in Uruguay offset about 50%–70% of the emission produced in the country. The annual carbon sequestration potential (afforestation-baseline) is 1 757 847, or 2 967 833 Mg C when products are included. In the future the C stock capacity increases and could store all the emissions.

Fast-growing species in tropical and subtropical forest plantations could enhance terrestrial sinks, mitigate the effects of deforestation, storage carbon rapidly, and act as a carbon sink, and this way reduce greenhouse gas emissions. Short-rotation bioenergy crops for energy production substitute fossil fuels and also effectively mitigate the greenhouse effect. Due to these reason plantations are an important factor of the global carbon cycle and climate change mitigation (Houghton et al. 1983; Kaul et al. 2010a, b; IPCC 2007; FAO 2011).

Forest plantations are an expanding land-use form and a significant source of raw material in the tropics and subtropics. Uruguay have supported consistently use of non-forest lands conversion to fast-growing intensively managed short-rotation plantations. This blueprint has proved to be suitable to produce raw material for energy use, pulp industry, and enlarge carbon stocks. Companies have planted different species during the past 71 years. This has enhanced a biodiversity and carbon stocks in overall. Forest management will improve the ability of forests to store carbon. Forest management (rotation periods, fast-growing species, fertilization etc.) are significant and necessary measures to increase mitigation of carbon and alleviate climate change. Studies have shown that the choice of planted species mix, hardwood and softwood, are remarkable method in meeting carbon targets. Ecosystem carbon pools, such as trees, soil, forest litter and wood products act as a net carbon storage (Cossalter and Pye-Smith 2003; Nabuurs et. al. 2008; IPCC 2007, 2011). Some of the aforementioned studies pointed out, as expected, that no thinning plantations have the largest biomass and carbon storage. The findings of this study also prove that no thinning provides a highest carbon stock. Forest management policy in Uruguay suggests that no thinning is conducted during a seven to ten–year rotation. After harvest all the harvest residues are left to the soil. Branches stay as a carbon sink and will be used as a nutrition for the next generation of planted trees. The optimal rotation for eucalyptus in Uruguay is 7 to 12, depending on the site index and forest management methods. In this study optimal rotation seemed to be 12-years, carbon stocks and revenues increased most compared to other simulations (Cossalter and Pye-Smith 2003; Nabuurs et. al. 2008; Montes del Plata 2013).

Deforestation, afforestation and mitigation are effective mechanisms in reducing emissions and decrease the global climate change. In this study – also in numerous other studies – it is presented that trees sequester more carbon that degraded (pasture, Pampa) and non-forest lands. Reforestation of pasture and degraded lands reduces logging of natural forests, and increases soil carbon and reduce net carbon emissions. The soil compartments sequester more than they emits (net sequestration) when afforestation’s are implemented in a degraded pasture land. Deforestation and afforestation, such as plantations, provide constantly flood and erosion control, more than non-forest lands. Needless to say, long rotation plantations are even more beneficial carbon storages, since they sequester carbon longer period of time. Longer rotation periods also ensure growth of more valuable saw logs. Plantations are also more profitable if longer rotation continue to increase yield (CAI) and are more productive than alternative investments. Change in the annual increment also affects largely to carbon sinks in the forest. Results in this study and many others show that increase in increment enhance carbon sequestration (Nabuurs et. al. 2008; IPCC 2007, 2011).

This study – like many others – proves that under no circumstances it is effective to biodiversity or carbon storage convert natural forests to short-rotation plantations. Deforestation of natural forests will lead to the significant degradation and affect availability of ecosystem services. A wide range of negative greenhouse gas emission effects could occur if forested area is conversed to agricultural land. Plantations in Uruguay store carbon responsibly when shifting land from grasslands and degraded lands to forests. Some companies in the country also manage native forests and conservation areas. Plantation provides work for local people, and contributes to exports, renewable energy supply and spike to GDP (Gross domestic product). Forest plantations in Uruguay may provide possible opportunities for CDM projects in the future. It is needed to point out that sinks have to be additional and create measurable mitigation. Changing the end use from pulp to logwood and boards secure carbon storage in products for longer time period (MA 2005; IPCC 2007).

There is a good probability that results of this study correspond to previous studies and are valid. The results of this study cannot be directly generalized to other countries and plantations, because the data is unique and bound to Uruguayan environment. Results can be compared – in some extent – to other similar studies. It is possible to conduct same type of research in other plantations by connecting them to the existing local data or collecting new data from the field. More research is needed to understand size of the total carbon stock in Uruguay. Previous carbon inventories are dismissive, ambivalent and outdated. Further research for pine plantations and natural forest would be interesting, also comparing of hardwood and softwood sequestration in the country. Estimates from different satellite images, remote sensing and carbon flux modeling should be conducted to achieve alternative and comparable results. Other interesting study would be, how is the climate change altering the MAP in Uruguay and what are the outcomes. How does this impact to carbon sequestration?

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APPENDIX

APPENDIX 1: Orders of magnitude (mass):

10^0, 1 tons T

10^6, 1 megatons Mt, 1 million tons

10^9, 1 gigatons Gt (one billion metric tons)

10^3 g, Kg, kilogram

10^6 g, Mg, megagram (ton, one thousand kilograms)

10^9 g, Gg, gigagrams

10^{12} g, Tg, teragram

10^{15} g, Pg, petagrams

10^{18} g, Eg, exagrams

(1 Pg C = 1 Gt C)

In some studies the data is expressed in mass of carbon, while in others data is reported in CO_2 equivalents. Conversion between C and CO_2:

C = 0.273 x CO_2

CO_2 = 3.66 (44/12) x C

The Intergovernmental Panel on Climate Change (IPCC), the UN climate change panel, uses a gigatonnes (Gt) of carbon dioxide equivalent (Gt CO2eq) to measure the global warming (IPCC 2013a).

APPENDIX 2, equations:

Used equation in the financial module:

CB_t, discounted = $CB_t * D_{F,t}$

$D_{F,t} = 1/1+r_{f1} + 1/1+r_{f2} + \ldots D_{F,t-1}/ 1/1+r_{F,t}$

$$NPVt = \sum_{tb}^{t} CB\ t, discounted$$

(Masera et al. 2003; Schelhaas et al. 2004)

The discounted returns (B) of a year multiplied with a discount factor $D_{F,t}$. $r_{F,t}$ is the financial discount rate for year t.