Regeneration of secondary forest or using palm oil to mitigate climatic change

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Abstract

Due to global climate change the pressure to undertake actions to mitigate increases. This thesis evaluates actions that will mitigate the release of anthropogenic greenhouse gases to the atmosphere. Methods to mitigate the effects of the most important greenhouse gas, CO_2, can broadly be divided into two categories: reduction of emissions and sequestration of atmospheric carbon. One option in each category is evaluated in this thesis to determine which is the most efficient in terms of carbon mitigation. The options investigated are palm oil production or the regeneration of secondary forests. The limiting factor in both processes is the available area. This study concludes that, when starting with a degraded *Imperata* grassland, palm oil production leads to a sequestration of 234,5 Mg C ha^{-1} after the first plantation cycle of 25 years. 51,9 Mg C ha^{-1} of this sequestration is carbon mitigated by the actual palm oil production over 25 years. Forest regeneration sequesters a total of 193,7 Mg C ha^{-1} during the same time-period. Allowing more time-steps results in bigger relative yields in the palm oil scenario. Starting a palm oil plantation in an area already containing tropical forest, or with peat soil, results in carbon emissions that require a period of at least 75 or 600 years to repay the incurred carbon debt. Although the conversion of grassland to a palm oil plantation yields the best results in terms of carbon mitigation, the choice for a mitigation option can be influenced by the preference for other secondary effects.

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Chapter 1: Introduction

The global climate is changing; global temperatures are rising due to the anthropogenic release of greenhouse gases to the atmosphere. One of the main effects of this change is the increased pressure on many species increasing extinction rates. The most important greenhouse gas is carbon dioxide, CO_2 (Lashof and Ahuja, 1990). It is important to limit the increase in atmospheric CO_2 concentrations as much as possible. Important sources of atmospheric CO_2 are the use of fossil fuels and changing use of land area.
Rise in CO_2 concentrations in the atmosphere is a result from the loss of long term carbon sinks such as fossil fuels and natural carbon rich ecosystems, like forests and peatlands. According to the IPCC (2007) land use related CO_2 emissions amount to 17,3% of total anthropogenic greenhouse gas emissions and fossil fuels consumption amounts to 56,6% of the total anthropogenic greenhouse gas emissions. When these sinks are accessed or consumed the stored carbon will be released into the atmosphere. To counter this process several methods to reduce the emission or store atmospheric carbon can be thought of. These methods can focus on either reducing the emission of greenhouse gasses or on recapturing emitted carbon.
Methods that reduce the emission of CO_2 focus on reducing the use of fossil fuels. The use of fossil fuels can be limited by using alternative ways to create energy. Examples include wind, solar energy or biofuels. Biofuels provide the advantage that they can be directly applied as a replacement of fossil fuels. Palm oil is one of the most competitive biofuels, with the highest yield per hectare (Johnston *et al.*, 2009) and it is more efficient to import palm oil than to use locally produced biodiesel oils in Europe (Thamsiriroj and Murphy, 2009). Palm oil production is already widely professionalised as it is one of the worlds most used edible oils. 30% of the world's edible oil consists of palm oil (Carter *et al.*, 2007). The relative use of palm oil as biofuel is increasing, currently 27% of the world wide palm oil production is used as biofuel as opposed to 24% five years ago and 18% ten years ago (USDA – FAS, 2012). Palm oil is one of the most promising biodiesel crops readily available and will therefore be the focus of this paper.
Recapturing atmospheric CO_2 can be achieved by changing carbon-poor ecosystems into carbon-rich ecosystems, for example the regeneration of grasslands into secondary tropical forests (Houghton *et al.*, 1993; Silver *et al.*, 2000). Reforestation has been suggested as a way to recapture C through accumulation and long-term storage of carbon in plant biomass and soil organic matter (Lugo, 1992; Brown *et al*., 1996; Fearnside and Guimares, 1996; Hiratsuka *et al.*, 2006). The regeneration of secondary tropical forests will be viewed as a second option in this thesis.
In this thesis the CO_2 mitigation of the production and use of palm oil will be compared with the mitigation effects of biomass in regenerating secondary tropical forests. To compare these, the carbon balance of a palm oil plantation will be compared with the carbon balance of a secondary forest. An important aspect of the carbon balance is taking in to account the initial carbon costs associated with land conversion. This conversion creates a carbon debt that has to be repaid before the system can gain a carbon profit. The carbon balance will be expressed in Mg C ha^{-1} yr^{-1}.

The research question for this thesis is: *"What is a more efficient way to mitigate carbon: the production of palm oil or the regeneration of secondary forests?"*

Approach

To create a carbon balance many variables will have to be taken into account. Variables that are important in the palm oil production chain are:

1. Original land use (degraded land, agricultural land, grassland, forest, peatland)
2. The CO_2 emission as a result of the land use change (direct and indirect)
3. The carbon stored in the palm oil trees on the plantation
4. The size of the harvest of fresh fruit bunches per hectare
5. The efficiency of the oil extraction from fresh fruit bunches
6. The production of fertilizer required for the plantation
7. CO_2 emission during the production process of palm oil to crude palm oil
8. The amount of fossil fuel that can be replaced by a litre of palm oil and associated carbon mitigation.

Variables that are important to assess the mitigation effects of regenerating secondary forest are:

1. The CO_2 emission as a result of the land use change, both direct and indirect.
2. The growth rate of a secondary forest
3. The maximum capacity of carbon storage in a secondary forest
4. The value of secondary forest for the local people in terms of non-timber forest products
5. Chances of forest fires, resulting in the release of CO_2

The variables apply to the situation on Kalimantan when possible. Chosen is to look into the Kalimantan situation because that is where the highest palm oil expansion rates are currently to be found. An additional benefit is that the situation on Kalimantan is relatively well documented.

Outline

The research question will be answered based on a carbon balance comparison consisting of aforementioned variables.

The variables important for the palm oil production will be elaborated upon in chapter 2. This results in a carbon balance for the production of palm oil consisting of a start-up cost and a yearly profit of mitigated carbon (in C Mg ha^{-1} yr^{-1}). The variables which are important for the carbon balance of secondary forest regeneration will be elaborated upon in chapter 3. The balance of the secondary forest will consist of a yearly sequestration of carbon, until a maximum capacity is reached. Chapter 4 will start with a comparison between the carbon balances of chapter 2 and 3. The remainder of chapter 4 will consist of an assessment of advantages and disadvantages of either carbon mitigation method not directly related to the carbon balance, but important for a practical application of the methods. In chapter 5 a conclusion will be reached based on the comparisons in chapter 4. Chapter 5 will also point out uncertainties in the data suitable for further research.

Chapter 2: The carbon mitigation of palm oil production

The purpose of this chapter is to establish a carbon balance to evaluate the production of palm oil. To achieve this, the palm oil production process is divided into several processes which influence the carbon balance. In the paragraphs 2.1 to 2.6 these processes will be quantified and their influence on the carbon balance highlighted. The carbon balance will be expressed in Mg of carbon per hectare per year. These estimated carbon fluxes can either be yearly fluxes or one-off emissions.

Most of the yearly carbon fluxes represent average carbon values per year when considering the entire plantation cycle of twenty-five years. The actual yearly fluxes differ depending on the age of the oil palm (*Elaeis guineensis*).

An oil palm starts bearing fruits after the second year and achieves maximum production after ten years. After twenty-five years the oil palm is no longer economically feasible and the palms will be grubbed up and a next generation of oil palms will be planted.

Other carbon flows are annual constant variables, like peat decomposition and fertilizer production. A third category of carbon sources are one-off emissions related to land conversion at the outset of the plantation. The relative influence of the one-off emissions will decrease when the plantation remains in operation.

