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- An example from a REDD project in Guatemala

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Steffen Lackmann
Umeå, Sweden 2010

Abstract

Deforestation and degradation account for nearly 20 percent of global greenhouse gas emissions today – playing a key role in the complex system of climate change. Most deforestation is undertaken in developing countries, resulting in loss of biodiversity and livelihoods for millions of people and animals. With an increasing recognition of this problem the term REDD (Reducing Emissions from Deforestation and Degradation) emerged during the last years. The basic idea behind a REDD regime is that developing countries receive financial incentives for preventing further deforestation to protect the worldwide climate. Whereas afforestation and reforestation projects were included in the initial Kyoto Protocol, REDD was only eligible for the voluntary carbon market, where criteria and best guidance for these project types were developed and where some avoided deforestation projects were implemented. One of these projects was the "Avoided Deforestation Project in the Sierra del Lacandón National Park", placed in the Maya Biosphere Reserve in Northern Guatemala. The company Carbon Decisions International was selected to create a deforestation model for the reference region of Petén. Within this context the objective of this thesis was to analyze the effects of forest fires on carbon stocks in the study area and to analyze which carbon pools were specifically affected by the fires. Furthermore, a close look on the regeneration of forests after fire was taken in order to better understand how carbon stocks recreate after disturbance regimes.

In order to enable this type of analysis, it was crucial to stratify the project area into homogenous carbon density classes. This was done by identification of strata with GIS, analysis of existing data, designing of a sampling framework and calculation of carbon contents with the help of the data collected in the field.

The results described the profound effect forest fires had on the carbon storage in the National Park Sierra del Lacandón. Comparing the non-affected forest and the areas with the most recent fire occurrence showed a mean carbon loss of 53 percent. Here, trees with a diameter at breast height (DBH) above 10 cm and roots were the main carbon pools and responsible for the largest share of greenhouse gas emissions. Carbon densities showed a high heterogeneity among the sample plots which was mainly due to missing stratification factors. Furthermore the estimation of root biomass and carbon stocks was proven to be unreliable and requires further consideration in future methodologies. Regeneration of forests after fire occurrences was shown to be a considerably long process where after more than 10 years biomass and carbon stocks represented only 58% of corresponding carbon stock levels before the fire. Also here, more stratification factors would have been needed to better analyze regeneration processes after fire since forests were affected very differently.

Keywords: REDD, Forest Fire, Carbon Storage, Tropical Rainforest, Guatemala

Abbreviations

AFOLU	Agriculture, Forestry and Other Land Use
COP	Conference of the Parties
IPCC	Intergovernmental Panel on Climate Change
LULUCF	Land-Use, Land-Use Change and Forestry
REDD	Reducing Emissions from Deforestation and Forest Degradation
VCS	Voluntary Carbon Standard
VERs	Verified Emission Reductions

Measures

$t\text{-}CO_2$	tonnes of carbon dioxide
$t\text{-}CO_2e$	Tonnes of CO_2 equivalent
DBH	Diameter at breast height
ha	hectare
Mg	Megagram
t	tonne

Contents

1. Introduction

United Nations Secretary-General Ban Ki-moon described climate change as the "defining challenge of our era". Increasing temperatures, changes in precipitation patterns, rising sea levels, and more frequent weather-related disasters pose risks for agriculture, food, and water supplies. Especially in developing countries climate change endangers the lives of humans and animals and severely undermines efforts to sustainable development (THE WORLD BANK 2010). Climate change is caused by the increasing release of anthropogenic greenhouse gas emissions in the atmosphere, where they trap heat and lead to global warming (FLANNERY 2006). In its 4th assessment report in 2007, the IPCC (Intergovernmental Panel on Climate Change) described the anthropogenic greenhouse effect, which is a milestone and strengthens actions to reduce greenhouse gas emissions around the world (IPCC 2007). Today, markets for environmentally friendly technologies, emission reduction projects and techniques to retain and bind carbon dioxide are booming and there is little doubt that climate change protection is one of the main challenges of the 21st century.

Deforestation and degradation, especially in developing countries, plays a key role in the complex system of climate change. It accounts for nearly 20 percent of global greenhouse gas emissions, more than the entire global transportation sector and second only to the energy sector (UN-REDD PROGRAM 2009). By now experts agree that that major adverse impacts of climate change can only be avoided if the global average temperature increment is stabilized within 2°C above pre-industrial levels. In order to achieve this goal, global emissions must be reduced by 50-85 percent by 2050 which is practically impossible without reducing emissions from deforestation and degradation (FISHER ET. AL 2007).

Tropical forests offer a particularly high potential in reducing global GHG emissions and combating climate change since trees in tropical forests are estimated to store about 50 percent more carbon than trees outside the tropics (MOUTINHO & SCHWARTZMAN 2005) and hold 25 percent of global carbon stored in forests (BONAN 2008).

With an increasing recognition of the importance of avoided deforestation and degradation to combat climate change, discussions emerged during the last years on whether or not this aspect should be included a Post-Kyoto agreement. In this context, the term REDD was developed: Reducing Emissions from Deforestation and Degradation. The basic idea behind REDD is that countries which are willing and able to reduce their emissions from deforestation and degradation should be financially compensated for doing so. To eliminate underlying drivers of deforestation, a future REDD mechanism would also have to be designed to address rural poverty of indigenous communities. In addition to climate protection and improvement in indigenous peoples' livelihoods, a REDD mechanism would also generate other sustainable development benefits and contribute significantly to biodiversity conversation (PARKER ET. AL 2008).

While the idea of REDD emerged already during the Kyoto Protocol negotiations, it was eventually excluded from the Marrakesh Accords in 2001. Among the lack of information and technology to guide measurement, reporting and verification for LULUCF projects (Land Use, Land Use Change and Forestry), the problem of leakage was the main reason for avoided deforestation not being included in the initial protocol. Leakage refers to an uncontrollable increase of emissions outside the project boundary due to the project activities. In the case of REDD this refers in particularly to the risk that that deforesting activities are re-located to areas outside the project boundaries and hence no net climate benefits are achieved (HOLLOWAY & GIANDOMENICO 2009). However, during the last years methodologies for measuring and verifying avoided emissions from REDD projects was developed significantly further. Also, programs were established to support countries' readiness for a future REDD mechanism, such as the UN-REDD Programme or the World Bank's Forest Carbon Partnership Facility. Furthermore, several forest carbon standards, such as the "Voluntary Carbon Standard" and "The Climate Community and Biodiversity Alliance", define the requirements for establishing REDD projects and allow these to be developed on a voluntary market already today.

On the voluntary market, avoided deforestation projects like REDD are established already and sell so-called Verified (or Voluntary) Emission Reductions (VERs), where one VER equals one tonne reduced CO_2equivalent (CO_2e). CO_2e is a measure for which different greenhouse gases are multiplied with their respective Global Warming Potential (GWP), i.e. their impact on the climate relative to the same amount of Carbon Dioxide, and aggregated to be expressed in carbon dioxide equivalents (OECD 2005). Buyers of VERs are mainly private persons or organizations and companies that intend to offset their emissions (HAMILTON ET. AL 2009).

1.2. Background

One of these emission reduction projects is the REDD project in Northern Guatemala. The project's main objective is to protect the forest area which is currently under strong pressures from land use change caused by the lack of rural employment opportunities which forces farmers and indigenous people to convert forests into agriculture or grazing land. The method of "slash and burn", where forests are cut down and burned, is common for shifting cultivation in the region since it is easy and inexpensive to apply – but often the fires spread into surrounding forest areas and cause further destruction (MALMER ET AL 2005). Currently, forest loss in Guatemala occurs at an annual deforestation rate of 1.43 percent which means a total forest loss of 73,148 hectares per year (Ministry of Environment and Natural Resources, Guatemala 2008).

The company Carbon Decisions International was selected by the project developers to establish a deforestation model for the reference region of Petén in Guatemala, which is envisioned to enhance the country's readiness for REDD and assist in establishing a sub-national baseline for REDD project activities. A baseline is defined in the Marrakesh Accords as "the scenario that reasonably represents the anthropogenic emissions by sources of greenhouse gases that would occur in the absence of the proposed project activity" (SHRESTHA ET. AL 2005). In the case of the REDD project in Guatemala the baseline refers to historical deforestation patterns in the region and projects the emissions from deforestation, which would occur without the REDD activity over the project period. Future emission reductions from avoided deforestation in this project can then be assessed against the baseline scenario.

A first step in creating a deforestation model is to stratify the study area into homogeneous carbon density classes (tonnes of carbon per hectare) in order to enable estimation of greenhouse gas emissions from deforestation at present and in the future. Carbon stocks per unit of area are depending on several factors which can be distinguished as physical factors (e.g. precipitation regime, temperature, soil type, topography), biological factors (e.g. tree species composition, stand age, stand density) and anthropogenic factors (e.g. disturbance history, logging intensity). Stratification normally increases accuracy and precision and reduces costs of carbon stock and carbon stock change estimations. The approach of projecting a particular carbon stock to a given forest area helps the project developer to determine the potential of reducing emissions from deforestation and degradation (ACHARD ET. AL 2009).

Usually the stratification of a project area requires a field inventory in order to determine the values for the single strata. Since so far there are no methodologies approved for estimating carbon stocks and carbon stock changes for REDD activities, it was necessary to establish a preliminary inventory method specifically for this study. This can be understood as a pilot sampling to identify important measures for future carbon stock monitoring in Petén. Official guidelines and proposed methodologies did not suggest a particular sampling design but defined a broad scope within this inventory method could be developed. Usually, the sampling design is supposed to find the right balance between precision and measurement costs and is determined by the project developer's technical and financial recourses.

Generally, several steps are necessary to stratify an area into homogenous carbon density classes which have to comply with official requirements for the implementation of REDD projects. In order to meet these requirements and to get an idea about key stages in project development, five broadly acknowledged guidelines were applied in this study:

- *“IPCC Good Practice Guidance for Land Use, Land-Use Change and Forestry” (2004)*: Provides methods and guidance for estimating, measuring, monitoring and reporting on carbon stock changes and greenhouse gas emissions from LULUFC activities under the Kyoto Protocol. IPCC was invited by UNFCCC to develop the good practice guidance after LULUCF projects were included in the Kyoto Protocol through the Marrakesh Accords in 2001 (PENMAN ET. AL 2004).

- *“2006 IPCC Guidelines for National Greenhouse Gas Inventories, Volume 4, Agriculture, Forestry and Other Land Use” (2006):* Provides guidance in preparing national greenhouse gas inventories in the agriculture, forestry and other land use sector (AFOLU) and integrates the previous version from 1996 (PAUSTIAN ET AL. 2006).

- *“GOFC-GOLD REDD Sourcebook” (version COP15-1 2009):* Guidance to develop reference levels and to design a system for measurement, monitoring and estimating carbon dioxide emissions and removals from deforestation, changes in carbon stocks in forest lands and forestation at the national scale, based on the national requirements set by the United Nations Framework Convention on Climate Change (UNFCCC) and the specific methodologies for the land use and forest sectors provided by the Intergovernmental Panel on Climate Change (IPCC). The sourcebook was developed by an ad-hoc REDD working group of “Global Observation of Forest and Land Cover Dynamics”, a technical panel of the Global Terrestrial Observing System (GTOS) (ACHARD ET. AL 2009).

- *“REDD-Methodology Framework” (version 1.0 – April 2009):* Provides guidance for constructing methodologies for REDD project activities compliant with the validation and verification requirements of the Voluntary Carbon Standard (VCS). Resulting methodologies are VCS approved without the requirement of a methodology validation. The framework is developed by Avoided Deforestation Partners.org and follows the structure and procedural steps defined in the VCS “Tool for AFOLU Methodological Issues” (AVOIDED DEFORESTATION PARTNERS 2009 A).

- *“Methodology for Estimating Reductions of Greenhouse Gases Emissions from Frontier Deforestation” (Version 01 2008):* A proposed methodology for estimating and monitoring greenhouse gases emissions of project activities that reduce frontier deforestation. It is a work in progress which will be further developed and its underlying conceptual approach is based on the AFOLU Guidance Document of the Voluntary Carbon Standard (PEDRONI 2008).

1.3. Objectives and hypothesizes

With this background and based on the stratification of the project area, the objective of this study is to analyze the effects of forest fires on carbon stocks in the study area in order to enable estimation of the project’s carbon storage potentials. Therefore a close look is taken on which carbon pools in the forest area are specifically affected by fire and if these can be further specified in a future methodology. Fire-affected forests in this context are forest areas which were affected by wildfires, spread out from shifting cultivations. Furthermore, the regeneration of forest after fire is analyzed since this has a direct impact on the amount of carbon stored per hectare.

