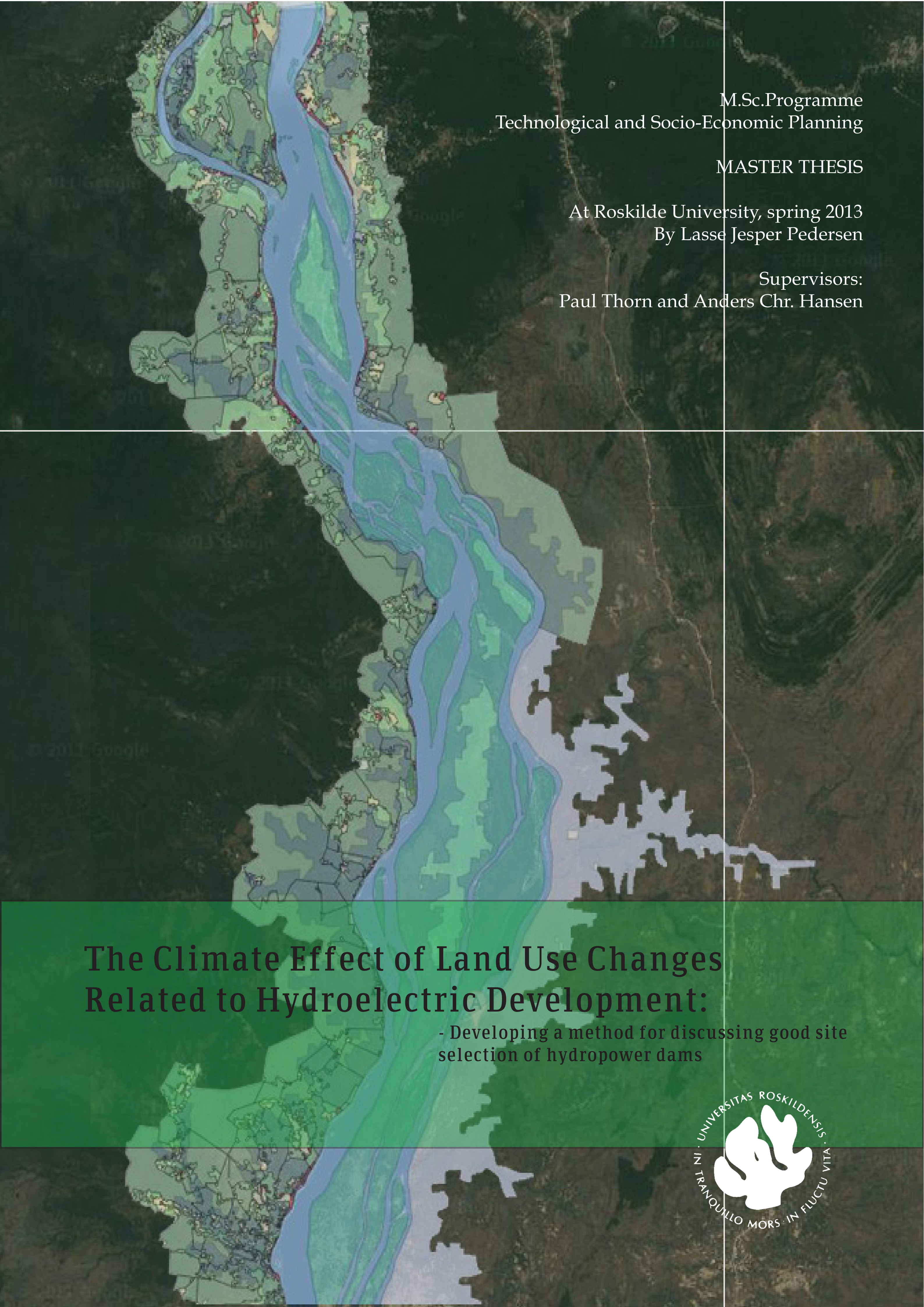

M.Sc.Programme
Technological and Socio-Economic Planning

MASTER THESIS

At Roskilde University, spring 2013
By Lasse Jesper Pedersen

Supervisors:
Paul Thorn and Anders Chr. Hansen

The Climate Effect of Land Use Changes Related to Hydroelectric Development:

- Developing a method for discussing good site selection of hydropower dams

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Abstract

Large dams vary considerably in their adverse climate impact. From a climate standpoint, there are good dams and bad dams. While some large dams are relatively benign, others appear to release substantial amount of greenhouse gases (GHGs) to the atmosphere. The presence of hydropower dams in the exclusive club of green energy sources must hence be taken up to consideration. The severity of the climate impacts from a hydroelectric project seems to be largely determined by the dam site. While dams at good sites can be very defensible from a climate standpoint, those proposed at bad sites can inherently be highly problematic.