From these different fluxes a stock will be taken applying different scenarios. The calculated scenarios differ in duration and in original land use. The different time steps are a single plantation cycle (25 years) or series of multiple plantation cycles (i.e. 2, 3 and 4 plantation cycles). The original land use is either grassland or tropical forest.

In the next paragraphs various processes are described that are of importance to the palm oil production and influence the carbon balance. The order in which they occur in commissioning and operation of the plantation will be held. For each process, the state of affairs, the different possible variables, and the load on the carbon balance will be described. In the last paragraph (§2.7) the balance will be made literally, by projecting the results of paragraphs 2.1 to 2.6 and balancing the results.

2.1 Former land use and land use change

Before a palm oil plantation can start, an area has to be cleared in preparation of the plantation. With this land conversion carbon stored in the current biomass will be released. There are big differences in the biomass stored in an ecosystem.

The systems with the most aboveground biomass (AGB) are tropical forests. These forests can be in pristine condition, partially logged or used as agroforests. Systems relatively poor in carbon like grasslands and degraded soils bring a lower cost to the carbon balance as they have less stored carbon to emit. While degraded soils typically contain less carbon than their non-degraded counterpart, when managed they can be just as productive (Goh et al, 1994; Goh et al 2000).

Besides the AGB there can also be large stocks of carbon in belowground biomass (BGB). There can be made a rough division between two types of soil, namely peat soils and mineral soils. In peat soils the stored carbon is mainly composed of peat and in mineral soils the BGB consists mainly of root mass.

2.1.1 Aboveground biomass

The calculations for the value of AGB in tropical forests range from 100 to 383 Mg C ha^{-1} (Henson, 2005; Rafli *et al*., 2007; Harris *et al*., 2008; Germer and Sauerborn, 2008; Gibbs *et al*., 2008). The AGB content for regular grasslands is 15 to 20 Mg C ha^{-1} in Indonesia (Lasco, 2002). Lower carbon contents ranging from 2,4 to 4 Mg ha^{-1} have been reported for degraded (*Imperata*) grasslands, with higher values outside Indonesia, e.g. 6,7 Mg C ha^{-1} in Papua New Guinea (Woomer *et al.*, 2000; Roshetko *et al*., 2002; Hartemink, 2004; van der Kamp *et al.*, 2009). For the stocks taken on the carbon balance a value of 230 Mg C ha^{-1} and 3,3 Mg C ha^{-1} will be used for tropical forests and degraded grasslands respectively.

2.1.2 Belowground biomass

The BGB of a forest is not significantly different of the BGB of a plantation according to Martin-Spiotta and Sharma (2012). The BGB of both is about 164 ± 4,0 Mg C ha^{-1} in the first meter of soil. The first meter of soil is taken into account, because according to Jourdan and Rey (1997) more than half of the root biomass of palm trees is found below the top 30 centimetres.

According to Fargione *et al.* (2008) there is a loss of 55 Mg C ha^{-1} when converting a tropical forest to a plantation. Reijnders and Huijbregts (2008) say converting a forest to a palm oil plantation results in a loss of 6,8 Mg C ha^{-1} until the soil decomposition stabilizes again. On this carbon balance the emissions calculated by Reijnders and Huijbregts will be used, they calculated the carbon loss of the soil based on direct measurements by Ishizuka *et al.* (2005). This loss will be added to the base stock of a standing forest of 164 Mg C ha^{-1} as shown by Martin-Spiotta and Sharma (2012). (Table 1)

Table 1: The belowground carbon stocks of a palm oil plantation and a tropical forest. The total carbon stocks are presented or the difference between both

Belowground C in plantation	*Location*	*Author*
164 ± 4,0	Pan tropical	Martin-Spiotta and Sharma (2012)
-55 compared to a tropical forest	n/a	Fargione *et al.* (2008)
-6,8 compared to a tropical forest	Malaysia	Reijnders and Huijbregts (2008)

The BGB content for grassland is 68,7 ± 15,8 Mg C ha^{-1} according to Silver *et al*. (2004). This value is based on pastures in Indonesia. The soil C pool of an *Imperata* grassland ranges from 36,2 Mg ha^{-1} to 61 Mg ha^{-1} in Indonesia (Woomer *et al.,* 2000; Roshetko *et al*., 2002; van der Kamp *et al*., 2009), similar or higher values can be found outside Indonesia from 55,9 to 85,7 (Hartemink, 2004; Sang *et al*., 2012), with an average of 47,3 Mg ha^{-1} in Indonesia (Table 2). For this paper the mean of 47,3 Mg C ha^{-1} will be taken on the carbon balance.

Table 2: The belowground carbon stocks in Imperata grasslands, with the corresponding standard deviation when available

Belowground C in grassland	*Region*	*Author*
36,2 Mg ha^{-1}	Indonesia, Kalimantan	van der Kamp *et al.*, 2009
44,6 ± 5,7 Mg ha^{-1}	Indonesia, Sumatra	Woomer *et al.*, 2000
55,9 ± 2,3 Mg ha^{-1}	Vietnam	Sang *et al.*, 2012
61 Mg ha^{-1}	Indonesia, Sumatra	Roshetko *et al*., 2002
85,7 ± 8,9 Mg ha^{-1}	Papua New Guinea	Hartemink, 2004

The biggest carbon emissions can be expected when converting a peat soil to a plantation. To make a peat soil suitable for planting, the soil has to be drained. This allows the peat to decompose resulting in a yearly emission of 10 to 15 Mg C ha^{-1} (Inubushi *et al.,* 2003; Fargione *et al.,* 2008). This decomposition continues for 120 years on average (Fargione *et al.*, 2008) resulting in a total emission of 1200 to 1800 Mg C ha^{-1}.

2.2 Carbon storage in oil palms

After the plantation area has been cleared of the former vegetation the area can be planted with oil palms. The carbon in biomass stocks that will be acquired by the oil palm during its life cycle of twenty-five years will count as a one-time sequestration on the carbon balance. This will be counted as a one-time sequestration because the carbon stored in the oil palms will be maintained during additional growth cycles of the plantation when this generation of oil palms is grubbed up and the next generation has grown.

The carbon stored in the aboveground biomass of oil palm plantations ranges from 48 Mg C ha^{-1} (Palm *et al.*, 1999), 68±39 Mg C ha^{-1} (Lasco *et al*., 2006), 76 (Rafli *et al*., 2007) to 80 Mg C ha^{-1} (Gibbs *et al*., 2008). This is an average of the maintained carbon stock during the twenty-five year life cycle of oil palms. On the carbon balance the value of 76 Mg C ha^{-1} will be taken.

For the belowground biomass a value of 157,2 Mg C ha^{-1} is assumed based on Martin-Spiotta and Sharma (2012) and Reijnders and Huijbregts (2008), see also §2.1.2, Table 1.

2.3 Harvest size of fresh fruits

The oil palms will grow for two years until they reach adolescence, when they start producing fruits. The size of the harvest grows until maximum yields have been reached when the oil palms are about 10 years old and maximum production will be maintained until the oil palms are 15 years old. After 15 years the yields begin to decline until the oil palms are no longer economically feasible. The oil palms are 25 years old at this point and are cut to make space for the next plantation cycle.

In the third year the oil palm yields fresh fruit bunches (FFB's) of about 5 kg per bunch. During the life of the oil palm this will increase to about 50 kg per bunch. Because of these changes over the life cycle the yields will be averaged to a yearly production in tonnes of FFB's per hectare. Butler *et al.* (2009) assume the average productive lifetime FFB yields to range from 17 Mg ha^{-1} yr^{-1} to 20,5 Mg ha^{-1} yr^{-1} based on average FFB yields in 2007 (FAO, 2008; from Butler *et al.*, 2009). Others (Yusoff, 2006; Mattson *et al*., 2000) report similar ranges for FFB yields, namely 19,1-20,1 Mg ha^{-1} yr^{-1} with an average of 19,6 Mg ha^{-1} yr^{-1}. This carbon balance will adopt this average yield of 19,6 Mg ha^{-1} yr^{-1}.