Based on the objectives described above, three hypothesizes are analyzed in this study:

1. Forest fires have a profound effect on carbon storage in the region of Petén and thus have a direct impact on a potential REDD project.

2. Not all carbon pools in the forest will be affected by fires and thus these can be further specified in a future methodology.

3. Considerable long time periods are needed after severe fire occurrences until biomass and carbon stocks reach previous levels.

2. Material and Methods

In order to verify or falsify hypothesizes and to address questions of my study I had the opportunity to work on the project sites in Guatemala, where I cooperated closely with Carbon Decisions International and several local partners.

The stratification of the project area into homogeneous carbon density classes was undertaken in several steps as the basis on which the main questions were analyzed. During the process of stratification, an important part of my work in Guatemala was to meet with organizations involved in the project in order to collect required data and to plan the field inventories in the research area.

2.1 The research area

Each REDD project has to specify how emission reductions will be measured. Of particular importance in this context is the reference level which defines the period and the scale against which the activities are measured (PARKER ET. AL 2008). The scale determines the boundaries of the so-called reference region which may include one or several sub-projects. Areas within the reference region are similar in terms of ecological conditions, access to the forest, drivers of deforestation, enforced policies and regulations and these similarities can be used to share experiences about deforestation patterns (PEDRONI 2008).

The REDD project in Guatemala includes three sub-projects; The Forest Concessions of the Maya Biosphere Reserve (528,224 ha), the Sierra del Lacandón National Park (171,300 ha) and the Laguna Lachuá National Park (14,500 ha). The Forest Concessions and Sierra del Lacandón are part of the Maya Biosphere Reserve. All three projects lay in the reference region of Petén and the north of the Departments Alta Verapaz and Quiché (Figure 1).

This study focused on the Sierra del Lacandón National Park, located in the southwestern part of the Maya Biosphere Reserve, directly on the border to Mexico. While there were inventories conducted in the other sub-projects which might be usable for carbon estimations, the Sierra del Lacandón Park showed the largest data gaps and thus the most urgent need for an inventory. Furthermore, this region had a large variety of characteristics, such as several ecosystems and altitudes, frequently fire-affected areas as well as primary forests and was therefore representative for the entire reference region. Within the last ten years 33.846 hectares of forest were affected by wildfires in the national park, implying an average of 3.385 hectares fire affected area per year (PEDRONI 2010).

There were only two ways to access the park which was important to consider during the planning and performing of field work; a road in the north-east of the park and the river "Usumacinta" in the south west which represents the border to Mexico.

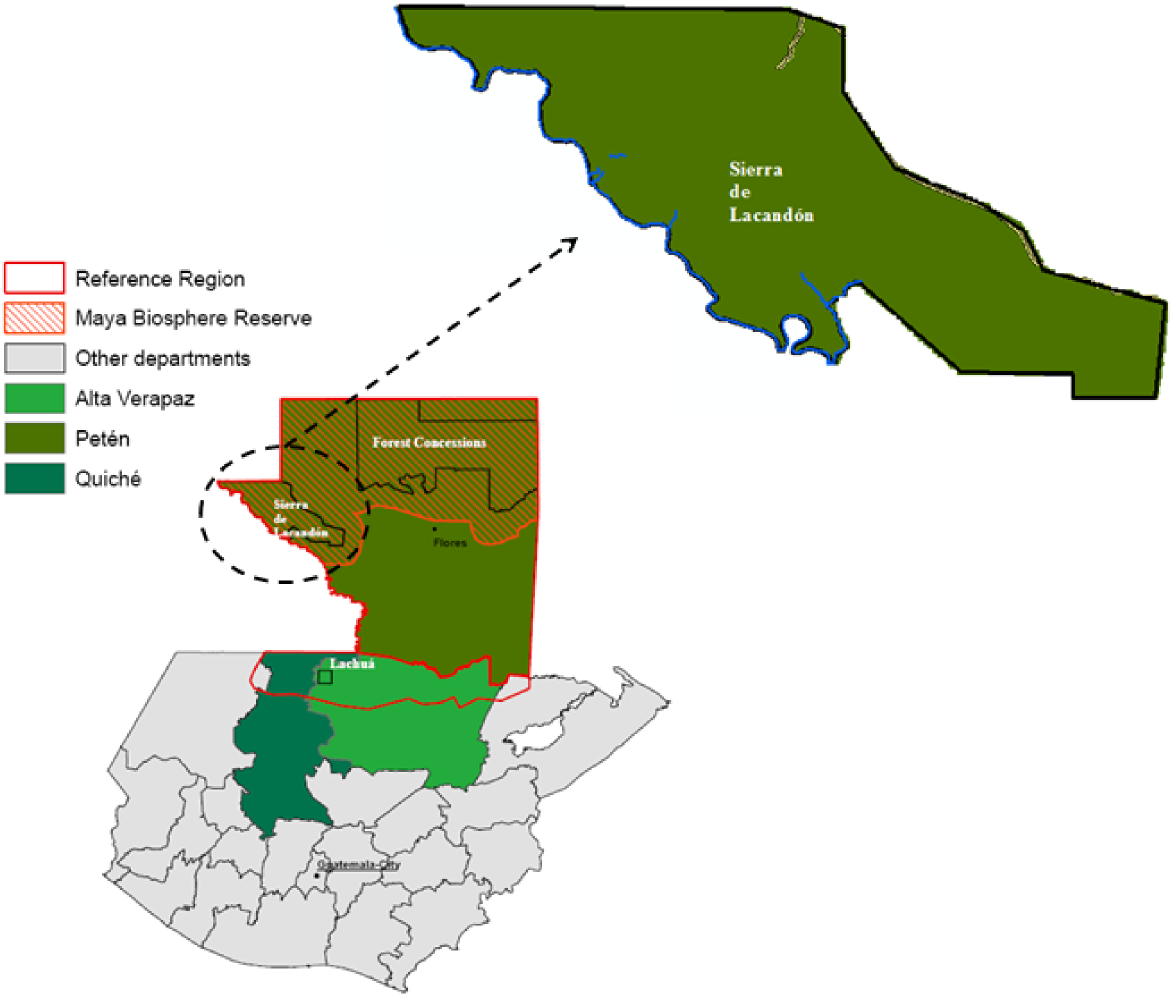


Figure 1: Location of REDD sub-projects within the reference region in Guatemala

2.2. Four steps to stratify the research area and estimate carbon stocks

The GOFC-GOLD REDD Sourcebook presents two different approaches for stratifying forests for national carbon accounting depending on access to relevant data and the country's financial and technological resources. Under approach A, all forests within the reference region are stratified up-front and through carbon estimates a map with carbon stock densities is created. This enables future monitoring to compare change in forest area with the pre-estimated carbon stock values. In approach B, carbon estimates are only made in the areas which have undergone change instead (ACHARD ET. AL 2009).

The stratification of the REDD project in Guatemala followed approach A which is described by the following steps.

2.2.1. Step 1: Identifying strata with Geographic Information System (GIS)

A basic step in the stratification of the project area was to identify the most relevant physical, biological and anthropogenic factors which determine a carbon density class and to summarize these with spatial data like maps, GIS coverage or satellite imagery. For this study ArcView 9.3 was chosen as a suitable tool to investigate these factors for the stratification with GIS.

In Guatemala there were several institutions which worked on creating suitable data to illustrate these factors in GIS, such as the National Forestry Institute (INAB), the National Council of Protected Areas (CONAP) and the University in Guatemala-City (Universidad Del Valle de Guatemala). All of these institutions were consulted in order to investigate and discuss the most significant stratification factors for the project.

In this process it was important to remember that GIS data has to fulfill certain requirements to be suitable for REDD activities. Especially data on biological and anthropogenic factors which can change over time should not be older than five years; for example a forest cover map for Guatemala which was created more than five years ago is most likely not up-to-date anymore due to the high deforestation rate (ACHARD ET. AL 2009). Furthermore data should have an appropriate resolution so that the strata delimited in the map correspond to the real size of the area and thus precise estimates can be established with the help of the map. The frontier methodology suggests an overall accuracy of 80 percent for carbon density classes (PEDRONI 2008).

Each stratum in a REDD-project is characterized by representing at least 10 percent of the total area and differs more than +/-20 percent of the mean carbon stock density (AVOIDED DEFORESTATION PARTNERS 2009 B). The fact, that the size of a single stratum has to be at least 10 percent of the total area means that the project area can be divided in maximum 10 strata and thus not too many stratification criteria should be chosen.

For this reason four main factors were selected which were considered to have the most impact on the carbon stock density in the project area in Guatemala:

Table 1: List of GIS-layers used for the stratification

ID	Factor	Type of carbon factor	Type of data
1	Land Use/Land Cover	Biological	Polygon
2	Forest types	Biological	Polygon
3	Vegetation Zone	Physical	Polygon
4	Forest Fire history	Anthropogenic	Raster

First of all, a land use/land cover layer illustrated the forest and non-forest areas in the region of Petén. As a second biological factor the forest type layer specified the characteristics of the forest land; for instance a mountainous pine forest can have a significantly different carbon stock than a plain broadleaved forest. The vegetation zone represented several physical factors at the same time; precipitation regime, temperature, soil type and topography were combined and described the growth patterns in different regions.

Finally, the forest fire history described anthropogenic disturbance patterns in the reference region and needed to be divided into four sub-classes regarding to the year of occurrence;

- No fire occurrence/non affected
- Forest fire occurrence more than 10 years ago
- Forest fire occurrence 5-10 years ago
- Forest fires occurrence 0-5 years ago

This classification accounts for the fact that a forest which was fire-affected more than 10 years ago had more time to regenerate than a recently burned forest and thus was likely to show a higher carbon stock per hectare. Forests which were frequently affected by forest fires during that time were classified by the most recent occurrence.

In a next step these layers needed to be combined in GIS in order to obtain the different strata. As a result each stratum contained several features; one from each layer. That meant that each forest type was split up according to its vegetation zone and the fire occurrence. For example a mountainous pine forest within the humid subtropical vegetation zone which was fire affected more than ten years ago could be a typical stratum.

The different strata for the National Park Sierra del Lacandón are listed in table 2.

Table 2: Strata representing carbon stock density classes for the National Park Sierra de Lacandón

ID	Ecosystem	Vegetation Zone	Forest Fire History
1	Highland broadleaved forest	Humid, subtropical	Non-affected
2	Highland broadleaved forest	Humid, subtropical	0-5 years ago
3	Highland broadleaved forest	Humid, subtropical	5-10 years ago
4	Highland broadleaved forest	Humid, subtropical	>10 years ago
5	Lowland broadleaved forest	Humid, subtropical	Non-affected
6	Lowland broadleaved forest	Humid, subtropical	0-5 years ago
7	Lowland broadleaved forest	Humid, subtropical	5-10 years ago
8	Lowland broadleaved forest	Humid, subtropical	>10 years ago

The stratification for the National Park Sierra de Lacandón was mainly determined by the two ecosystem features and the four fire history classes while the vegetation zone was the same for the entire park. This classification resulted in eight different carbon stock strata and is shown in figure 2.