This paper provides a simple, yet robust, methodology for comparing proposed hydroelectric project sites in terms of their negative climate impacts. This was done through a thorough literature study, with offset in the UN concept of Land Use, Land-Use Change and Forestry (LULUCF). The concept is defined by the United Nations Framework Convention on Climate Change (UNFCCC) as a "*gas inventory sector that covers emissions and removals of greenhouse gases resulting from direct human-induced land use, land-use change and forestry activities*". The findings of the literature study provided the foundation to discuss which variables contributed the most to changes in greenhouse gas budgets for hydroelectric energy production, and in combination with a 2 month fieldtrip to Cambodia, these findings also facilitated a calculation of the approximate cumulative greenhouse impact of the proposed Sambor Hydropower Dam Reservoir in Cambodia. The fieldtrip additionally complimented the study by drawing attention to how local factors can play a significant role in GHG budgets. The variables, which seemed to affect the GWP of hydropower dams the most, appeared to be the total flooded area (including indirectly implicated lands) and the depth of the reservoir. Additionally there seems to be a tendency where land-use changes are more significant in the tropical region than elsewhere, and hence that hydropower development in the warmer climates bears with it a much higher degree of risk, with regard to their climate impact - if appropriate considerations are not carefully planned for.

With reservation to the many uncertainties coupled with these kinds of budgets, the total release of GHGs in carbon dioxide equivalents from the proposed Sambor Dam reservoir was estimated to be between 153.17 and 204.41 Mt over a 100 year timeframe, or to have a CO_2 to energy ratio of 205 to 274 tCO_2 pr. GWh, which is substantially higher than other alternative energy solutions, but, also, substantially lower than thermal alternatives.

Master Thesis by Lasse Jesper Pedersen, Spring 2013.

Main supervisor: Paul Thorn
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The Climate Effect of Land Use Changes related to Hydroelectric Development:

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Roskilde University
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Abbreviations

ABL – Atmospheric Boundary Layer
AGB – Above Ground Biomass
AGGI – The NOAA annual GHG index
B_C – Organic Carbon Burial Rates
BM – Biometric Method
CDM – Clean Development Mechanism
COP – Conference of the parties
CRDT – Cambodian River Development Team
DBH – Diameter at Breast Height
DOC – Dissolved Organic Carbon
DOM – Dissolved Organic Matter
DWP – Dry Weight Percentage
E - East
EC – Eddy Covariance
EIA – Environmental Impact Assessment
EPA – Environmental Pollution Agency
EXIM – Export-Import (Banks)
FA – Flooded Area
GHG – Green House Gas
GMS – Greater Mekong Sub-region
GPG – Good Practice Guidelines
GPP – Gross Primary Production
GtC – Gigaton Carbon
GWP – Global Warming Potential
IHA – International Hydropower Association
IHP – International Hydrological Program
IL – Implicated Lands
IPCC – Integrated Pollution Prevention and Control
IRN – International Rivers Network
LAI – Leaf Area Index
LMB – The Lower Mekong Basin
LOI – Loss On Ignition
LUE – Light Use Efficiency
LULUCF – Land Use, Land Use Change and Forestry
N - North
NBE – Net Biome Exchange (≈NBP)
NBP – Net Biome Production (≈NBE)
NE – North East
NEE – Net Ecosystem Exchange (≈NEP)
NEP – Net Ecosystem Production (≈NEE)
NGO – Non-Governmental Organization
NPP – Net Primary Production
NOAA
NW – North Wets
NZ – New Zealand
OC – Organic Carbon
OM – Organic Matter
PBL – Planetary Boundary Layer
PDF – Public Democratic Republic (used in Lao PDR)
R – Respiration
R_a – Autotrophic Respiration
R_h – Heterotrophic Respiration
RA – Reservoir area
S - South

SD – Standard Deviation
SE – South East
SEA – South East Asia
sg – Specific Gravity
SOC – Soil Organic Carbon
SOE – State Owned Enterprise
SW – South West
TAGB – Total Above Ground Biomass
TOC – Total Organic Carbon
UA – Unidentified Area
UN – United Nations
UNESCO – United Nations Educational, Scientific, and Cultural Organization
UNFCCC – United Nations Framework Convention on Climate Change
USD – U. S. Dollar
W - West
WB – World Bank
WWF – World Wildlife Foundation
Yr – Year
Yrs – Years