2.4 Oil extraction from fruits

After the fruits have been harvested oil will have to be extracted from these fruits. Although each fruit consists for 50% of oil, not all of this oil can be harvested. Estimates on the output from the literature vary between 20% (Prasertsan and Prasertsan, 1996), 25% (Mattson *et al*., 2000) and 29% (Yusoff, 2006). Some distinguish between crude palm oil and palm kernel oil (Butler *et al.,* 2009 and Fargione *et al.,* 2008). Butler *et al.* (2009) give a value of 21% to crude palm oil and 5% to palm kernel oil. For this carbon balance a value of 25% palm oil from fresh fruit bunches will be adopted, which is an average of the aforementioned percentages. With an average harvest of 19,6 ton FFB yielding 25% palm oil this results in 4,9 ton palm oil per hectare per year.

2.5 Carbon emissions associated with palm oil production

Greenhouse gas emissions during the life cycle of palm oil production can be divided into three emission processes according to Reijnders and Huijbregts (2008). The first is the emission of CO_2 due to the use of fossil fuels for plantations inputs, processing of harvest and logistics. The second is the loss of biomass from forest conversion and soils (paragraph 2.1). The third is the anaerobic conversion of palm oil waste which releases CH_4 (Houghton *et al*., 2001), a greenhouse gas with a global warming potential of 24,5 times the potential of CO_2. Yusoff and Hansen (2007) make a slightly different division of emission aspects of the palm oil production. They divide emissions resulting from the plantation, transport and processing. Both agree that the respiration of inorganics during the processing phase and the depletion of fossil fuels used to produce fertilizer for the plantation make up the heaviest part of the environmental burden.
According to Reijnders and Huijbregts (2008) the fuel input required to produce a ton of palm oil corresponds with 0,27 Mg carbon. This includes the production of fertilizers, transport and processing. Reijnders and Huijbregts (2008) estimate that the CH_4 release from palm oil mill effluent is about 32-48 kg CH_4 ha^{-1} yr^{-1}, when this is corrected for the much bigger greenhouse impact of CH_4 this equates to a carbon equivalent of 0,04-0,07 Mg C per ton of palm oil.
Optimisation of the milling process can halve the influence of the respiratory inorganics on the life cycle balance of palm oil production (Yusoff and Hansen, 2007). By making the transportation more efficient and by improving the production and use of fertilizers the fossil fuel impact can be reduced by more than 60% (Yusoff and Hansen, 2007).
Combining these two results in carbon costs of 0,32 Mg carbon per ton palm oil with a potential reduction of at least 50% in the future this could be reduced to 0,16 ton carbon per ton palm oil. The current practice costs 0,32 Mg carbon per ton of palm oil, with an annual production of 4.9 ton palm oil this results in a carbon cost of 1.568 Mg C ha^{-1} yr^{-1}, therefore this value will be taken on the balance.

2.6 Fossil fuel replacement by palm oil in litres

Fossil fuels can be replaced by biofuels, but there is usually a difference in energy value of the fuel per litre. Due to this difference in energy content a bigger volume of biofuel has to be consumed to deliver the same energy. According to Benjumea *et al.* (2008) the energy value of diesel is 38,662 MJ/L and the energy value of palm oil biodiesel is 34,436 MJ/L. Therefore to deliver the same energy output as a litre diesel 1,12 litre of palm oil biodiesel is required. The density of palm oil is 864,42 kg/m^3 (Benjumea *et al.,* 2008). When combined with the annual production per hectare of a palm oil plantation of 4.9 tons of palm oil, this amounts to 5669 L palm oil per hectare per year. This palm oil displaces 5061 L of diesel.
The density of diesel is 835 kg/m^3 and when diesel is burned it emits 0,86 kg C kg^{-1} diesel (EUCAR, 2007). This emission matches with 0,72 kg C L^{-1} diesel. When the emission per litre of diesel is combined with the yearly displacement of diesel due to palm oil this shows the direct profit of palm oil on the carbon balance, which is 3,644 Mg C ha^{-1} yr^{-1}.

2.7 The carbon balance of palm oil plantations

In

Table 3 a carbon balance is established taking in the carbon stock for a single plantation cycle when replacing a tropical forest. The balance consists of single emissions from the AGB land conversion (§2.1.1), the BGB land conversion (§2.1.2), and the AGB and BGB stored in the palm trees on the plantation (§2.2). Changing costs depending on the number of plantation cycles that are taken into account are the fossil fuel costs associated with palm oil production (§2.5) and the fossil fuel saved by the use of palm oil (§2.6).
The carbon debt is the lost carbon from converting a forest to a palm oil plantation. If there is a net gain of carbon this is shown as a carbon profit. This carbon balance and carbon balances of the 7 other scenarios are included in

Attachment A. The scenarios differ in number of plantation cycles (1 to 4 cycles) or the initial converted land (Forest or Grassland).

Table 3: A carbon balance based on a 25 year cycle for a palm oil plantation replacing a tropical forest

Carbon stock (in Mg C ha^{-1})		Carbon emission (in Mg C ha^{-1})	
Aboveground C Plantation	76	Aboveground C Forest	230
Belowground C Plantation	157,2	Belowground C Forest	164
Fossil Fuel displacement	91,1	Fossil Fuel cost	39,2
Carbon debt	108,9		
Total	433,2		433,2

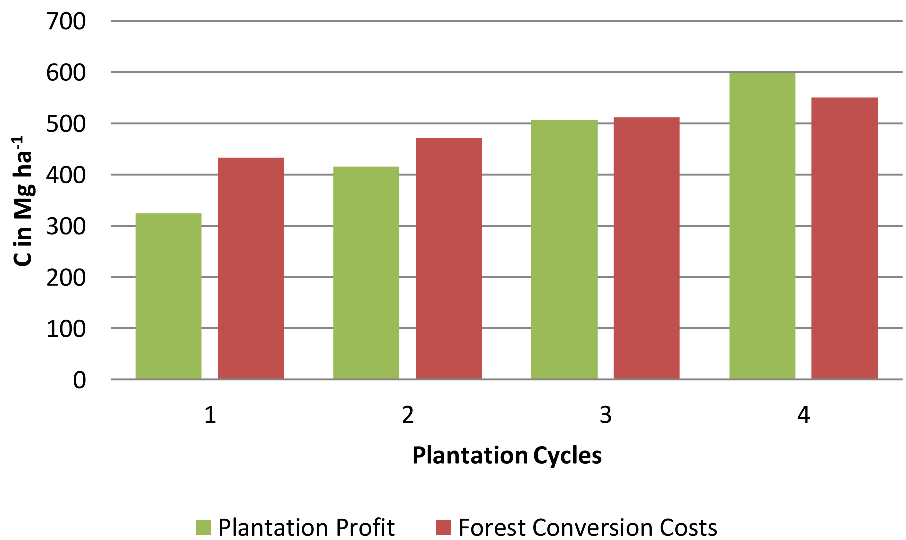

Figure 1: Accumulative carbon storage over time in a palm oil plantation (green) and cost associated with tropical forest conversion and palm oil production (red)