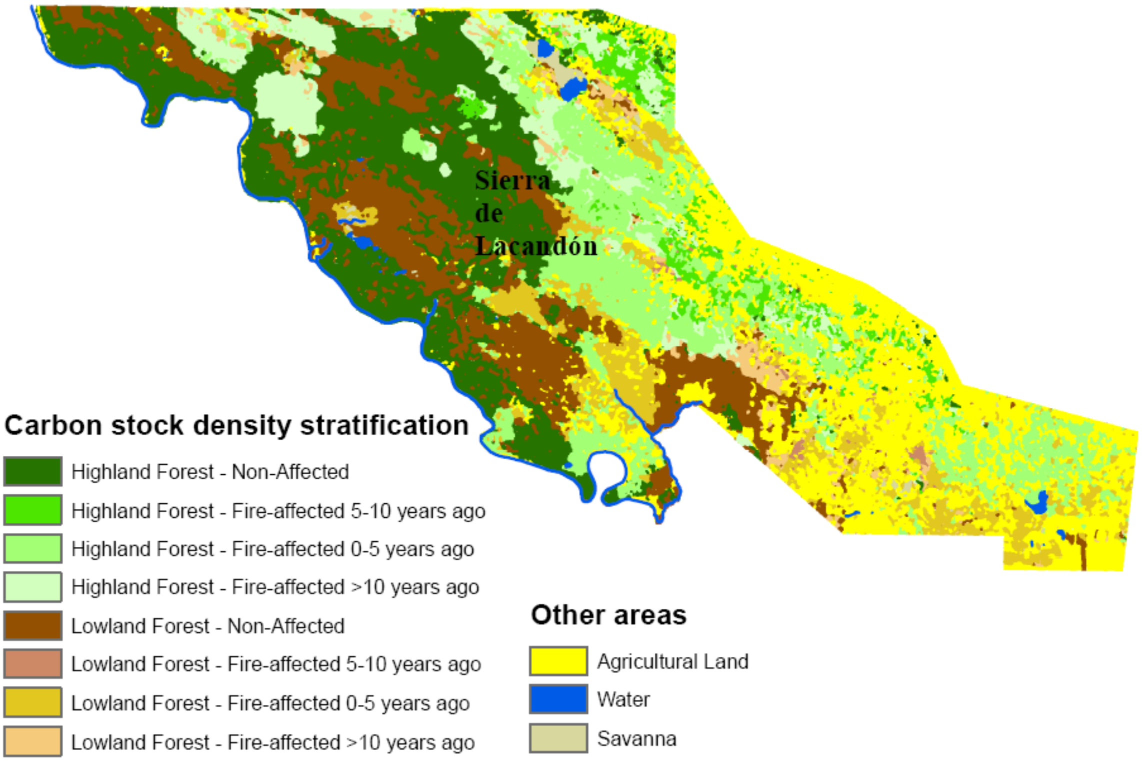


Figure 2: Stratification for the carbon inventory in the National Park Sierra de Lacandón

2.2.2 Step 2: Data investigation

The values for single strata (tonnes of carbon per hectare) were determined through analyzing existing inventory data or by collecting new data in the field. Using already existing inventory data would have been the easiest and most cost-efficient way of quantifying carbon stocks. In this case it would have been required, that the data were less than ten years old, were derived from multiple measurement plots, included all species with a minimum diameter of 30 cm at breast height and showed a good coverage over all classes. For REDD projects, the data investigation is only required for the areas where deforestation is expected (PEDRONI 2008).

In Petén there were several existing inventories which fulfilled the requirements to estimate carbon stocks; a National Forest Inventory, several regional forest inventories and a small inventory established in the context of a scientific study. Except for the scientific study, none of the inventories did specifically focus on carbon stocks but rather on forest management and biodiversity values. A carbon analysis in additional plots in combination with an overall carbon stock stratification would strengthen the scientific study, providing a model for using other existing data for carbon purposes.

Furthermore the existing inventories did not cover all strata in the reference region. Especially in the National Park Sierra de Lacandón data gaps remained and therefore additional field measurements were required. Figure 2 shows the location of already existing inventory plots.

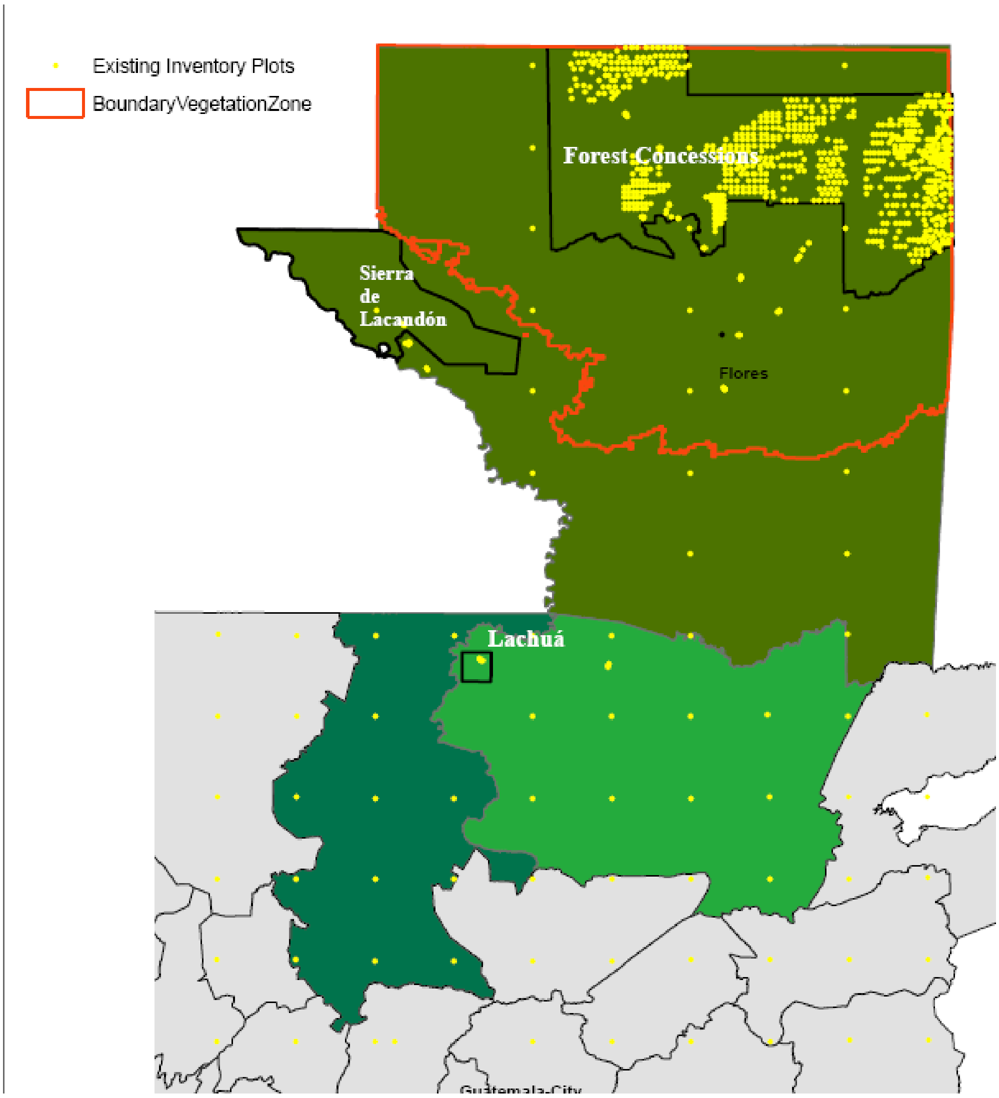


Figure 3: Location of existing inventory plots

2.2.3. Step 3: Designing a sampling framework

Since data from existing inventories was insufficient for covering all strata, it was necessary to collect additional data in the field. Several procedures needed to be considered in order to design an inventory framework, which are described below.

2.2.3.1. Carbon pools

For the carbon stock inventory it was crucial to understand that there were several pools in the forest where carbon could have been stored and thus might have been released through deforestation and degradation processes. Generally it was distinguished between aboveground biomass, belowground biomass, dead wood, litter and soil organic carbon (PENMAN ET. AL 2004). Furthermore harvested wood products could have been considered as a carbon pool but was excluded from most of the guidelines and proposed methodologies and was therefore not included in this study.

When designing a sampling framework it was first of all important to decide which of the carbon pools should have been included in the inventory. This decision was depending on whether a carbon pool was expected to be a significant carbon source in the project or not. The relevance of single carbon pools could have differed significantly between forest types and categories of land use change; for instance a forest with high carbon contents in the mineral soil which was converted to cropland emits significantly more carbon than a forest converted to pasture and an old growth forest contains more carbon in dead wood than a newly planted forest.

The guidelines propose different criteria for deciding whether or not a carbon pool is significant. While the frontier methodology recommends including carbon pools which represent 10 % of the total carbon emissions, the GOFC-Gold REDD sourcebook defines “key categories” as carbon pools contributing at least 25 % of the total emissions in a forest area (PEDRONI 2008, ACHARD ET. AL 2009).
In all carbon inventories the main criterion is the “principle of conservativeness” which ensures that carbon emission reductions are not overestimated (ACHARD ET. AL 2009). It allows omitting carbon pools in future measurements except trees but it excludes the possibility to add more carbon pools to the inventory program.

Therefore all carbon pools were included in this inventory in order to investigate their relevance in the Petén region. Aboveground biomass was sub-divided into trees with a diameter at breast height (DBH) of 10 cm and upwards, 5-10 cm and living biomass below a DBH of 5 cm including herbs.

2.2.3.2. Temporary or Permanent plots

Sampling plots can be temporary or permanent depending on the objectives of the project. In Sierra del Lacandón permanent sampling plots were chosen because these were in general statistically more efficient in estimating changes of carbon stocks over the project period. But other than with temporary plots there is the risk that permanent plots might get treated differently by land managers if the location becomes commonly known (Penman et. Al 2004). If this occurs the plots are not representative anymore and the results would get biased. That is why the permanent plots in this inventory were marked with an iron pole in the ground and corresponding GPS coordinates were taken. At a later time it is thereby possible to find the plots easily with the help of a metal detector and a GPS instrument.

2.2.3.3. Plot design and measurement procedure

Especially the size of a sample plot is a trade-off between accuracy, precision and time/costs of the measurement (Penman et. Al 2004). Precision increases with the plot size and especially heterogeneous forests (i.e. forest with a high spatial variation in carbon stocks) require larger sizes to reach a certain precision. Furthermore the stand density is a determining factor for the size of the plot since an adequate number of trees should be measured. IPCC suggests in its Good Practice Guidance a plot size between 100 m² for dense stands and 600 m² for open stands (Penman et. Al 2004) while the frontier methodology recommends a size between 100 m² and 1000 m² for REDD projects (Pedroni 2008).

In order to achieve more accurate results a nested sample plot of 1000 m² was applied to this study. Nested means in this context that there were several sub-plots within the whole plot boundary which represented the measurement area for certain carbon pools. A rectangular shape of the plot was the most common method in the region and thus the most appropriate for this study (Figure 3). Chapter 4.3.3.5 "Field Measurements and Data Analysis for Estimating Carbon Stocks" in the IPCC Good Practice Guidance was used as the main guideline for the sampling design (Penman et. Al 2004).

Figure 4: Nested sample plot designed for carbon stock inventories in the National Park Sierra del Lacandón

The delimitation of the sample plot in the field started from a GPS point which was marked with an iron pole as described above. From there a 50 m intersection line was established northwards which was helpful as a reference during the measurements and simplified the process of finding the boundaries of the plot (Picture 1). Within 10 m in both directions from the intersection the diameter at breast height (DBH) and the height of all tress with a DBH of 10 cm upwards and respectively 5 cm upwards on half of the plot (500 m²) were measured. Tree heights were estimated because the forests were in

Picture 1: Establishment of the intersection line

most cases too dense to apply height measurement instruments and would have increased the risk of biased results.

Unlike aboveground biomass it is much more difficult and time-consuming to measure belowground biomass and methods for that are not as well established (PAUSTIAN ET AL. 2006). That's why a "root-to-shoot ratio" was applied to this study where a ratio between belowground and aboveground biomass was used to estimate all biomass of live roots.

Living biomass below a DBH of 5 cm was sampled on 25 m², for objectivity reasons always in the lower right corner of the entire sample plot. Because these plants were too small to measure diameters, all of them were cut down and weighed in order to estimate the biomass. Furthermore a small proportion of the plants were collected in a bag for a further carbon analysis in a laboratory. Here, it was tried to objectively find the right ratio of wood and leaf materials with different densities, corresponding to their proportion on the sub-plot.

On the lower left corner of the 25 m² plot a 4 m² sample was established for collecting and measuring litter, including all dead biomass below a diameter of 10 cm. It was also weighted and a sample taken for the laboratory (Picture 2).

Another carbon pool which needed to be measured is the soil organic carbon. In carbon inventories soil samples are taken with a metallic cylinder at a certain depth (PAUSTIAN ET AL. 2006). Normally carbon contents in soils are highest in the upper layers and decrease exponentially with depth (JOBBÁGY AND JACKSON 2000). The Good Practice Guidance recommends taking the soil sample at 30 cm since this is the depth were changes in soil carbon are likely to be constant enough to be detected over the project period (PENMAN ET. AL 2004). In this inventory one sample per plot was taken with a metallic cylinder with a volume of 100 cm³ at a depth of 30 cm, always within the 25 m² sub-plot. During this process it was very important to observe that the sample was taken

Picture 2: Collection and weighting of litter

horizontally and that the soil did not get compressed because otherwise the result (carbon content per unit cm³) would have gotten biased. Scaling up the soil volume to the size of one hectare means that the carbon content of 3,000 m³ (=0.3 x 10,000) of soil per hectare could be defined.