Units

Gt – Gigaton ($1 \cdot 10^9 tonnes$)
Mt – Megaton ($1 \cdot 10^6 tonnes$)
KWh – Kilowatt hours ($1 \cdot 10^3\ watt$)
MWh – Megawatt hours ($1 \cdot 10^6\ watt$)
TWh – Terawatt hours ($1 \cdot 10^{12}\ watt$)

Molecular formulas

C - Carbon
CFC - Chlorofluorocarbon
CH_4 – Methane
CO_2 – Carbondioxide
N_2O – Nitrodioxide
NH_4 – Ammonium
NO_3 - Nitrate

Table of Contents

List of figures, tables, pictures and maps

INTRODUCTION

Chapter 0: Introduction

Power generated from the energy of moving water has been utilized for irrigation in ancient Mesopotamia and Egypt since the 6th millennia BC (Association for Industrial Archaeology, 2000). Today, electric energy generated by hydropower is the biggest source of renewable energy in the world (BP, 2011), and is also considered an important way to limit the amount of greenhouse gasses (GHGs) released into the atmosphere from power generation. In the Kyoto Protocol, hydropower is included in the range of Clean Development Mechanism (CDM) projects, available for countries to support the developing world, in order to meet their certified emission reduction goals in the cheapest possible way. Hydropower is generally considered a renewable energy source (IEA, 2011; World Energy Council, 2009)with little or no climate impact (IHA, 2010; IPCC, 2007; WCD, 2000).

However, in the wake of several social and environmental catastrophic hydropower undertakings by the end of the 90's, concerns over its social and ecological impacts at long last seemed to be acknowledged by the international community, as (among others) the World Bank (WB) fully withdrew from supporting hydropower projects in the developing world in 1999. Yet, after having stalled the lending for a few years, the WB chose to re-engage in hydropower projects from 2002 (World Bank, 2009). While having enhanced efforts to accommodate risks of environmental and social impacts through a number of research, the bank financed the Nam Theun II dam in Cambodia, which was meant as a model project for best practice standards applicable to future hydropower projects in the region (World Bank, 2009). This is nonetheless a goal many believe the bank has failed miserably to achieve (Imhof et al., 2006). At the same time, a group under the bank started to develop a working paper on "Social and Environmental Criteria for Good Site Selection of Hydropower Projects" to build on experiences from hydropower development in Latin America (Ledec& Quintero, 2003). The paper acknowledges site selection as the alpha and omega in limiting social and environmental impacts.

Between 2002 and 2004, the WB lent an average of 250 million USD annually to large-scale hydropower, and by 2008 this amount had increased significantly as the WB lent more than 1 billion USD to new projects all over the world (World Bank, 2009), an amount, which, in the coming years, is expected to double (Berliant, 2009). For comparison, WB funding for wind, solar, biomass and small hydro in total comprised no more than 476 million USD in 2008 (Berliant, 2009).

As the international community was gradually pulling out of hydropower projects in the decade leading up to the total draw back in 1999, China and China's state owned enterprises (SOE) who have had a significantly bad reputation from earlier hydropower projects all over the world, quickly filled the gap left by the WB (Osborne, 2007). The brief WB abandonment therefore unexpectedly created an enormous market for exporting Chinese hydropower technology. In general, this coincided with an emerging wish in developing countries, and in the rapidly expanding economies of South East Asia (SEA) especially, to reduce their dependence on the import of oil. Hence, the accumulative convergence of the two, fostered an enormous room for Chinese SOEs, and international financiers to enter into a growing hydropower market (Brewer, 2011).

0.1 Problem area

Generally, hydropower is understood as a green source of energy. Its position in this fashionable group is, however, threatened as the IPCC and UNESCO has joined several scientists (IPCC, 2008; UNESCO, 2009) in a lively discussion which began in the beginning of the 21st century, arguing whether or not hydropower production in fact posed a significant contribution to the greenhouse effect (Fearnside, 2005, 2004, 2002; Giles, 2006; Rosa et al., 2004, 2002; Soumis et al., 2004; St. Louis et al., 2000; Tremblay et al., 2005). While some argue that the problem is negligible, others have in several cases calculated hydroelectric production to release more carbon dioxide (CO_2) equivalent to the atmosphere than conventional oil, coal and gas plants (Fearnside, 2005; Lima et al., 2008). The principal argument is that when water is released from the bottom of reservoirs through dam turbines, the water contains massive amounts of methane gasses, which traditionally would be stored at the bottom of the reservoir or be released as CO_2 at the reservoir surface. When the water is released, dissolved methane is thus depressurized and released directly into the atmosphere (Abril, 2005; Delmas et al., 2001; Fearnside, 2005; International Rivers, 2007; Lima et al., 2008; Nette, 2009).