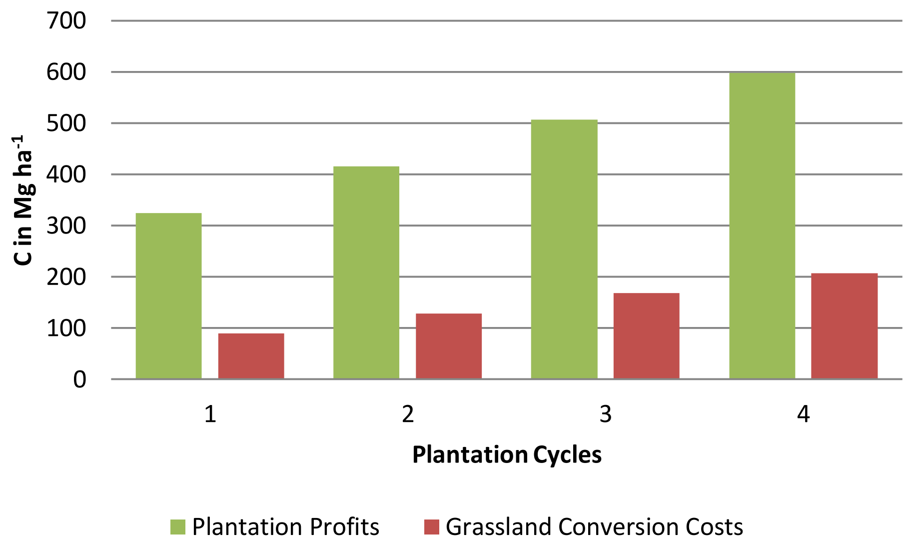

Figure 2: Accumulative carbon storage over time in a palm oil plantation (green) and carbon cost associated with grassland conversion and palm oil production (red)

Figure 1 and Figure 2 compare the cost and profit of a palm oil plantation. In Figure 1 it is shown that the initially high carbon cost from converting a tropical forest to a palm oil plantation takes approximately three plantation cycles (75 years) to get to a breakeven point. Grassland conversion (Figure 2) is already storing carbon after the first plantation cycle. The main part of the carbon profit after the first plantation cycle is due to the additional storage of the plantation itself instead of the palm oil. After one cycle the carbon profit of solely the palm oil is already bigger than that what was stored in the degraded grassland.

If regular grassland is converted instead of degraded grassland the initial carbon costs will increase by about 25 Mg ha^{-1}.

In §2.1.2 the costs of converting a peat soil are estimated to be at least 1200 Mg C ha^{-1}. To compensate for these emissions the plantation has to be maintained for at least another 24 cycles to pass the breakeven point. This corresponds to 600 years of maintaining a palm oil plantation; this will never be the best option to mitigate atmospheric carbon.

Chapter 3: The carbon mitigation of secondary forest regeneration

In this chapter a carbon balance will be established to evaluate the carbon mitigation effects of secondary forest regeneration. To achieve this, the regeneration process is divided into several carbon fluxes. In the paragraphs 3.1 to 3.5 these processes will be quantified and their influence on the carbon balance will be highlighted. The carbon balance will be expressed in Mg of carbon per hectare per year. These estimated carbon fluxes can either be yearly fluxes or one-off emissions. The yearly fluxes will be expanded to a 25-year time-step to compare the results with the results of chapter 2.
Regarding reforestation we will assume that the initial state is degraded grassland. After clearing, the land will lay fallow during which the area will slowly change into a secondary forest. The resulting species composition of the secondary forests is therefore dependent on the present mature species in the area. These species can affect the actual growth speed of the forest. In this chapter average growth rates based on the available literature will be assumed.
The chapter will conclude with a carbon balance comparing all inbound and outward carbon flows. Based on this carbon balance a conclusion will be made regarding the carbon mitigation efficiency of secondary forest regeneration.

3.1 Land use change required for secondary forest regeneration

In §2.1 we assumed several initial ecosystems: tropical forest and tropical grassland. The soil in the area can either be mineral or peat based. In this chapter we will disregard the option of clearing a forest to create a secondary forest, since this cannot lead to higher carbon stocks. The option of using a peat soil will also be ignored here since every agricultural use of a peat soil (Palm oil plantation or otherwise) results in high carbon emissions due to peat decompositions. The last option is what will be looked into here; the regeneration of a grassland into a secondary forest.

3.1.1 The aboveground biomass of a tropical grassland

There are several types of grassland; pastures, agricultural grassland and degraded grassland. Here the degraded *Imperata* grasslands are assumed. These store slightly less carbon than other grasslands, mainly in the belowground biomass (§3.1.2). For a pasture the standing biomass would range from 5,4 to 9,7 Mg ha^{-1} (Sang *et al.*, 2012) or even 15 to 20 Mg ha^{-1} on regular grassland (Lasco, 2002).
Reported *Imperata* grassland carbon stocks diver strongly, with the values for Indonesia ranging from 2,4 to 4 Mg ha^{-1} and higher values for, for example, Papua New Guinea of 6,7 Mg ha^{-1} (Table 4). An average of 3,3 Mg ha^{-1} is assumed for this carbon balance.

Table 4: Aboveground carbon stocks on Imperata grasslands, with the corresponding standard deviations, for different regions

Aboveground C	*Region*	*Author*
2,4 ±0,5 Mg ha^{-1}	Indonesia, Sumatra	Woomer *et al.*, 2000
3,45 Mg ha^{-1}	Indonesia, Kalimantan	van der Kamp *et al*., 2009
4 Mg ha^{-1}	Indonesia, Sumatra	Roshetko *et al*., 2002
6,7 ± 0,9 Mg ha^{-1}	Papua New Guinea	Hartemink, 2004

3.1.2 The belowground biomass of a tropical grassland

Aboveground biomass always increases with reforestation, but the increase of underground carbon remains uncertain, because grasslands are generally associated with high levels of soil C (Conant *et al*., 2001). The carbon storage potential of tropical pastures can be higher than the storage of soil C in mature tropical forests (Detwiler, 1986; Neill *et al*., 1996). The soil C pool of an *Imperata* grassland ranges from 36,2 Mg ha^{-1} to 61 Mg ha^{-1} in Indonesia (Woomer *et al.,* 2000; Roshetko *et al*., 2002; van der Kamp *et al*., 2009), similar or higher values can be found outside Indonesia from 55,9 to 85,7 (Hartemink, 2004; Sang *et al.*, 2012), with an average of 47,3 Mg ha^{-1} in Indonesia (Table 5). This average will be used, because it is assumed that the available *Imperata* grasslands lie within this range.

Table 5: Belowground carbon stocks in Imperata grasslands, with the corresponding standard deviations, for different regions

Belowground C	*Region*	*Author*
36,2 Mg ha^{-1}	Indonesia, Kalimantan	van der Kamp *et al*., 2009
44,6 ± 5,7 Mg ha^{-1}	Indonesia, Sumatra	Woomer *et al.*, 2000
55,9 ± 2,3 Mg ha^{-1}	Vietnam	Sang *et al.*, 2012
61 Mg ha^{-1}	Indonesia, Sumatra	Roshetko *et al*., 2002
85,7 ± 8,9 Mg ha^{-1}	Papua New Guinea	Hartemink, 2004

3.2 Carbon accumulation speed of a regenerating secondary forest

Carbon accumulation of a regenerating forest mainly depends on the growth speed of the trees. Since every tree species has its own growth rate and a secondary forest can be very bio diverse. The average growth rate of a forest depends on the species composition of the forest.
Other important factors, which are beyond the scope of this paper, are precipitation patterns and soil types (Silver *et al.*, 2000; Martin-Spiotta and Sharma, 2012).