As the last carbon pool, dead wood was sampled using a "line-intersect method". The diameter of all dead stems was measured exactly at the point where the stem is crossing the intersection line and was used to estimate the volume per hectare. Additionally each piece of dead wood was classified by its stage of decay into three density classes using the "machete test"; each stem of dead wood was stricken with a machete – if the blade rebounded it was "solid", if it entered slightly it was "intermediate" and if the wood fell apart it was "rotten" (PENMAN ET. AL 2004). The density was decisive for the carbon content; a tree which was decomposed to a high degree already released high amounts of its carbon content and thus contained less than a tree which recently died. Also here a sample was collected for further analysis in the laboratory.

After the field measurements the results were analyzed and carbon contents estimated using appropriate tools as will be described in step 4.

2.2.3.4. Sampling size and plot allocation

The allocation of the sample plots in Sierra del Lacandón had to be done in small clusters because of the limited access possibilities in the area and in order to minimize travel costs. That's why the plots were either close to the road in the North eastern part or along the river "Rio Usumacinta" in the western part of the park.

Clusters of plots can be laid out totally randomly or systematically (PENMAN ET. AL 2004). The systematic sampling uses a regular grid of sample plots which is then placed randomly over the area of interest. Because the plots are evenly distributed over the area it increases the precision of the results and simplifies the field work. A systematic allocation with a distance of 200 meters between the plots was chosen for this study. The sampling plots were distributed over the different strata and coordinates were set in the GIS map which could be later found with help of a GPS-device.

In order to achieve precise results, a certain sampling size is required, i.e. a certain number of plots per stratum. This sampling size can be calculated depending on the chosen level of error and the confidence level. Following the suggestions of the *Good Practice Guidance* a 10% level of error and a 95% confidence level were chosen for this inventory (PENMAN ET. AL 2004). With help of the "Winrock Terrestrial Sampling Calculator" (WALKER ET. AL 2007) the sampling size was calculated taking into account the total project area size, the area size of each stratum, the plot size, mean carbon stock per hectare for each stratum and the standard deviation of the carbon stocks. Since there was no existing data for the carbon stock in the study area, it was first of all necessary to investigate the carbon densities in the field by conducting a pilot sampling in each stratum.

The “Winrock Terrestrial Sampling Calculator” showed that at least 90 plots were required in total to fulfill a certain precision level of which 69 plots were processed and available until the time of this study. Depending on the size of each stratum the 69 plots were distributed as shown in table 3:

Table 3: Distribution of inventory plots over the different strata

Fire History	Ecosystem	Number of Plots
1	Lowland forest; non-affected	23
2	Lowland forest; fire affected >10 years ago	-
3	Lowland forest; fire affected 5-10 years ago	7
4	Lowland forest; fire affected 0-5 years ago	-
1	Highland forest; non-affected	25
2	Highland forest; fire affected >10 years ago	6
3	Highland forest; fire affected 5-10 years ago	5
4	Highland forest; fire affected 0-5 years ago	3

2.2.3.5. Required equipment

Certain equipment was crucial in order to be able to carry out the inventory in the field. Of major importance was a GPS-device. In this study a Garmin GPS 12 XL was used to locate the sampling plots in the field which were afterwards illustrated in the GIS map and could easily be found again for future monitoring measurements. Additional to the GPS a Suunto KB-20 compass was used for the orientation in the field and for setting the boundaries of the sampling plot.

For sampling the carbon pools different measurement gears were used; A 5 meters diameter tape for measuring the DBH of the trees, a weighting scale with a 5 kilogram resolution for estimating the weight of small biomass and litter, and a metallic cylinder with the measure of 8.75 cm in height, 3.8 cm in diameter and thus a volume of 52 cm^2 for taking the soil sample.

2.2.4. Step 4: Calculation of carbon contents

Data obtained in the field were used to calculate carbon contents in each carbon pool. The general procedure was to express the values of the biomass data on an oven-dried basis and convert these values afterwards to carbon by multiplying with the carbon fraction value of the dry biomass. Carbon fraction values either have to be investigated by analyzing carbon contents of biomass samples in the laboratory or default values from official guidelines can be applied (PENMAN ET. AL 2004). The carbon stock changes in each carbon pool are afterwards reported as emissions by converting these values into carbon dioxide (CO_2). Non- CO_2 greenhouse gas emissions, such as CH_4 and N_2O, are only counted when they represent more than 10% of the baseline emissions but were conservatively omitted in this inventory.

In this study the “spreadsheet tool for the calculation of greenhouse gas emission reductions in REDD projects” was used to calculate the carbon contents in the different carbon pools. This tool summarized the equations and carbon fraction values for all carbon pools considered in the study and enabled the user to simply convert field data into dry biomass and carbon dioxide values (PEDRONI 2010). The calculation procedure for each carbon pool within the spreadsheet tool is described below:

2.2.4.1. Aboveground biomass

The IPCC Good Practice Guidance recommends estimating biomass and carbon stocks on permanent plots with a direct approach using allometric equations. Depending on the forest type there are several allometric equations for estimating aboveground biomass (kilogram dry matter per tree) for tropical and temperate hardwood and pine species. These equations use the diameter at breast height as the independent variable and are based on a multi-species database that contains biomass data from more than 450 individuals (PENMAN ET. AL 2004). In this study the equation for tropical moist hardwoods was applied:

$$Y = \exp[-2.289 + 2.649 \bullet \ln(DBH) - 0.021 \bullet (\ln(DBH))^2]$$

Where

Y = aboveground dry matter, kg $(\text{tree})^{-1}$

DBH = diameter at breast height, cm

Ln = natural logarithm

Exp = “e raised to the power of”

Furthermore the palm tree species *Chrysophylla* sp was very common in the project region but the biomass does not relate very well to the diameter and thus the height was used as the independent variable. In order to calculate the dry matter of these palm trees following allometric equation was applied (PENMAN ET. AL 2004):

$$Y = 0.182 + 0.498 \bullet HT + 0.049 \bullet (HT)^2$$

Where

Y = aboveground dry matter, kg $(\text{tree})^{-1}$

HT = height of the trunk, meters (for palms this is the main stem, excluding the fronds)

In order to convert biomass into carbon contents the values of the dry aboveground biomass were multiplied with the accordant carbon fraction value. Since no local values were available the default value of 0.5 from the IPCC Guidelines was applied.

2.2.4.2. Belowground biomass

Methods for measuring belowground biomass (roots) are not as well established as for aboveground carbon pools. In most cases it is difficult and time-consuming to measure roots and methodologies are not standardized so far (PENMAN ET. AL 2004). Therefore, a “root-to-shoot ratio” was used here to estimate belowground biomass in the project area. This ratio of belowground to aboveground biomass usually considers all biomass of dead and live roots and differs depending on the ecological zone and the amount of aboveground biomass per hectare (Table 4).

Table 4: "Root-to-shoot ratios" in different ecological zones (PAUSTIAN ET AL. 2006)

Ecological Zone	Aboveground Biomass	Ratio (dry matter root – dry matter shoot)	Source
General ratio for tropical rainforests	-	0.37	FITTKAU AND KLINGE 1973
Tropical moist deciduous forest	<125 tonnes/hectare	0.20 (0.09-0.25)	MOKANY *ET AL*. 2006
	>125 tonnes/hectare	0.24 (0.22-0.33)	
Tropical dry forest	<20 tonnes/hectare	0.56 (0.28 - 0.68)	MOKANY *ET AL*. 2006
	>20 tonnes/hectare	0.28 (0.27 - 0.28)	

Values for the ratios were obtained from two different scientific studies; the first study (Fittkau and Klinge 1973) represents a general ratio of 0.37 for estimating belowground biomass in tropical forests. Mokany et al. analyzed 786 estimates of root and shoot biomass from 266 sources in order to present more vegetation specific ratios. The values in brackets show the variation of data found while the value in front of the brackets represents the median of the variation.

Since it was not known which ratio is most suitable for the National Park Sierra del Lacandón the general ratio of 0.37 was applied in order to estimate the belowground biomass and carbon stocks.

2.2.4.3. *Litter and biomass below a DBH of 5 cm*

For litter and biomass below a DBH of 5 cm the same procedure was applied in order to determine the carbon contents; both were collected and weighted in the field. A subsample was taken and oven-dried in the laboratory in order to obtain the wet-to-dry ratio. These ratios were used to convert the entire biomass into an oven-dried basis. The dry matter value was multiplied with the carbon fraction default values 0.37 for litter and 0.5 for biomass below a dbh of 5 cm.

2.2.4.4. Soil

The carbon content of the soil sample taken in the field was analyzed in the laboratory of the University Del Valle de Guatemala. A special instrument, the "Thermo Scientific Flash EA 1112

Nitrogen and Carbon Analyzer", was used to analyze soil organic carbon contents in the soil with a flash dynamic combustion method; the sample was introduced in the combustion reactor where it was exposed to temperatures about 1800°C followed by a precise determination of the elemental gases produced. By eliminating all inorganic carbon in a first step this instrument could be used to measure only organic carbon contents in the sample (THERMO FISHER SCIENTIFIC 2007).

In order to determine the carbon content per hectare the following equation was applied (PENMAN ET. AL 2004):

$$\boxed{\text{SOC} = \text{Volume of Soil per hectare} \bullet \text{Bulk Density} \bullet [\text{SOC}]}$$

Where

SOC = Soil Organic Carbon stock for the soil of interest;

Volume of Soil per hectare = Depth • 10,000

Bulk Density = grams of soil/unit of volume of soil sample

[SOC] = concentration of soil organic carbon in a given soil mass; grams of carbon (at a depth of 30 cm)/100 g of soil (from the lab analyzes)

2.2.4.5. Standing dead wood

The measurement process for standing dead wood was the same as for living trees but it was not possible to apply the same equations and default values since dead trees represent less biomass unless it died recently and was only missing leaves. Estimation of dead tree biomass with signs of decomposition, meaning loss of twigs, branches or crown, was limited to the main trunk of the tree (AVOIDED DEFORESTATION PARTNERS 2009).

Therefore an equation was applied to this study which estimates only the commercial volume of the tree. This equation was developed in an earlier study in the region of Petén (CONTRERAS 1999):

$$\boxed{\text{Volume } (m^3/\text{hectare}) = 0.0567 + (0.5074 \bullet DBH^2 \bullet h_c)}$$

Where

DBH = diameter at breast height

h_c = commercial height

The volume was afterwards multiplied with the carbon fraction default value of 0.38, independent on the stage of decay, and the dry-to-wet matter ratio which was investigated in the laboratory.

2.2.4.6. *Lying dead wood*

All diameters of lying dead wood crossing the intersection line were measured before in the field. With help of these diameters the amount of dead wood per hectare could be calculated with the following equation (PENMAN ET. AL 2004):

$$\text{Volume } (m^3/\text{hectare}) = \pi^2 \bullet (D_1^2 + D_2^2 + \ldots + D_n^2) / (8 \bullet L)$$

Where

$D_1^2 + D_2^2 + \ldots + D_n^2$ = Diameter of each of n pieces intersecting the line, in centimeters (cm). The round equivalent of an elliptically shaped log is computed as the square root of ($D_{minimum} \bullet D_{maximum}$) for that log.

L = the length of the intersection line, in meters (m).

Additionally, lying dead wood was classified by its stage of decay into "solid", "intermediate" or "rotten" dead wood. Samples from each decay class were analyzed in the laboratory in order to be able to convert the volume per hectare into an oven-dried basis. These dry-matter values were multiplied with the carbon fraction default values of 0.48 for solid dead wood, 0.37 for intermediate and 0.3 for rotten dead wood.

2.2.4.7. *Conversion from carbon to carbon dioxide*

After analyzing carbon stocks and carbon stock changes in the project area emissions were reported by converting tonnes of carbon into tonnes of carbon dioxide (CO_2). In the official reporting requirements this is done by multiplying the carbon stock changes with 44/12 (PENMAN ET. AL 2004).

2.3. Statistical analysis

After the field investigation the data was analyzed and tested for significances with help of the statistical analysis program Minitab 15 (MINITAB INC. 2007). An analysis of variance (ANOVA) was performed in order to investigate the correlation between the dependent variable "carbon per hectare" and the independent variables "fire history" and "ecosystem". Therefore the "General Linear Model" was applied as a suitable tool with $p \leq 0.05$ as the level of statistical significance.