These newly found effects are today included and preached happily by the growing range of NGO's who are advocating against a growing hydropower industry; an industry that they have attacked for decades for ruining the ecology of the rivers on which millions of people depend (e.g. the International Rivers Network (IRN) and the Save the Mekong Coalition). In opposition to these arguments is the hydropower industry (obviously), led by the International Hydropower Association (IHA), who claims that harms which have been related to hydropower are widely exaggerated. Consequently, as hydropower started to gain a lot of negative attention on the GHG issue, the industry came to present their own analysis showing very different numbers, and in which several of the cases included in fact turned out as carbon sinks (IHA, 2010; Soumis et al., 2004).

Given the increasing attention large-scale hydropower is receiving in these years, as a source of "green" energy, it is becoming extremely urgent to disentangle the dispute. The hypothesis here is that:

> *…One of the reasons why hydropower GHG-discussion seems so persistent after more than a decade is that there are both good and bad examples - that some dams are releasing substantial amounts of GHGs, and that some are not.*

Therefore, rather than engaging in endless and generalizing discussions, the object of investigation should preferably be to unravel the mechanisms that cause an increase in project GHG releases, and to develop a methodology for assessing hydropower construction plans with regard to limiting their climatic impact. In other words, seek to identify how to increase the number of good examples instead of engaging in one sided and unconstructive discussion of the bad.

First and foremost, understanding the issue of GHGs related to the damming of rivers is extremely complex and both camps in the discussion have rather well documented research of their respective belief (See for example the famous correspondence between Philip M. Fearnside and Luiz Pinguelli Rosa (Fearnside, 2005, 2004, 2002; Rosa et al., 2004, 2002)). This suggests several things. It could be either different ways of presenting or calculating the emissions, or the inclusions/exclusion of different factors in the equations. It could be the different ways of defining the affected area, or it could be that the emissions are extremely difficult to calculate and/or reliable data is difficult to recover, causing the authors to choose the better or the worst case in order to make their point, etc. Even the industry has had to admit that there are some cases where there could be a problem related to GHGs from turbines and sluice gates. In 2008-09, together with the International Hydrological Program (IHP) under UNESCO, the IHA finally agreed to participate in a Hydropower GHG research project in order to "*find definitive answers and build consensus*", as it was stated on the 1st of June 2011 where the IHA invited the press to come and hear "*the latest update on the state of the science*" (IHA, 2011).

Previously, the argument was that in reservoirs, although man-made, carbon still cycled along natural and closed paths, and was thus not adding to global warming. But new arguments slowly succeeded in eroding that certainty. A reservoir's slow and deep water, as compared to a river, showed a shift of carbon emission from CO_2 to the more "greenhouse potent" gas CH_4 (Rosa et al., 2002). Despite the frontiers have drawn closer, the dispute is still persistent. Hence, there is still a need to investigate what causes an increase in the global warming potential (GWP) from hydropower production, and even more importantly, how these can be limited. When skimming the literature, one obvious difference between the two "camps" are the "believers" wish to discuss the demarcation of the problem; demanding a scale up in order to include second and third order effects. Especially the climate effect of *land-use changes caused by inundation of land* have been stressed as one of the most relevant factors in addition to emissions from turbines and sluice gates (Fearnside, 2005; Graham-Rowe, 2005; International Rivers, 2007; McCully, 2006).

0.2 Research question

It is clear that hydropower development can cause serious social and environmental damage if appropriate precautions are not made, or taken into consideration, before project initiation. These risks were accommodated comprehensively by the WB financed report which identifies 'good site selection' as the Alfa and Omega in sustainable hydropower planning. However, correlating with the obvious fact that the report was written before GHG issues received proper recognition, GHGs are only mentioned very superficially as something which might require further recognition in future work. It is thus the argument that "good" site selection needs to include the means to limit the climate impacts of hydropower development.

Therefore, in order to contribute to unravelling the controversy and to cast some light on the mechanisms that renders some dams good and some dams bad, seen from a climate perspective; this report seeks to bring light on the climate effect of land-use changes, and contribute to the understanding of good site selection for hydroelectric planners by answering the following research questions:

How do land-use changes resulting from the construction of hydroelectric reservoirs affect the total reservoir carbon balance?