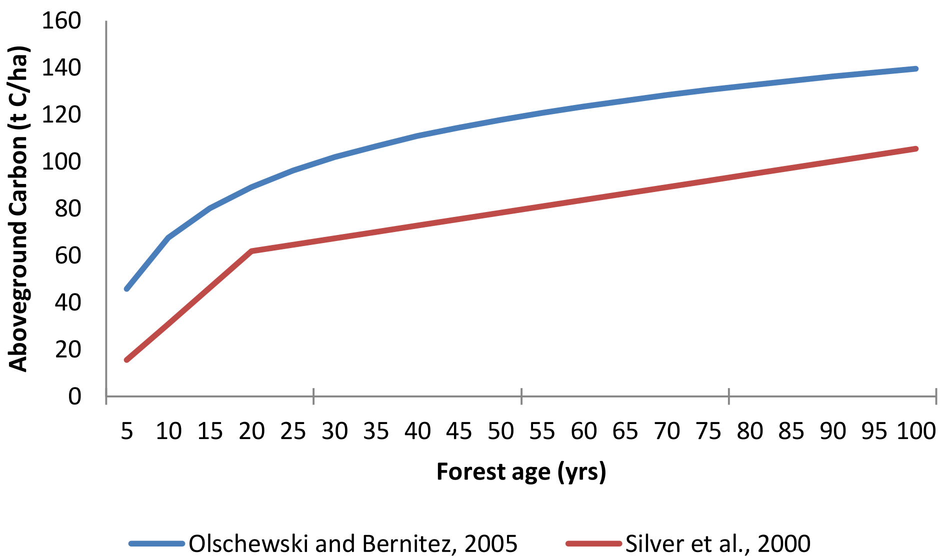

Figure 3: Carbon sequestration in aboveground biomass according to the results as described by Olschewski and Benítez (2005) and Silver et al (2000). Olschewski and Benítez applied a logistic regression where Silver et al. used yearly standardized growth rates

Olschewski and Benítez (2005) build a regression model to predict the biomass of a secondary forest after pasture abandonment: $B = -9.28 + 62.587 * \ln(Age)$, r^2=0,58. The result needs to be converted to a number representing carbon rather than biomass. Olschewski and Benítez propose to do this by multiplying the biomass by 0,5, an estimate more often used, for example by Schlesinger (1999), and Germer and Sauerborn (2008).
Silver *et al.* (2000) use literature data from tropical forest of different ages to reach an average overall growth rate and a growth rate in the first 20 years. The overall rate of aboveground biomass accumulation was 2,36 Mg ha^{-1} yr^{-1} (Silver *et al*., 2000). The average growth rate for young secondary forests (<20 years) is 6,17 Mg ha^{-1} yr^{-1}(Silver *et al.*,2000). Based on the overall growth rate, which is based on forests up to 80 years old, the biomass accumulation rate for forests between 20 and 80 years old is 1,09 Mg ha^{-1} yr^{-1}. Since these values are also measured in biomass they need to be converted to carbon using the same conversion method used for the results from Olschewski and Benítez (2005).
Figure 3 shows the carbon accumulation over time for secondary forest regrowth based on afore mentioned data.
The range in data for the Silver *et al*. (2000) article was for a 20-30 year old forest 7,5 – 126,5 Mg C ha^{-1} (Drew *et al*., 1978; Toky and Ramakrishnan, 1983; Saldarriaga *et al.,* 1988; Lugo, 1992; Aide *et al.*, 1995; Hughes *et al*., 1999) and the range for a 50 year old forest is 22,5 – 137 Mg C ha^{-1} (Greenland and Kowal, 1960; Singh, 1975; Singh and Ramakrishnan, 1982; Lugo, 1992; Hughes *et al*., 1999). The data range for an 80 year old forest is 67 – 98,5 Mg C ha^{-1} (Saldarriaga *et al.*, 1988). Olschewski and Benítez (2005) used data from De Koning et al. (2002), whose data ranged from approximately 75 Mg C ha^{-1} to 150 Mg C ha^{-1} in 25 year old secondary forests in Ecuador.

Table 6: Comparison of aboveground carbon stored after an amount of years (25, 50, 75, 100 years), based on Figure 3

	25 years	*50 years*	*75 years*	*100 years*
Olschewski and Benítez (2005)	96,1 Mg C ha^{-1}	118 Mg C ha^{-1}	130 Mg C ha^{-1}	139 Mg C ha^{-1}
Silver *et al.* (2000)	64,4 Mg C ha^{-1}	78,1 Mg C ha^{-1}	91,7 Mg C ha^{-1}	105 Mg C ha^{-1}
Average used on carbon balance	80,3 Mg C ha^{-1}	97,9 Mg C ha^{-1}	111 Mg C ha^{-1}	122 Mg C ha^{-1}

Table 6 gives the total carbon stored in time steps of 25 years, which correlates with a palm oil plantation cycle. Although the data of Silver has a broader basis in literature, their overall resulting curve seems rather conservative in numbers. Therefore an average of both curves will be used as an estimation of the carbon stored in the aboveground biomass over time.

3.3 Maximum carbon storing capacity

The maximum carbon storing capacity is the total of above- and belowground carbon that can be stored on a hectare of tropical forest when the forest has reached maturity. The actual carbon stored in mature secondary forest is approximately the same as the carbon stored in a primary forest.

3.3.1 Maximum aboveground carbon

Saldarriaga *et al.* (1988) found aboveground carbon in Colombia and Venezuela to range from 112 – 136 Mg ha^{-1} (μ = 128 Mg ha^{-1}). Yamakura *et al.* (1986) found much higher aboveground carbon values for tropical forests on Borneo; 255 Mg C ha^{-1}. The biggest range is reported by Harris *et al.* (2008) based on satellite scans. They came to forest carbon stocks between 73 and 383 Mg C ha^{-1}. Others found aboveground carbon stocks for mature tropical forests to be somewhere in between; 148 ± 76 Mg C ha^{-1} (Germer and Sauerborn, 2008) and 166 Mg C ha^{-1} (Fargione *et al.*, 2008).

For the carbon balance a mature tropical forest will, based on Table 7, have an aboveground carbon capacity of 184 Mg C ha^{-1}.

Table 7: Total of aboveground carbon stored in tropical forests, with corresponding standard deviations if available

Aboveground C (in Mg ha^{-1})	*Location*	*Author*
148 ± 76	Indonesia	Germer and Sauerborn, 2008
158 ± 30	Colombia and Venezuela	Saldarriaga *et al.*, 1988
166	n/a	Fargione *et al.*,2008
228 ± 78 *	Kalimantan, Indonesia	Harris *et al.*, 2008
255	Kalimantan, Indonesia	Yamakura *et al.*, 1986

* Estimated mean and standard deviation based on reported results.

3.3.2 The belowground carbon capacity of a tropical forest.

According to Martin-Spiotta and Sharma (2012) forest age explains little to no variability in soil C, in contrast with aboveground measurements. Therefore the yearly soil C accumulation has

not been taken into account in §3.2. The BGB of a tropical forest is about 164 ± 4,0 Mg C ha^{-1} in the top 100 cm of the soil, independent of time or species composition. The value reached by Martin-Spiotta and Sharma is based upon a review of several pan-tropical studies.
For this carbon balance a value of 164 Mg C ha^{-1} will be added as carbon stock independent of time.

3.4 Non-Timber Forest Products

Secondary forest regeneration may not only drive land use change and may reduce the area available for food crops (Smith and Scherr, 2003), but secondary forests also provide the local people with fruit, medicinal plants and firewood. These effects are greater when the secondary forests are in the vicinity of mature forests (Smith *et al*., 2001), because the mature forest provide a source of seeds for the secondary forest. Secondary forests can also attract animals suitable for hunting.
Forests are important to habitat and socio-cultural framework of local peoples (Byron and Arnold, 1999). For example, 72% of the people in rural Malinau, Indonesia, use forest products to supplement their diet and income (Levang *et al.,* 2005). And in many parts of Indonesia, forest gardens are responsible for 50-80% of the income of farm households (Salafsky, 1993; Joshi *et al.*, 2000).
Because of all the benefits a secondary forest may provide for the local population, it is expected that the conversion of a hectare of grassland to a secondary forest, may reduce the area required for agriculture. When a secondary forest replaces a hectare of agricultural land, the replacement of the agricultural land can be less than a full hectare. Although these effects can be substantial a proper quantification of these effects is not available. Therefore this effect will not be accounted for in this carbon balance.