3. Results

In the analysis of variance (ANOVA) it was first of all tested how the total carbon stock per hectare was correlated to the variable "fire history" and "ecosystem". Afterwards the correlation between the single carbon pools and the variables was investigated. Table 5 shows the results from the analysis.

Table 5: Tested variables and results in ANOVA

Dependent variable	Independent variable	F	P	S (Standard Deviation	R-Sq (%) (Coefficient of Determination
Tonnes of Carbon/hectare	Fire history	6.05	0.001	91.7	21.8
Tonnes of Carbon/hectare	Ecosystem	0.04	0.846	102.16	0.06
Aboveground Biomass	Fire history	5.96	0.001	67.1	21.6
Belowground Biomass	Fire history	6.41	0.001	24.8	22.82
Trees > 10 cm DBH	Fire history	6.31	0.001	67.21	22.56
Trees 5-10 cm DBH	Fire history	2.47	0.070	2.14	10.23
Minor vegetation	Fire history	8.31	0.000	1.63	27.72
Litter	Fire history	0.04	0.989	2.57	0.18
Standing Dead Wood	Fire history	0.16	0.923	0.840	0.73
Lying Dead Wood	Fire history	3.01	0.036	4.24	12.20
Roots	Fire history	6.41	0.001	24.8	22.82
Soil Organic Carbon	Fire history	0.33	0.802	24.03	2.70

It was shown that there was a significant correlation between “tonnes of carbon per hectare” and “fire history” (p = 0.001) but not between “tonnes of carbon per hectare” and “ecosystems” (p = 0.846). Figure 5 supports this result; while the amount of tonnes of carbon/hectare was declining with more recent fire occurrences there were no obvious differences between the carbon stocks of the ecosystems “Highland” and “Lowland”.

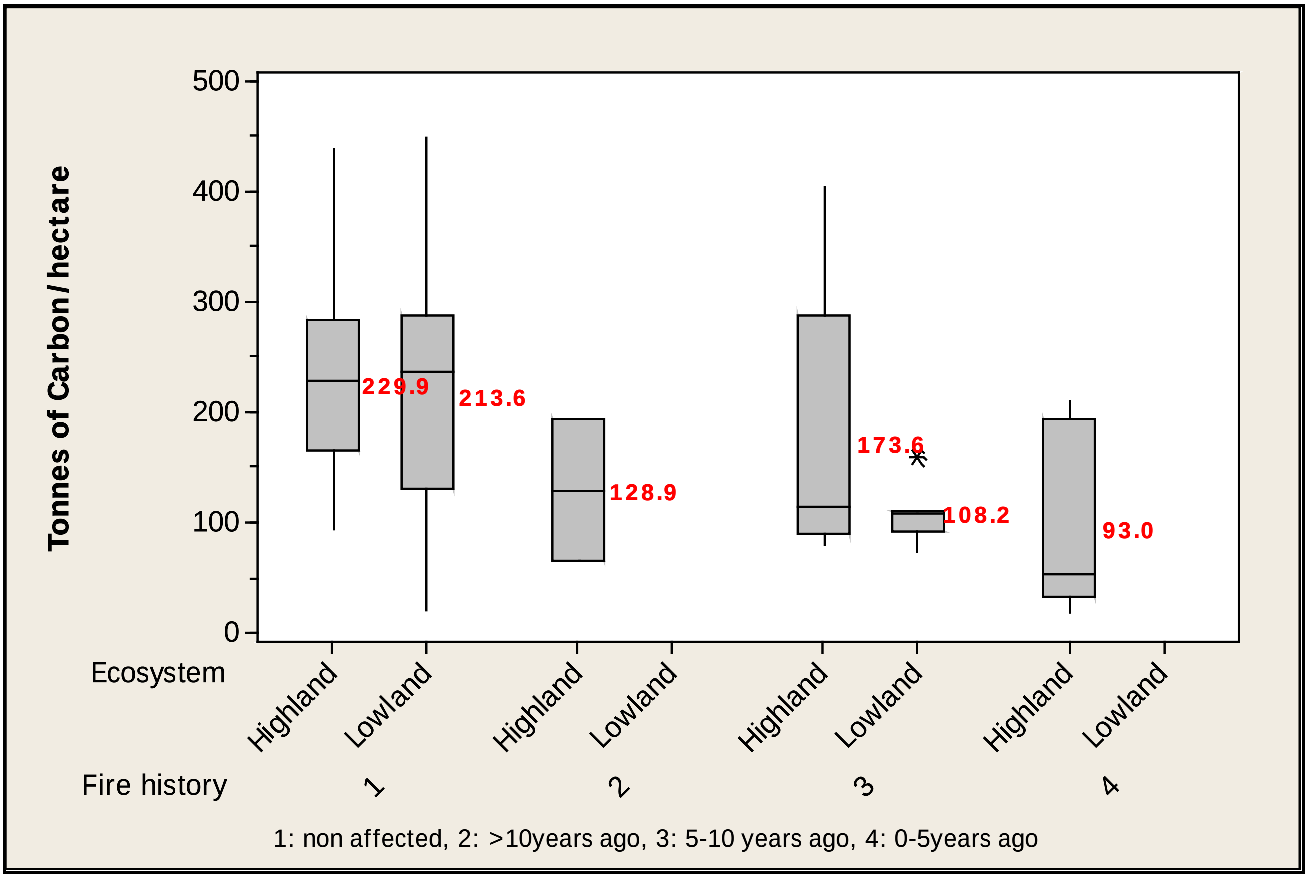


Figure 5: Carbon stock distribution (tonnes/hectare) in different strata (excluding soil). Red values represent the mean value of the distribution while the horizontal line within the box plot represents the median.

Furthermore it was obvious that there was a high variation in tonnes of carbon per hectare within each stratum which explained the high standard deviation (91.7) and a low coefficient of determination (21.8) as presented in table 5.

Since there was no correlation between carbon stocks per hectare and the ecosystems, this differentiation was not made in the further analysis of the single carbon pools.

Figure 6 shows how the total amount of carbon per hectare was declining with more recent forest fire occurrences. While it considerably decreased from the non-affected forests to the ones which were affected more than 10 years ago (41.7 %), the difference within the affected fire history classes was less; tonnes of carbon per hectare even increased slightly by 4.8 % between the forest fire history classes 2 and 3 and decreased by 31.3 % between the classes 3 and 4. Looking at only non- affected forests and forests with the most recent fire occurrence identified a difference of 129 tonnes of carbon per hectare.

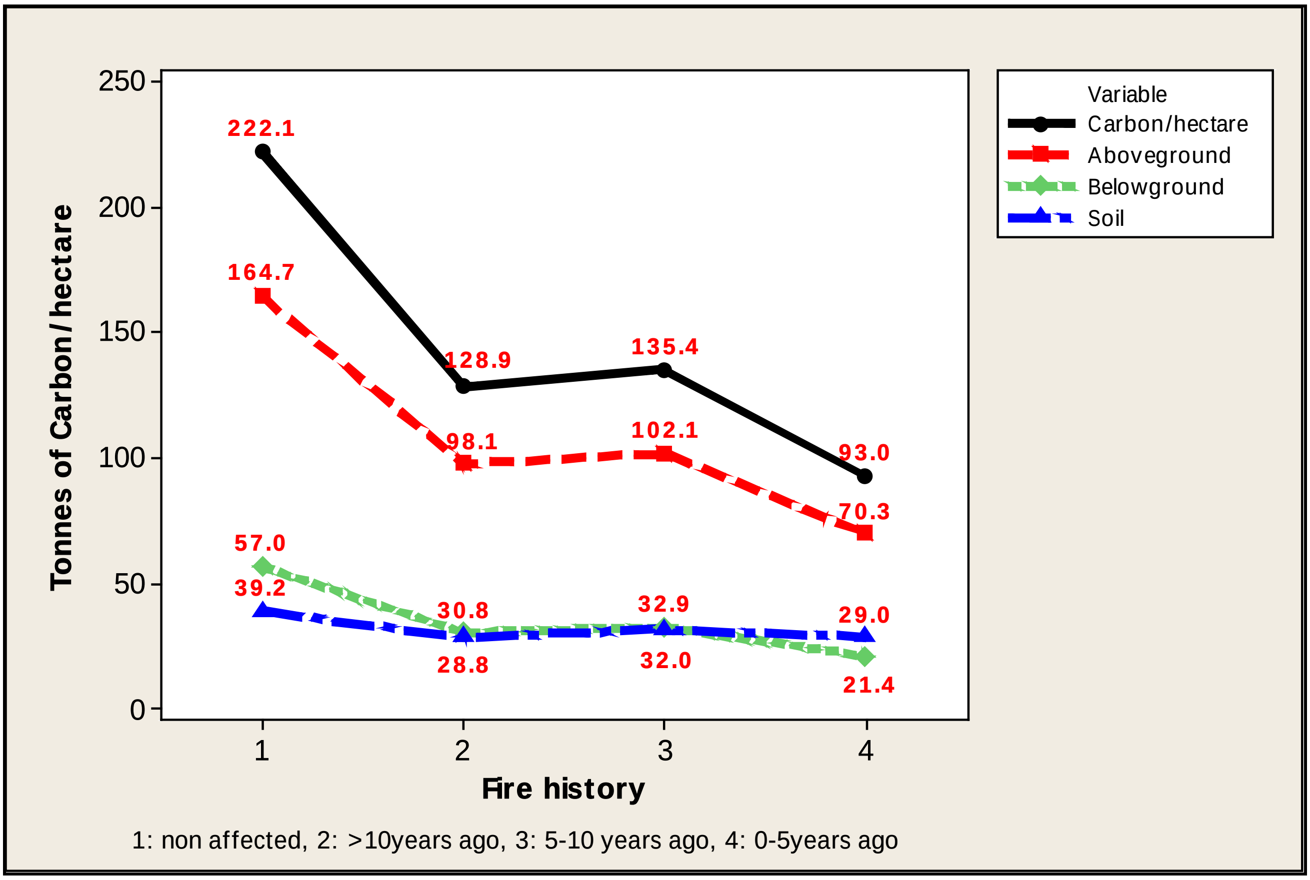
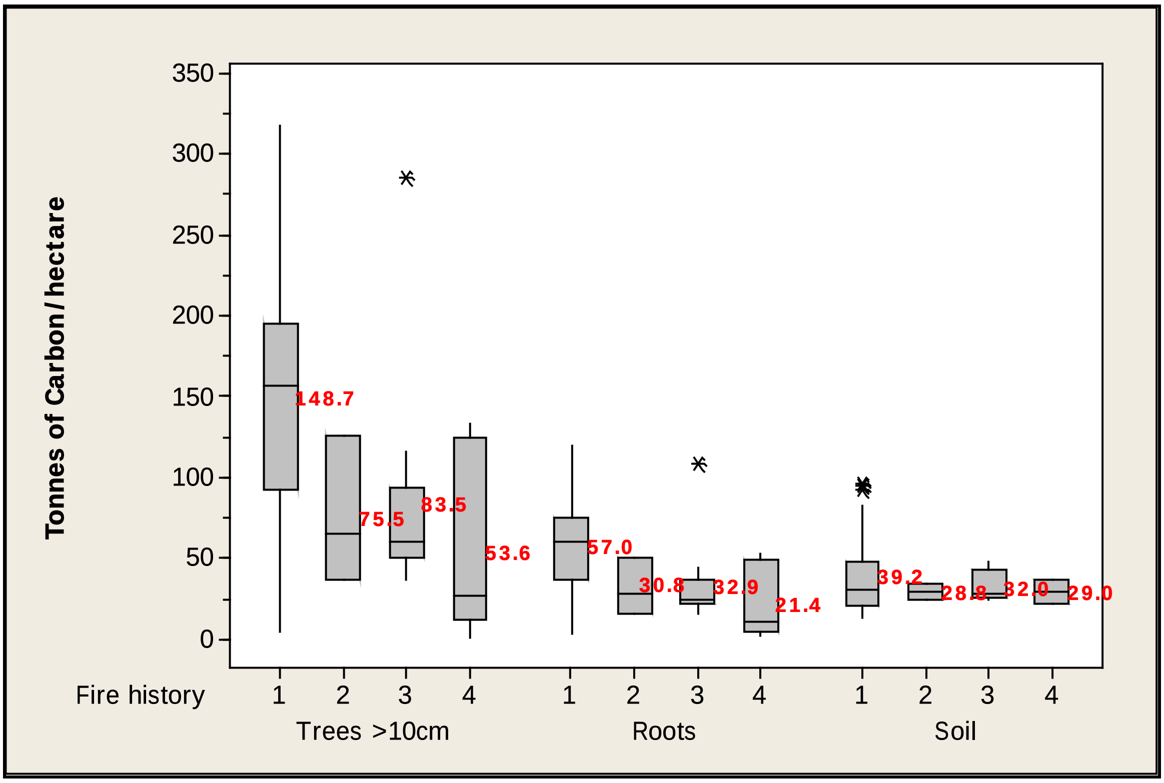


Figure 6: Relation between total carbon stocks and fire history. Total carbon/hectare (excluding soil). Aboveground carbon pools: Trees >10cm DBH, Trees 5-10 DBH, Minor vegetation, Litter, Standing- and Lying dead wood. Belowground carbon pools: Roots.

Furthermore the analysis of variance showed a significant correlation of carbon stocks in above- ($p = 0.001$) and belowground pools ($p = 0.001$) towards fire history. Amounts of carbon/hectare in aboveground carbon pools (trees >10 cm DBH, trees 5-10 cm DBH, minor vegetation, litter, lying and standing dead wood) and belowground carbon pools (roots) represented a similar progression over the fire history classes. While decreasing significantly between the forest fire history classes 1 and 2 and respectively between 3 and 4, there was a marginal difference between the classes 2 and

3 (Figure 6). Soil organic carbon had to be considered separately in the analysis since data was not available for all the plots. However, the amount of carbon stored in the soil did not show a significant correlation to the fire history. When combining mean carbon values for soil and roots, belowground carbon pools represented 37.7 % and aboveground carbon pools 62.3 % of the total carbon stock.

In order to understand how total carbon stocks were correlated to the fire history, each carbon pool was analyzed and tested for significance. Here the analysis of variance identified significant correlations between the carbon stocks and forest fire history for the carbon pools “trees >10 cm DBH” (p = 0.001), “minor vegetation” (p = 0.000), “lying dead wood” (p = 0.036) and “roots” (p = 0.001) (Table 5).



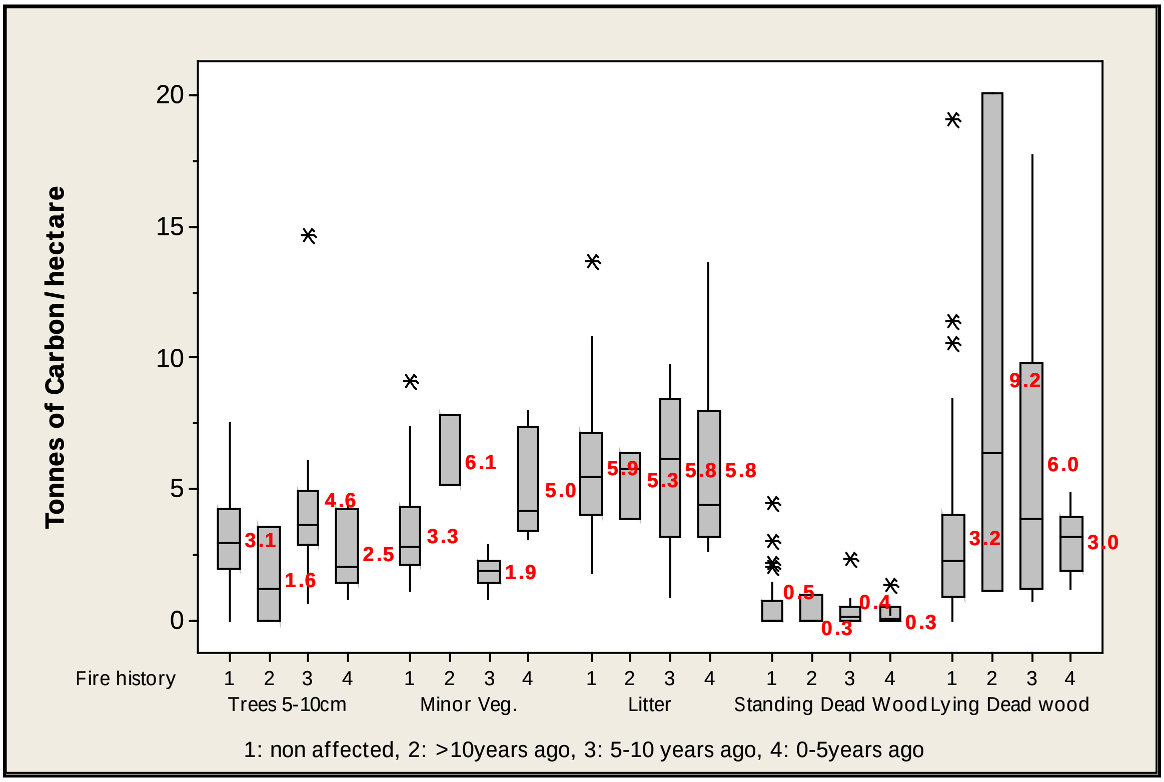


Figure 7: Correlations between single carbon pools and fire history

Figure 7 illustrates the correlations between the single carbon pools and fire history. Carbon stored in trees >10 cm DBH and roots showed a similar correlation to fire history as the total amount of carbon did; the amount of carbon was decreasing with more recent fire occurrences while the mean increased slightly between the fire classes 2 and 3. In contrast the carbon pools “minor vegetation” and “lying dead wood” were affected differently by forest fire; the mean amount of carbon in lying dead wood was almost three times higher in forests which were fire- affected more than 10 years ago than in non- affected forests. Within the fire- affected forests the amount of carbon decreased by approximately 30% between the fire classes 2 and 3 and between 3 and 4 respectively. Forests which were fire- affected more than 10 years ago also represented the highest mean carbon storage within the carbon pool “minor vegetation” (6.1 tonnes/hectare). In opposite to the other carbon pools the lowest mean amount of carbon was identified here in the fire class 3 (1.9 tonnes/hectare) and increased again towards the most recent fire occurrence class 4 (5.0 tonnes/hectare). Thus, minor vegetation was the only carbon pool which showed higher mean carbon storage in the most recently fire affected areas than in non-affected forests.

Besides the significant correlations between carbon stocks and fire history, there are four carbon pools which did not show any significance during the analysis of variance; trees with a DBH between 5-10 cm, litter, standing dead wood and soil. Looking at the mean carbon stock values of these carbon pools illustrated the marginal difference and an uneven distribution between the fire history classes.

Summarizing all strata in the project area was resulting in a mean carbon stock of 229 tonnes of carbon per hectare (including soil organic carbon). Trees with a DBH above 10 cm and roots were here the most important carbon pools with a share of 55.0 and 21.4 percent respectively of the total. A third major carbon pool was "soil" which stored 16.2 percent of the total carbon stock in the project area while the remaining five carbon pools represented together only 7.4 percent of the total amount.

Carbon stock changes were converted to tonnes of carbon dioxide (t-CO_2) in order to describe emission values. Considering the total carbon stock change of 129 tonnes between the non-affected forests and the forest which were affected 0 to 5 years ago (and thus least time to recover), this meant an emission of about 473 tonnes of CO_2 per hectare (511 t- CO_2 when including soil). Most of these emissions came from the main carbon pools "trees >10 cm DBH" (67.0 %) and "roots" (25.1 %) which also showed the biggest relative loss of carbon compared to the other pools (64.0 % and 62.5 % respectively). Soil was the source for 7.2 percent of the total emissions per hectare while the remaining carbon pools together caused only 0.7 percent of the total amount (Figure 8).

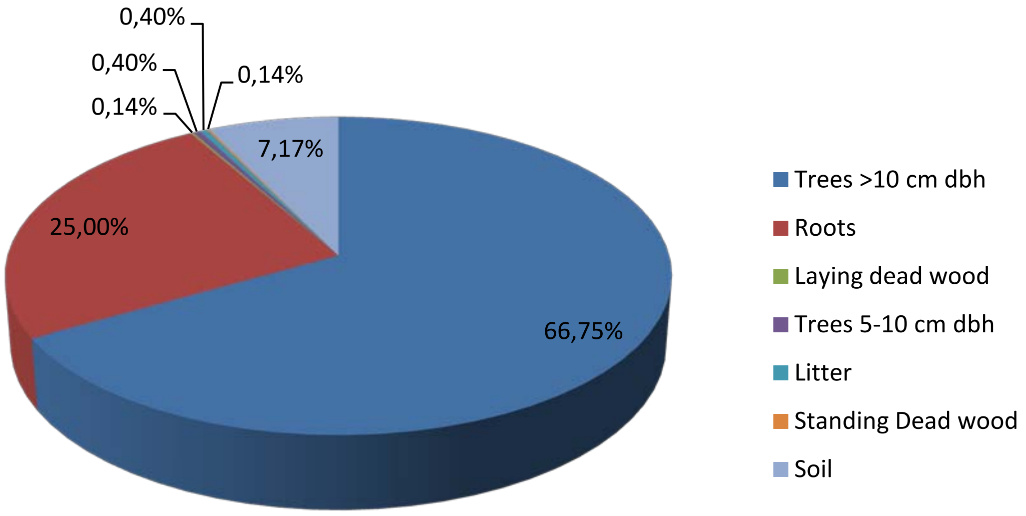


Figure 8: CO2 – emissions from the single carbon pools caused by forest fire in the project area

4. Analysis and discussion

The findings above suggest a clear correlation between the total amount of carbon per hectare and fire history which indicates the serious impact forest fires have on carbon storage in the National Park Sierra de Lacandón. Looking at the single carbon pools in the project area demonstrated that “trees >10 cm DBH” and “roots” did not only store most of the carbon but were also most affected by fire and thus represented the major source of total CO_2 emissions. Besides “trees >10 cm DBH and roots”, also the carbon pools “minor vegetation” and “lying dead wood” showed a significant correlation to fire history.

However, results did not show an evident correlation between tonnes of carbon per hectare and different ecosystems. Furthermore there was an obviously high variation of carbon within each stratum which implied a high heterogeneity of carbon among the sample plots.

While some results could clearly be explained by apparent circumstances and processes, other results might have been biased by the choice of material and methods in combination with high variability and require more detailed analysis. Therefore the discussion below is divided into an “environmental” and a “material and methods”- part. Here it was not possible to find a clear delineation, meaning that results could have been discussed by considering both natural processes and the choice of material and methods.

4.1. Environmental processes

The results showed that “trees >10cm DBH” and roots are the main carbon pools in the project area and responsible for most of the CO_2-emissions. Since emission trading from forestry carbon projects like REDD started just during recent years, research on carbon storage within single carbon pools is limited. However, trees and roots represented the biggest biomass stock in the project area and with the highest carbon fraction of 0.5 compared to other carbon pools they automatically accounted for most of the carbon storage. A carbon fraction of 0.5 in tropical plants seemed to be a sound value since it was not only suggested in the official guidelines described above but already earlier mentioned in other scientific studies (WARD 1990).

It sounds reasonable that the main carbon pools are also responsible for most of greenhouse gas emissions. But this did not necessarily explain why trees >10 cm DBH and roots were most affected by fires when looking at the relative carbon loss between the non-affected forests and the forests with the most recent fire occurrence while trees between 5-10 cm DBH and minor vegetation (< 5 cm DBH) seemed to be only slightly affected. Cochrane and Ryan (2009) describe different types of wildland fires which are rarely constant or homogenous in their behavior or effects over large areas due to variations in fuels, weather and topography. Fires can be classified as surface fires, ground fires or crown fires with rather different effects on carbon pools. Severe fires are capable to kill 23-44% of trees >10 cm DBH in relatively intact forests due to the fact that natural fires are uncommon in the Central American tropics and mostly connected to extreme droughts and human ignition (Cochrane 2003, MALMER ET AL. 2005, GOLDAMMER AND SEIBERT 1990): Most large trees are not adapted to forest fires and have a thin bark which is vulnerable to fire damage. Earlier forest fire research also shows that especially small trees < 5 cm DBH are severely affected by forest fires. For instance a study on the impact of droughts and forest fires on tropical lowland Dipterocarp forest in East Kalimantan after the heavy wildfires in Borneo 1982-1983 demonstrates that 99 % of the trees < 4 cm DBH died. Compared to that, 50 % of the trees with a diameter between 20 – 25 cm died and only 20 – 35 % of the trees with a diameter above that were killed by the fire (GOLDAMMER AND SEIBERT 1990). These results do not match with the findings in this study which can be explained with the classification of the fire history classes; the most recent fire occurrence represented areas which were affected 0-5 years ago. This implies that some of these areas had up to 5 years to regenerate and recover forest. Goldammer and Seibert (1990) describe the regeneration process 5 years after the Borneo fire and conclude that moderately and heavily damaged areas are rapidly dominated by pioneer trees species, shrubs and respectively weeds while in slightly affected areas even primary Dipterocarp species could recover quickly. Nykvist (1996) also addresses the re-growth of secondary vegetation after the Borneo fires and describes a fast invasion of grasses already 15 month after the fire. Grasses, but also ferns, herbs and pioneer trees dominate 2-5 years after the fire and decrease afterwards again which agrees with the results in this study. At the same time the re-growth of primary tree species is reduced since surface fires destroy seedlings and saplings by up to 85 % (COCHRANE 2003, NYKVIST 1996).