3.5 Carbon release due to forest fire

A large area of East Kalimantan was burned twice in the last two decades of the 20th century. The chances of forest fires might increase in the future because of global climate change. In 1982-1983 and in 1997-1998 both fires occurred after a prolonged drought caused by El Niño events (Hiratsuka *et al.*, 2006). A total of 5,2 million hectares of forest was burned on Kalimantan during the last fire ('97-'98) (Hiratsuka *et al.*, 2006). These forest fires cause significant carbon emissions (Auclair and Carter, 1993, Page *et al.*, 2002).
If fire kills large primary tree species and the burned area becomes dominated by few pioneer tree species the lost biomass is unlikely to be restored (Toma *et al.*, 2005), therefore the replacement of pioneer species with primary tree species is required to facilitate carbon storage potentials similar to those of primary forests (Hiratsuka *et al*., 2006). Degraded lands without parent trees may not have the potential success for succession leading to replacement

3.6 The carbon balance for secondary forest regeneration

In Table 8 a carbon balance is established taking the carbon stock for a 25 year secondary forest regeneration period with the costs of converting grassland.
The balance consists of a one-off grassland conversion emission as established in §3.1.1 and §3.1.2. And the yearly carbon sequestration in the regenerating secondary forest following the

curves plotted in §3.2 and the total belowground carbon as described in §3.3. Carbon balances for the additional time-steps can be found in Attachment B.
The carbon balances show the carbon gained by secondary forest regeneration as the Carbon Profit. Figure 4 compares the total cost with the total gain of secondary forest regeneration and shows the effects of secondary forest regeneration through time for carbon mitigation. There are no additional carbon costs after land conversion and the profits only increase due to increasing aboveground biomass, because the belowground biomass is assumed to be constant.

Table 8: A carbon balance of the carbon profit of a 25 year secondary forest regeneration period and the initial cost of converting tropical grassland

Carbon stock (in Mg C ha^{-1})		Carbon emission (in Mg C ha^{-1})	
Aboveground C Secondary Forest	80,3	Aboveground C Grassland	3,3
Belowground C Secondary Forest	164	Belowground C Grassland	47,3
		Carbon Profit	183,5
	244,3		261,7

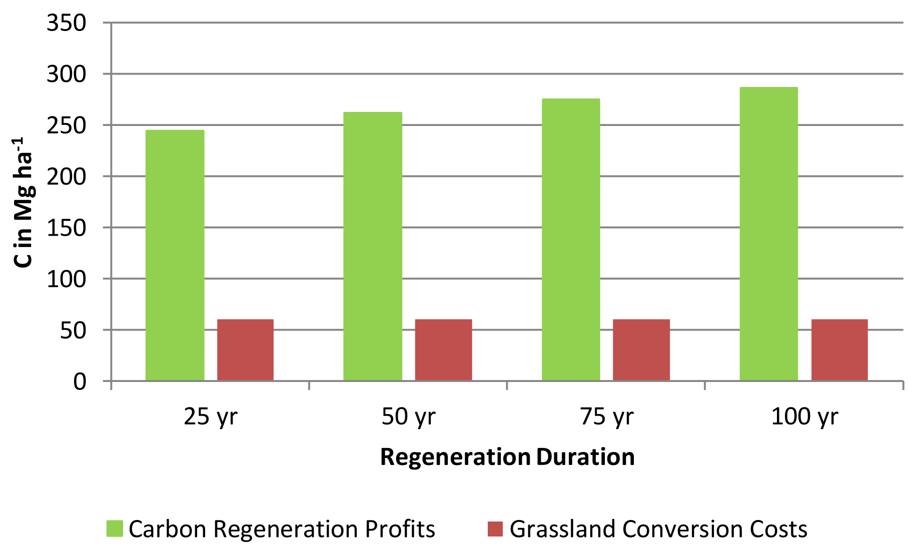

Figure 4: Carbon profits following secondary forest regeneration compared to the associated cost of grassland conversion

Chapter 4: A comparison between palm oil and secondary forest regeneration

This chapter will start with a comparison of the final carbon balances from Chapter 2 and Chapter 3 in terms of carbon mitigation (§4.1). Because carbon mitigation won't be the only reason to enforce a certain policy, additional effects of either scenario have to be taken into account. In §4.2 and §4.3 these advantages and disadvantages will be looked at to put the scenarios in perspective. §4.4 compares the total of all advantages and disadvantages.

4.1 Comparing carbon profits

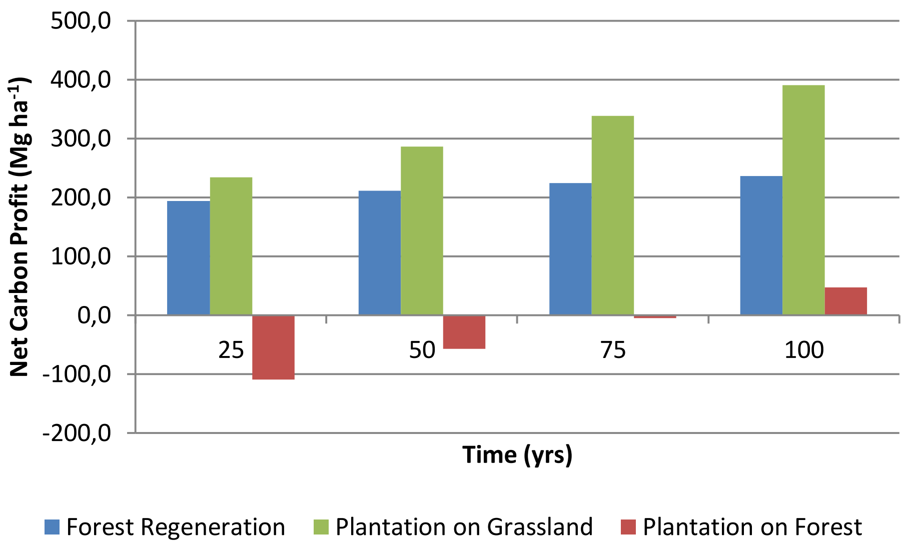

Figure 5: A comparison of the carbon profits of secondary forest regeneration and palm oil production on former grassland and forest respectively in 25-year time-steps

In Figure 5 the comparison is made between using a hectare of mineral soil in the tropics to produce palm oil or to allow for secondary forest regeneration. As seen in Figure 5 converting a hectare of tropical grassland into a palm oil plantation will yield the biggest carbon profit. The carbon profit of a plantation is bigger in each plantation cycle than the carbon profit of a regenerating secondary forest during each 25-year time step. Therefore the relative profit of a plantation will only increase overtime.

When converting a tropical forest to a palm oil plantation the break-even point is after about 75 years, or 3 plantation cycles. The plantation will overtake the regenerating forest in terms of carbon profit after 200-225 years.

According to these calculations using grassland to establish a palm oil plantation is always the better choice when only carbon mitigation is considered, but the actual choice might also depend on other factors. The advantages and disadvantages of palm oil plantations and secondary forest regeneration aside from carbon profits will be elaborated upon in the next paragraphs.

4.2 Other advantages and disadvantages of palm oil production

The main benefit of palm oil plantation is in the money earned by the sale of palm oil. In 2010 Indonesian palm oil and palm kernel production generated $11,1 billion (FAO, 2012; from Carlson *et al.*, 2012). With this additional income it is expected that less people grow their own food, this may lead to more professionalised agriculture. Professionalised agriculture may have the benefit of being more efficient, therefore requiring less land and associated land use change. Sandker *et al.* (2007) expect primary and old secondary forest, required for the slash-and-burn practices of the local people, to become scarce in the vicinity of villages with oil palm plantations. Reducing the fallow period will reduce the yields of the agriculture, therefore driving land use change.

The creation of palm oil plantation may require additional employment and lead to labour migration. Migration causes people to leave their old homes and create new homes, which will probably require more land use change.

The creation of large-scale monoculture palm oil plantations will increase the vulnerability of the plantation to pathogens, according to the Janzen-Connell hypothesis (Connell, 1978; Liu *et al.*, 2012).