Another result of this study demonstrates that there is no significant correlation between carbon stocks per hectare and the ecosystems which would mean that the carbon stock stratification by ecosystems was not necessary. A difference in carbon stocks could have been expected in relation to the stature of the different forests but it was hardly seen even in the ranges of carbon (figure 5), and as such out of reach for quantification in this study. One main reason was that data for lowland forests was only available for two out of four fire history classes which made a statistical analysis difficult. However, it was likely that highland forests were affected differently by forest fires and thus differed in carbon stocks. First of all fires burn more rapidly up a steep slope than on plane areas because fire and heat moves up more quickly and dries out the vegetation (Rothermel 1985). Especially slopes which face south, southwest and west receive more sun and are thus warmer and drier to start with. Furthermore, highland forest might not only burn more intensely but also more frequently because of water deficiencies on steep slopes and shallow soils which results in more severe damages and increased loss of biomass (Goldammer and Seibert 1990). After a fire occurrence, the regeneration process can differ between highland and lowland forest as a study on the impacts of fires in the Central American tropics shows (Koonce and González-Cabán 1990); nutrients are lost through surface runoff after fire which means that slopes are most vulnerable to nutrient depletion. This has an impact on the regeneration process of forests on slopes, meaning a lower biomass growth and thus lower carbon fixation after fire.

4.2 Results biased by Material and Methods

4.2.1. Stratification

Each stratum was supposed to represent at least 10 % of the total project area and differ by more than +/- 20 % of the mean carbon stock density. This was the case for most of the strata chosen in this study, except the mean carbon stock values of non-affected highland and lowland forests and the highland forests which were fire affected 5-10 years ago. However, stratification is an ex-ante exercise where differences in carbon stocks can only be estimated with the help of stratification factors. Doing ex-post analysis showed that stratification by fire history classes was useful but especially the high variation of carbon within each stratum indicated that areas were affected very differently and that more stratification factors would have been necessary in order to better analyze the impact of forest fires. Several parameters determined the impact of fires on forest carbon stocks which were closely correlated to each other.

4.2.1.1. Stratification by intensity of previous damage

Cochrane (2003) notes that fires in previously burned or logged forests are more severe while primary closed-canopy forests are almost resistant to fires due to their high moisture content and the absence of understory vegetation (Koonce and González-Cabán 1990, Beaman et al. 1985). Goldammer (1990) concludes that the fire intensity in East Kalimantan was positively correlated to the intensity of previous logging. This is due to the fact that disturbances disable the forest to maintain the high moisture content and lead to more fuel loads on the forest ground through secondary vegetation growth and abandoned wood debris. Furthermore, secondary vegetation is less efficient in taking water from the deep soil under dry periods and dries out more easily which higher the risk for additional and more severe fire occurrences (Malmer et al. 2005, Uhl and Kauffman 1990). Following fires have the potential to be ten times higher in intensity and can spread twice as fast depending on several parameters (Cochrane 2003).

4.2.1.2. Stratification by ecosystem type and conditions

Cochrane and Ryan (2009) describe the fuel load as one of the most important parameters for forest fire and collect values for surface fuel loads for several tropical ecosystem types and conditions from many different scientific studies in different countries. The fuel load is the weight of all fuels present per unit area of a site and differs significantly between different ecosystem types and conditions. While primary forests show an average fuel load of 55.6 Mg/ha, the process of logging and burning increases this value by more than three times up to 178.8 Mg/ha and respectively 180.8 Mg/ha. The highest fuel load of almost 400 Mg/ha is represented in slashed primary forests (UHL AND KAUFFMANN 1990, COCHRANE ET AL. 1999, GUILD ET AL. 1998). Besides the fuel load, parameters like the distribution of the fuel by type (live or dead), size distribution, orientation (lying or standing), heat content (volatile or non-volatile), condition (sound or rotten), and spatial arrangement are determining if and how a site will burn (COCHRANE AND RYAN 2009).

4.2.1.3. Stratification by distance to forest edges

In cases where previous damages are unknown, a simplified approach could be applied by considering distances to forest edges such as roads, settlements and other deforested areas. Usually, fire frequency and forest damage are high close to forest edges and decrease exponentially with the distance (COCHRANE 2003). This was also the case for the National Park Sierra del Lacandón; the degree of previous damage in certain areas was not exactly known but a more intensified land-use around settlements was obvious. Figure 2 shows huge areas of agricultural land around the settlements in the south-eastern part of the Park while the non-affected areas were located further away towards the inside of the Park. Forests which are one-time fire-affected will not make a net contribution of carbon to the atmosphere in a long perspective as long as they are followed by carbon fixation during forest succession (TINKER ET AL. 1996). Even if many large trees may die, these and the surviving trees provide soil protection, nutrient filtering and water use which creates favorable conditions for efficient secondary succession (MALMER ET AL. 2005). Goldammer and Seibert (1990) also describe the fast recovery of slightly damaged logged-over or burned forests with a relatively rapid recovery of Dipterocarp species under a shelter. On the other hand forests with previous logging or fire damage are more vulnerable to additional fires and have a higher risk of developing severe crown fires with accordingly large CO_2 emissions (MALMER ET AL. 2005). Nutrient reserves after additional fires are expected to become progressively poorer until finally forest succession is not efficient anymore and only fire climax grassland remains. Frequently damaged forests after the Borneo fire 1982-1983 did not show any considerable recovery of primary forest communities but an invasion of pioneer species like weeds and grasses (GOLDAMMER AND SEIBERT 1990). Nykvist (1996) concludes that the total aboveground biomass of standing crops 8 years after severe fires was only 24 % of the corresponding biomass before the fire.

For the project area in the National Park Sierra del Lacandón this implies that forests close to the settlements could have been expected to be more frequently affected by wild fires, spreading from shifting cultivation. Thus, these areas would have represented lower carbon stocks per hectare. Looking at the carbon stock distribution in the different strata (Figure 5) shows that the amounts of carbon in non-affected and affected forests partly overlapped which indicated that some areas could recover quickly. The mean values instead demonstrated that forests in Sierra del Lacandón recovered about 20 % of its biomass and carbon stocks until 5-10 years after the fire but afterwards stayed on a constant level. This level represented 58 % of the corresponding carbon stocks before the fire which gave evidence about the slow recovery process in the project area.

In the context of this REDD project it was not possible to consider too many stratification factors since each stratum still had to represent 10 % of the total project area but the differences in fire intensities and recovery processes showed the need for more stratification factors. A combination of the ecosystem type and the distance to forest edges would have been a relatively simple and plausible way to better analyze the impact of forest fires.

4.2.2. Sampling design

When designing a field inventory a special focus is usually put on the objectivity and the relation of precision, accuracy and time/cost of the measurement procedure. This was also done in this study but there were still aspects which could have been discussed and may be improved in future inventories. One of these aspects was the choice of carbon pools which should be included in the inventory. Methodologies and guidelines for REDD projects differ in their recommendations of when a carbon pool should be included in the inventory but at least it should represent 10 % of the total carbon emissions. For the future measurements in the project in Guatemala it means that only trees > 10 cm DBH and roots need to be included in the inventory and all other carbon pools can be conservatively omitted which saves time and thus costs (PEDRONI 2008, ACHARD ET. AL 2009).

Another aspect was the inventory of minor vegetation and litter. Both were collected on a sub-plot and weighted in the field. Afterwards a small proportion was collected in a bag for further analysis in a laboratory. Minor vegetation and litter included all biomass below a diameter of 5 cm and respectively 10 cm DBH such as grasses, leafs and woody biomass which could result in a wide range of carbon densities. The IPCC Good Practice Guidance recommends collecting "well-mixed sub-samples" in order to determine the dry-to-wet matter ratio for these plots which is then multiplied with the carbon content (PENMAN ET. AL 2004). In the field, it was very difficult to objectively collect this "well-mixed sub-samples", meaning to find the right ratio of wood and leaf materials corresponding to their proportion on the sub-plot. Thus, results for carbon per hectare stored in minor vegetation and litter might easily have gotten biased. On the example of litter in non-affected highland forests, an error of 10 % (20 %) in the determination of the dry-to-wet matter ratio would have resulted in a variation of +/- 0.75 tonnes of carbon/hectare (+/-1.5 tonnes of carbon/hectare). For the REDD project in Guatemala this variation was not critical since litter and minor vegetation were even with a 20 % higher carbon value still far away of being a significant carbon pool. But, when analyzing the impact of forest fire this variation could have played a critical role. Furthermore, minor vegetation and litter might have a significantly higher share in upcoming REDD projects where a more objective method would be required in order to achieve sound results.

4.2.3. Guidelines/equations used for calculating carbon contents

In order to calculate biomass and carbon stocks, different allometric equations and default values were applied from the official guidelines available until the time of this study. Alternatively to allometric equations it is possible to develop these allometric relations for a certain region through destructive harvesting but that method is very time consuming and expensive. Research has shown that species- specific allometric relations are not required in order to achieve reliable results for carbon stocks (BROWN 2002). Instead, using generalized allometric equations which were developed for broad forest types and ecosystems is highly efficient since the DBH alone explains more than 95 % of variation in carbon stocks in the tropics, even in highly diverse regions. Furthermore, allometric equations are normally based on a large number of trees with a wide range of diameters (BROWN 1997). However, it is still recommended to verify the equation by destructive harvesting of a few trees of different sizes. If the estimated biomass is within +/- 10 % of the amount predicted by the equation, this equation can be considered as being suitable for the project area (BROWN 2002, PENMAN ET. AL 2004).

Different to the allometric equations for aboveground biomass, the estimation of belowground biomass and carbon stocks seemed to be less reliable although roots and soil were important carbon pools. Estimating root biomass in the field is a time consuming and expensive method and therefore a root-to-shoot ratio was applied. Looking at the recommendations for these ratios in different guidelines and studies showed a high variation. The AFOLU- Guidelines name a general ratio of 0.37 for tropical rain forest, which was also applied to this study, but differentiate at the same time between different ecological zones (PAUSTIAN ET AL. 2006). Here, tropical moist deciduous forests with an aboveground biomass above 125 tonnes per hectare represent a mean root-to-shoot ratio of 0.24 with a variation from 0.22 to 0.33. While the general ratio was derived from a study in 1973 (FITTKAU AND KLINGE 1973), the more specified ratios came from a recent study in 2006 (MOKANY ET AL. 2006). Cairns et al. (1997) investigates root biomass allocations in upland forests around the world and concludes that tropical forests have the highest heterogeneity in the relation of above- and belowground biomass with a mean ratio of 0.24. None of the factors aboveground biomass density, latitude, temperature, precipitation, temperature-precipitation ratios, tree type, soil texture or stand age have a strong explanatory value for root-to-shoot values but it was shown that aboveground biomass density, latitude and age together are the most important predictors by explaining 84 % of the variation (CAIRNS ET AL. 1997, MOKANY ET AL. 2006). However, although root-to-shoot ratios show high variations and are difficult to predict by any of the factors, there are several studies indicating a ratio between 0.2 and 0.3 for tropical forest (SEILER AND CRUTZEN 1980, CAIRNS ET AL. 1997, MOKANY ET. AL 2006). Considering that roots were found to be responsible for second most of the emissions in the project in Guatemala the estimation of the root biomass was of major importance. Assuming that a ratio of 0.24 would have been the real value for the relation of above- and belowground biomass in Guatemala, this would have lowered the importance of roots as a carbon pool considerably; while the amount of carbon would have decreased by about 17 tonnes of carbon per hectare, roots would only have represented 15 instead of 25 percent of the total carbon emissions in the project area.

Furthermore it was unclear how carbon emissions from roots should have been measured since these might not be directly emitted to the atmosphere. Guidelines generally distinguish between three levels of estimating greenhouse gas emissions. The simplest level 1 (Tier 1) assumes that all carbon is emitted in the same year of the disturbance while levels 2 and 3 (Tier 2 and 3) consider the flux of carbon between different carbon pools after a disturbance (PAUSTIAN ET AL. 2006). Thus, carbon from roots might be stored in the soil for a long time after the fire and cannot be accounted in the total emissions.

This study was supposed to illustrate the potential and importance of roots as a carbon pool but since the method of estimating root biomass is not reliable, it was in practice not applied to the REDD project in Guatemala.

5. Concluding remarks

In the beginning of this study it was stated that forest fires have a profound effect on carbon storage in the region of Petén and thus have a direct impact on a potential REDD project. Here, it was assumed that not all carbon pools in the project area are affected equally and thus can be further specified in a future methodology. Furthermore it was suggested that considerable long time periods were needed after severe fire occurrences until biomass and carbon stocks reach previous levels.

Based on these hypotheses and the stratification of the project area the impact of wildfires on the carbon stock in the National Park Sierra del Lacandón was analyzed. Comparing different strata in the project area proved the profound effect wildfires have on carbon stocks and indicated the potential this project could have in the context of REDD. But it also showed the need for further research and improvements in the methodologies.

The stratification was done with the purpose of classifying the project area by carbon densities (tonnes of carbon per hectare) in order to be able to estimate greenhouse gas emissions from deforestation today and in future. That means, knowing the carbon density for certain areas helps the project developer to calculate greenhouse gas emissions when these areas undergo deforestation. In the case of wildfires this estimation of greenhouse gas emissions is very complex and can vary a lot depending on several factors as shown in the analysis and discussion. Generally, it can be said that wildfires had a profound effect on carbon storage in Petén when looking at mean values. But in order to be able to estimate emissions from wildfires in future, fire intensities and fire conditions (primary forest, previously logged or burned forest, distance to forest edge etc.) need much more consideration during the stratification process. This does not only account for the project in Guatemala but in fact has a global importance. As shown in the discussion, damages in tropical forests through loggings or wildfires can increase the amount of fuel loads by up to three times and thus higher significantly the risk for long term damages through additional and more severe fires.

Similar to the impact of forest fires on carbon stocks also the analysis of regeneration processes are in need of more stratification factors. Looking at the mean values demonstrated that carbon stocks after more than 10 years after fire occurrences were still considerably lower than in non-affected forests. Thus long time periods can be expected until previous carbon stock levels are reached. The degree and frequency of the damage is also determining the regeneration processes and thus crucial for further analysis.

The analysis of the single carbon pools demonstrated that only trees > 10 cm DBH and roots have to be included in a future inventory, meaning that all other carbon pools can be conservatively omitted which saves time and costs. But especially the estimation of biomass and carbon stocks in roots was shown to be insufficient in achieving reliable results. Roots were an important carbon pool in the REDD project in Guatemala and thus it will be crucial that future methodologies apply further research on the question how carbon stocks in roots can be estimated in a more accurate and still cost-efficient way.

6. References

Achard, F., Brown, S., De Fries, R., Grassi, G., Herold, M., Mollicone, D., Pandey, D., Souza, C. (2009*) GOFC-GOLD, A sourcebook of methods and procedures for monitoring and reporting anthropogenic greenhouse gas emissions and removals caused by deforestation, gains and losses of carbon stocks in forests remaining forests, and forestation*. GOFC-GOLD report version COP15-1 (GOFC-GOLD Project Office, Natural Recourses Canada, Alberta, Canada). p. 48 - 55

Avoided Deforestation Partners, A (2009) *"REDD Methodology Framework". Version 1.0 – April 2009*. p. 1

Avoided Deforestation Partners, B (2009) *REDD Methodological Module – "Methods for stratification of the project area". Version 1.0 – April 2009.* p. 1.

Beaman, R.S., Beaman R.H., Marsh, C.V. and P.V. Woods (1985) *Drought and Forest Fires in Sabah in 1983*. Sabah Society Journal 8:10-30

Bonan, G.B. (2008) *Forests and Climate Change: Forcings, Feedbacks, and the climate benefits of forests*. In Science Magazine 13, June 2008, pp. 1444-1449.

Brown, S. (1997) *Estimating biomass and biomass change of tropical forests: a primer*. FAO Forestry paper no. 134. Rome

Brown, S. (2002) *Measuring carbon in forests: current status and future challenges.* Environ. Pollut. **116** 363-372

Cairns, M.A., Brown, S., Helmer, E.H., Baumgardner, G.A. (1997) *Root biomass allocation in the world's upland forests.* Oecologia (1997) **111**: 1-11

Cochrane, Mark A. (2003) *Fire science for rain forests*. Nature Vol. 421, 27 February 2003

Cochrane, Mark A. and Kevin C. Ryan (2009) *Fire and fire ecology: Concepts and principles.* Tropical Fire Ecology. Climate Change, Land Use, and Ecosystem Dynamics. Springer-Praxis Books in Environmental Science.

Cochrane, Mark A., Alencar, A., Schulze, M.D., Souza, C. Jr., Nepstad D., Lefebvre, P. and E. Davidson (1999). *Positive feedbacks in the fire dynamic of closed canopy tropical forests.* Science, **284**, 1832-1835

Contreras, J.F. (1999) *Plan General de Manejo Concesión Forestal San Andrés*. Documento en formato Acrobat. Flores, Petén, Guatemala. 35p.

Fisher, B.S., N. Nakicenovic, K. Alfsen, J. Corfee Morlot, F. de la Chesnaye, J.-Ch. Hourcade, K. Jiang, M. Kainuma, E. La Rovere, A. Matysek, A. Rana, K. Riahi, R. Richels, S. Rose, D. van Vuuren, R. Warren. (2007) *Issues related to mitigation in the long term context. In Climate*

Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Inter-governmental Panel on Climate Change [B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, L.A. Meyer (eds)], Cambridge University Press, Cambridge, p. 229.

Fittkau, E.J. and N.H. Klinge (1973) *On biomass and trophic structure of the central Amazonian rainforest ecosystem.* Biotropica 5: 2-14.

Flannery, T. (2006) *The Weather Makers – How man is changing the climate and what it means for life on earth*. p. 28. Atlantic Monthly Press, New York.

Goldammer, J.G. and B. Seibert (1990) *The impact of Droughts and Forest Fires on Tropical Lowland Rain Forest of East Kalimantan*. Ecological Studies 84 – Fire in the Tropical Biota. Ecosystem Processes and Global Challenges. Edited by J.G. Goldammer, Springer Verlag Berlin

Guild, L.S., Kauffmann, J.B., Ellingson, L.J., Cummings, D.L., Castro, E.A., Babbitt. R.E. and D.E. Ward (1998) *Dynamics associated with total aboveground biomass, C, nutrient pools, and biomass burning of primary forest and pasture in Rondônia, Brazil during SCAR-B.* Journal of Geophysical Research, **103**, 32091-32100

Hamilton, K., Sjardin, M., Shapiro, A. and T. Marcello (2009) *Fortifying the foundation: State of the Voluntary Carbon Markets 2009*. Ecosystem Market Place, Washington DC & New Carbon Finance, New York. p. 7-8.

Holloway, V. and E. Giandomenico (2009) *Carbon Planet White Paper: The history of REDD policy.* Carbon Planet Limited, Adelaide. p. 6.

IPCC (2007) *Summary for Policymakers. In Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M. and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Jobbágy, E. G. and Robert B. Jackson (2000) *The vertical distribution of soil organic carbon and its relation to climate and vegetation.* The Ecological Society of America. Ecological Applications, 10(2), 2000, pp. 423– 436

Koonze, A.L. and A. González-Cabán (1990) *Social and Ecological Aspects of Fire in Central America.* Ecological Studies 84 – Fire in the Tropical Biota. Ecosystem Processes and Global Challenges. Edited by J.G. Goldammer, Springer Verlag Berlin

Malmer, A., van Noordwijk, M. and L. A. Bruijnzeel (2005) *Effects of shifting cultivation and forest fire.* Forests, Water and People in the Humid Tropics, ed. M. Bonell and L.A. Bruijnzeel. Cambridge University Press. UNESCO 2005.

Ministry of Environment and Natural Resources, Guatemala. (2008) *The Forest Carbon Partnership Facility (FCPF) – Readiness Plan Idea Note (R-PIN)*. pp. 2-4

Minitab Inc. (2007) *Minitab 15 for Windows*

Mokany, K., Raison, J.R. and A.S. Prokushkin (2006). *Critical analysis of root:shoot ratios in terrestrial biomes.* Global Change Biology **12**: 84-96.

Moutinho, P., Schwartzman, S. (2005) *Tropical Deforestation and Climate Change*. Amazon Institute for Environmental Research, p.15.

Nykvist, N. (1996) *Regrowth of Secondary Vegetation after the "Borneo Fire" of 1982-1983.* Journal of Tropical Ecology, Vol. 12, No. 2. (Mar. 1996), pp. 307-312

OECD (2005) *Glossary of Statistical Terms*; http://stats.oecd.org/glossary/detail.asp?ID=285, 26th of May 2010

Parker, C., Mitchell, A., Trivedi, M. and N. Mardas (2008) *The little REDD Book – A guidance to governmental and non-governmental proposals for reducing emissions from deforestation and degradation.* Global Canopy Program, Oxford, UK. p. 12., p.19

Paustian, K., Ravindranath, N.H. and Andre van Amstel (2006) *2006 IPCC Guidlines for National Greenhouse Gas Inventories. Volume 4. Agriculture, Forestry and Other Land Use*. IPCC National Greenhouse Gas Inventories Programme. Published by the Institute for Global Environmental Strategies (IGES), Hayama, Japan. pp. 14 – 142

Pedroni, L. (2008) *Methodology for Estimating Reductions of Greenhouse Gases Emissions from Frontier Deforestation* (IDESAM; CDassist; Fundacao Amazonas Sustentável). pp. 11-12., p. 50, pp. 14-15, p. 89

Pedroni, L. (2010) *Spreadsheet tool for the calculation of greenhouse gas emission reductions in REDD projects.* Carbon Decisions International, Preliminary untested version, 16 March 2010.

Penman, J., Gytarsky, M., Hiraishi, T., Krug, T., Kruger, D., Pipatti, R., Buendia, L., Miwa, K., Ngara, T., Tanabe, K. and F. Wagner. (2004) *Good Practice Guidance for Land Use, Land-Use Change and Forestry*. Institute for Global Environmental Strategies (IGES) for the IPCC. p. 501, pp. 458-464, 458, 459, 472, 486, 234

Rothermel, R.C. (1985) *Fire behavior consideration of aeral ignition. Prescribed Fire by Aerial Ignition.* Intermountain Fire Council, 143-158

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

Shresta, R.M., Sharma, S., Timilsina, G.R., and S. Kumar. (2005) *Baseline Methodologies for Clean Development Mechanism Projects.* UNEP Risø Centre Denmark. p. 14

Thermo Fisher Scientific (2007) *Elemental Analysis – Flash EA 1112 Nitrogen and Carbon Analyzer for Soils, Sediments and Filters.* Thermo Fisher Scientific Inc. 2007

The World Bank. (2010) *Climate Change and & the World Bank*; http://beta.worldbank.org/climatechange/overview, 4th May 2010

Tinker, P.B., Ingram, J.S.I. and S. Struwe (1996) *Effects of slash-and-burn agriculture and deforestation on climate change*. Agriculture, Ecosystems and Environment 58: 13-22.

Uhl, C. and J.B. Kauffman (1990) *Deforestation, fire susceptibility and potential tree responses to fire in the Eastern Amazon.* Ecology **71** (2): 437-449

UN-REDD Program. (2009) *About REDD+* (FAO, UNDP, UNEP); http://www.un-redd.org/AboutREDD/tabid/582/language/en-US/Default.aspx, 20th of April 2010

Walker, S.M., Pearson, T. and S. Brown (2007) *Winrock Terrestrial Sampling Calculator.* Bio Carbon Fund, Winrock International.

Ward, D.E. (1990) *Factors Influencing the Emissions of Gases and Particulate Matter from Biomass Burning.* Ecological Studies 84 – Fire in the Tropical Biota. Ecosystem Processes and Global Challenges. Edited by J.G. Goldammer, Springer Verlag Berlin

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