4.3 Other advantages and disadvantages of secondary forest regeneration

As mentioned before (§3.4) forest can provide different non-timber forest products (NTFP's), e.g. fruits, medicinal plants, and firewood, the collection of which can have a positive effect on reducing land use change, supplementing income without having a negative influence on the carbon balance (Smith *et al*., 2001; Levang *et al.,* 2005).

Forest regeneration has the benefit of not requiring labour to ensure its growth. Therefore, secondary forest regeneration can take place in remote areas.

Species richness is higher in secondary forests compared to oil palm plantations (Gillespie *et al.*, 2012). Amphibian species in oil palm plantations were dominated by habitat generalists and human commensal species (Gillespie *et al.*, 2012), whereas secondary forests retained a much higher proportion of endemic species (Gillespie *et al.*, 2012). Therefore secondary forests may be important for the conservation of lowland amphibian diversity; in contrast oil palm plantations have a relatively low conservation value (Gillespie *et al.*, 2012).

Other studies show similar results for other taxonomic groups, they have found reduced diversity and/or major shifts in community composition in oil palm plantations for shrews, squirrels and bats (Danielsen and Heegaard, 1995); large mammals (Maddox *et al.*, 2007); birds (Danielsen and Heegaard, 1995; Peh *et al.*, 2006; Azhar *et al.*, 2011); lizards (Glor *et al.*, 2001); butterflies (Koh and Wilcove, 2008); beetles (Chung *et al.*, 2000; Davis and Philips, 2005); ants (Brühl and Eltz, 2010) and terrestrial isopods (Hassall *et al.*, 2006). (From Gillespie *et al.*, 2012)

According to the insurance hypothesis (Yachi and Loreau, 1999) the increase of biodiversity will increase the stability of the secondary forests compared to the stability of the palm oil plantations.

The secondary forests have positive effects on the soil quality. Unmanaged secondary forests are effective at improving the soil fertility and sequestering carbon on degraded lands (Sang *et al.*, 2012). The accumulation of aboveground biomass performs many important ecosystem functions in addition to storing C, including reduction of erosion and nutrient leaching, ameliorating microclimatic conditions and providing shelter and structural complexity for wildlife. (Silver *et al.*, 2000)

Secondary forests will probably have a bigger positive influence on tourism than plantations, although Sandker *et al.* (2007) don't expect tourism to provide sufficient incentives to prevent forest conversion.
In forests there is a chance of forest fires, as described in §3.5, which can negate all reached effects. The chances of forest fires are expected to be much smaller in plantations as they have people actively protecting their interests.

4.4 Comparing secondary benefits

Plantations will bring great benefits to the economy in exchange for biodiversity, whereas regenerating forests will mainly benefit ecosystem qualities. Table 9 compares the effects as described in §4.2 and §4.3. If every + is counted as an equal positive effect (+1) and a - as an equal negative effect (-1), a palm oil plantation and a regenerating secondary forest both have an effect of +2 after conversion of a degraded grassland. This leaves the choice for either option for preferred secondary effects to the policy maker.

Table 9: The effects of either of the measures denoted as +(+) (strongly) positive, o neutral or -(-) (strongly) negative

Effects	*Palm oil plantation*	*Secondary forest regeneration*
Income	++	o
Employment	+	o
Biodiversity	--	++
Soil benefits	o	+
Reduced fire chance	+	-

Chapter 5: Discussion and Conclusion

In §5.1 a comparison will be made between the results in chapter 4 and conclusions found in other publications. §5.1 will end with recommendations for further research that will improve the results from this thesis. In §5.2 a conclusion will be reached which will consist of an advice on how to apply the available land to either of the evaluated options.

5.1 Discussion

Most papers compare the carbon mitigation potential from a palm oil plantation with the carbon stored in the tropical forest initially used. This paper makes a comprehensive comparison between palm oil plantations and secondary forest regeneration on more suitable ecosystems. This paper does agree with other studies that the development of a palm oil plantation on a peat soil should be avoided in regard to carbon mitigation effects.
Although this thesis is based on results from other studies, the results of this paper are not always in accordance with the results from other papers. In the following subsections the results of several studies with similar objectives to this study are compared to the results presented in this thesis. To what extent their results differ from, or match the results presented here will be assessed and explained.

5.1.1 Other studies on palm oil plantations

Righelato and Spracklen (2007) state that we should move away from biofuels, because they always cost more carbon due to land conversion than they will repay over 30 years. Although the results presented here agree with their findings in the case that the initial land use is tropical forest, Righelato and Spracklen did not study how the use of other land types could run a carbon profit when producing biofuels. They also fail to considerate the use of palm oil although it is established to be one of the most profitable vegetable oils (Gibbs *et al.*, 2008). The use of palm oil has the benefit that it starts with substantial carbon storage in plantation biomass.
While Germer and Sauerborn (2008) reach similar carbon costs for forest conversion as presented here, the carbon profit reached when establishing a palm oil plantation on grassland is only 20% of the carbon profit calculated in this paper. Most of the difference can be explained by the fact that Germer and Sauerborn do not apply direct values to the belowground biomass, but calculate soil organic matter as a small fraction of the aboveground biomass. This paper uses a relatively great independent value for belowground carbon.
Fargione *et al.* (2008) calculated that the time required for palm oil plantations to repay their carbon debt, obtained by clearing a tropical forest, is 86 years. This seems in accordance to the slightly more than 75 years calculated in this thesis. Fargione *et al.* do not calculate the carbon mitigation impact of palm oil plantations on degraded soils, although they state the expectation that using degraded lands would bring the highest yields, which is in accordance with the results of this thesis.
The conclusions of Gibbs *et al*. (2008) are similar to the results presented here. They also state that expansion in low-carbon ecosystems can yield positive carbon mitigation effects on the short term (< 10 years), and agree that the payback time for clearing tropical forests is too large to facilitate carbon mitigation efforts.

5.1.2 *Other studies on secondary forest regeneration*

The biomass regeneration estimated over time projects that 210 year of secondary forest regeneration will be needed to reach the carbon levels of primary forests which is comparable to the results of Saldarriaga *et al.* (1988) who estimate that 189 years are required for a forest to reach primary forest carbon levels.

Hiratsuka *et al.* (2006) estimate the naturally recovered carbon of a tropical forest after fire to be 3,7-12,5 Mg C ha^{-1} in aboveground tree biomass after 5 years. The estimated carbon in this thesis is a lot higher (30,6 Mg C ha^{-1} in aboveground biomass after 5 years). Hiratsuka *et al.* conclude that the biomass dynamics after fire depends on the type of tree species that emerge after fire, which could partially explain the gap between the results in this paper and the results from Hiratsuka *et al.* Another part of the gap could be explained by the fact that in this paper the forest regeneration does not start after a forest fire, but starts with degraded grassland.

5.1.3 *Recommendations for further research*

The palm oil production process and the associated carbon stocks are well documented. However the carbon stocks in the living biomass (in both AGB and BGB), assumed for the initial land use, are less clear. This is mainly due to the wide variation in the data, rather than a lack of data.

Growth rate studies, especially on the long-term, are rare. One of the most comprehensive was the study done by Silver *et al.* (2000) which only sited information from Saldarriaga *et al.* (1998) and Aide *et al.* (1995) for data on secondary forests aged 60 and older. Therefor more studies on accumulation rates in older secondary forest would help to evaluate the impact of secondary forest regeneration as a way to mitigate climate change over longer timespans.

The results on forest regeneration can be improved with information on precipitation patterns and soil quality. Information on precipitation patterns is readily available in most papers, but requires more specific information on the location that is being assessed for secondary forest regeneration. Influence of soil components on forest regeneration growth rates is a more complicated subject that is not completely covered in current literature.

One of the main problems for proper quantification is a lack of data on the size and impact of indirect land use change (iLUC). iLUC can be an important source of additional CO_2 emissions. Many direct land use changes have a potential iLUC side effect. Often these iLUC side effects will be augmented by other side effects of the land use change, increasing or decreasing the potential for iLUC. For example the in §3.4 and §4.3 mentioned use of NTFP's or the professionalization of agriculture mentioned in §4.2.

Another problem that was not discussed in this paper is the influence and emissions patterns of other greenhouse gases, like CH_4 and N_2O. These strong greenhouse gases have more complex pathways and can be emitted as a by-product of biomass accumulation. A crude estimate based on fertilizer usage estimated by combining the fertilizer estimates from Yusoff and Hansen (2007) with the IPCC emission factors (de Klein *et al.*, 2006; Forster *et al.*, 2007) projects a potential of 9,5 Mg $CO_{2\text{-eq}}$ ha^{-1} per plantation cycle. This would reduce the CO_2 mitigation potential by almost 20%.

5.2 Conclusion

When starting with a low carbon (grassland) ecosystem, the conversion to a palm oil plantation is more favourable than conversion to a secondary forest. This is mainly based on the potential for carbon mitigation. Regenerating secondary forests start with a carbon sequestration rate of about 3,2 Mg C ha^{-1} yr^{-1} on average over the first twenty-five years, but drops below 1 Mg C ha^{-1} yr^{-1} after that. Palm oil has a constant emission mitigation of about 2 Mg C ha^{-1} yr^{-1} in addition to the carbon sequestered in the biomass of the oil palms.

The choice for either option will be influenced however by practical limitations and preferences. For example, when the available area is easily accessible, than palm oil will be the preferable option, but if the area is remote or is of importance to biodiversity the preferred choice should be to regenerate a secondary forest.

Regenerating a secondary forest will also be preferable in terms of carbon mitigation if the area contains a peat soil. If the area contains a full grown forest maintaining this forest will be the better option assuming that policy terms are shorter than 75 years.

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Attachment A

Carbon balances for a palm oil plantation for 1 to 4 plantation cycles and two different types of original land use, tropical forest and degraded grassland.

A.1 Carbon balances on former forest

Table 10: Identical to
Table **3**; this table compares the cost of one plantation cycle when a plantation replaces a tropical forest.

Carbon stock (in Mg C ha^{-1})		Carbon emission (in Mg C ha^{-1})	
Aboveground C Plantation	76	Aboveground C Forest	230
Belowground C Plantation	157,2	Belowground C Forest	164
Fossil Fuel displacement	91,1	Fossil Fuel cost	39,2
Carbon debt	108,9		
Total	433,2		433,2

Table 11: A carbon balance of the carbon profit of a double plantation cycle and the initial cost of converting a tropical forest

Carbon stock (in Mg C ha^{-1})		Carbon emission (in Mg C ha^{-1})	
Aboveground C Plantation	76	Aboveground C Forest	230
Belowground C Plantation	157,2	Belowground C Forest	164
Fossil Fuel displacement	182,2	Fossil Fuel cost	78,4
Carbon debt	57,0		
Total	472,4		472,4

Table 12: A carbon balance of the carbon profit of a triple plantation cycle and the initial cost of converting a tropical forest

Carbon stock (in Mg C ha^{-1})		Carbon emission (in Mg C ha^{-1})	
Aboveground C Plantation	76	Aboveground C Forest	230
Belowground C Plantation	157,2	Belowground C Forest	164
Fossil Fuel displacement	273,3	Fossil Fuel cost	117,6
Carbon debt	5,1		
Total	511,6		511,6

Table 13: A carbon balance of the carbon profit of a quadruple plantation cycle and the initial cost of converting a tropical forest

Carbon stock (in Mg C ha^{-1})		Carbon emission (in Mg C ha^{-1})	
Aboveground C Plantation	76	Aboveground C Forest	230
Belowground C Plantation	157,2	Belowground C Forest	164
Fossil Fuel displacement	364,4	Fossil Fuel cost	156,8
		Carbon profit	53,6
Total	597,6		597,6

A.2 Carbon balances on former grassland

Table 14: A carbon balance of the carbon profit of a single plantation cycle and the initial cost of converting tropical grassland

Carbon stock (in Mg C ha^{-1})		Carbon emission (in Mg C ha^{-1})	
Aboveground C Plantation	76	Aboveground C Grassland	3,3
Belowground C Plantation	157,2	Belowground C Grassland	47,3
Fossil Fuel displacement	91,1	Fossil Fuel cost	39,2
		Carbon profit	234,5
Total	324,3		324,3

Table 15: A carbon balance of the carbon profit of a double plantation cycle and the initial cost of converting tropical grassland

Carbon stock (in Mg C ha^{-1})		Carbon emission (in Mg C ha^{-1})	
Aboveground C Plantation	76	Aboveground C Grassland	3,3
Belowground C Plantation	157,2	Belowground C Grassland	47,3
Fossil Fuel displacement	182,2	Fossil Fuel cost	78,4
		Carbon profit	286,4
Total	415,4		415,4

Table 16: A carbon balance of the carbon profit of a triple plantation cycle and the initial cost of converting tropical grassland

Carbon stock (in Mg C ha^{-1})		Carbon emission (in Mg C ha^{-1})	
Aboveground C Plantation	76	Aboveground C Grassland	3,3
Belowground C Plantation	157,2	Belowground C Grassland	47,3
Fossil Fuel displacement	273,3	Fossil Fuel cost	117,6
		Carbon profit	338,3
Total	506,5		506,5

Table 17: A carbon balance of the carbon profit of a quadruple plantation cycle and the initial cost of converting tropical grassland

Carbon stock (in Mg C ha^{-1})		Carbon emission (in Mg C ha^{-1})	
Aboveground C Plantation	76	Aboveground C Grassland	3,3
Belowground C Plantation	157,2	Belowground C Grassland	47,3
Fossil Fuel displacement	364,4	Fossil Fuel cost	156,8
		Carbon profit	390,2
Total	597,6		597,6

Attachment B

Carbon balances after different time steps for secondary forest regeneration.

Table 18: A carbon balance of the carbon profit of a 25 year secondary forest regeneration period and the initial cost of converting tropical grassland

Carbon stock (in Mg C ha^{-1})		Carbon emission (in Mg C ha^{-1})	
Aboveground C Secondary Forest	80,3	Aboveground C Grassland	3,3
Belowground C Secondary Forest	164	Belowground C Grassland	47,3
		Carbon Profit	193,7
	244,3		244,3

Table 19: A carbon balance of the carbon profit of a 50 year secondary forest regeneration period and the initial cost of converting tropical grassland

Carbon stock (in Mg C ha^{-1})		Carbon emission (in Mg C ha^{-1})	
Aboveground C Secondary Forest	97,9	Aboveground C Grassland	3,3
Belowground C Secondary Forest	164	Belowground C Grassland	47,3
		Carbon Profit	211,3
	261,9		261,9

Table 20: A carbon balance of the carbon profit of a 25 year secondary forest regeneration period and the initial cost of converting tropical grassland

Carbon stock (in Mg C ha^{-1})		Carbon emission (in Mg C ha^{-1})	
Aboveground C Secondary Forest	111,1	Aboveground C Grassland	3,3
Belowground C Secondary Forest	164	Belowground C Grassland	47,3
		Carbon Profit	224,5
	275,1		275,1

Table 21: A carbon balance of the carbon profit of a 100 year secondary forest regeneration period and the initial cost of converting tropical grassland

Carbon stock (in Mg C ha^{-1})		Carbon emission (in Mg C ha^{-1})	
Aboveground C Secondary Forest	122,4	Aboveground C Grassland	3,3
Belowground C Secondary Forest	164	Belowground C Grassland	47,3
		Carbon Profit	235,8
	286,4		286,4