Additionally, the identification of relevant variables will also provide the means to discuss the climate effect of a certain project before its commencement. In order to take the results 'over the desk' and test their durability and applicability on an actual case, the proposed Sambor Dam in Cambodia, which is currently in its final planning stages, has been chosen. The Sambor Dam is an interesting case as it is one of the 11 proposed and highly controversial dams on the Mekong River mainstream, with many interesting features. The case will highlight the importance of considering *local factors* and *quantitatively* set the stage of hydropower projects in an aggregated carbon budget as the one proposed. The project hence seeks to answer the following sub questions:

a) *What are the main contributing factors in the carbon balance?*
b) *What is the approximate cumulative greenhouse effect of the land-use changes associated with the building of the Sambor Dam in Cambodia?*
c) *How can the climate impact of dams be mitigated through good site selection?*

0.3 Limitations

To define the magnitude of GHG fluxes from a given reservoir, one must consider the difference between *gross* and *net* GHG emissions. According to Varfalvy, in UNESCO and IHA (2009) *gross emissions* are those measured at the air-water surface, whereas *net emissions* are gross emissions minus pre-impoundment ("*natural*") emissions (both terrestrial and aquatic) in the whole watershed area:

1) Upstream;
2) Downstream, and;
3) At estuaries.

Due to the limited amount of resources and time, it will not be possible to look into all the conceivable factors. The discussion is therefore limited to the direct and indirect effect of land-use changes upstream, related to, and sensitive to, *site selection*. That is *primarily the upstream* affect.

Chapter 1: The basic concept of Climate Change, photosynthesis and the carbon cycle

The fundamental concept of conventional dams is the storage of gravitational potential energy of water in the hydropower reservoir. The amount of water stored can be understood as the "battery" of the dam. When the reservoir is filled with water, the battery is fully charged. The size of the reservoir defines the size of the battery. In order to maximize the potential energy of the dam, large areas of land are therefore often swallowed by the dam reservoir - and as a consequence, large amounts of organic material will be flooded. Most of the carbon sequestrated in the biomass will consequently be returned to the atmosphere in some way or another.

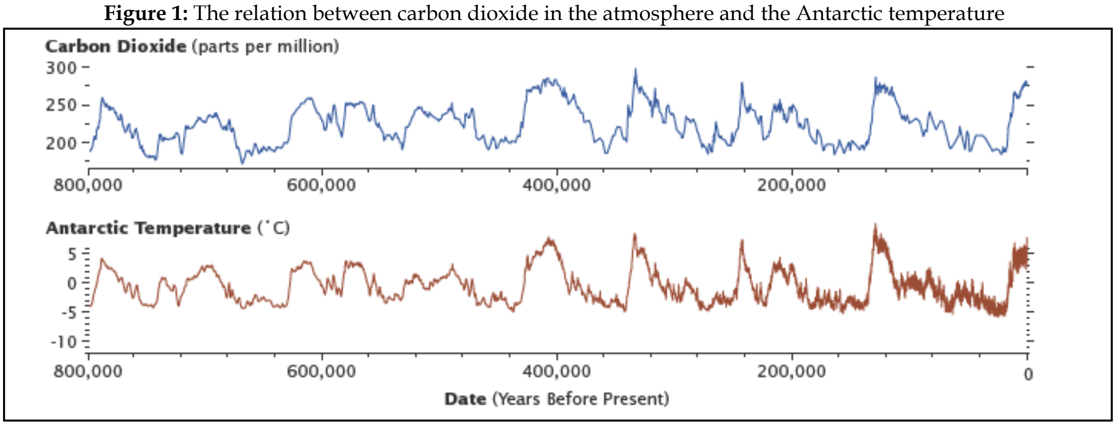
Furthermore, some lakes and reservoirs, especially those found in tropical regions are known to be considerable sources of carbon emissions (Bastviken et al., 2011, 2004; Farrèr and Senn, 2007; Teodoru et al., 2012; Walter et al., 2007). In addition to the carbon that is returned to the atmosphere from the organic material which were flooded when the reservoir was filled, the reservoir in itself will most likely add to the total amounts of GHGs from the project. In order to understand these processes and how the effect can be mitigated, a much more thorough understanding of the issue is necessary.

1.1 Climate change

Variations in the earth's orbit have always influenced the amount of energy the earth receives from the sun, which in turn have led to cycles of ice ages and warm periods. Although, there is little doubt or scepticism today in the belief that human life is effecting the climate in a direction where we (rather sooner than later) will reach a tipping point[1], where abrupt climate changes become irreversible (Cook, 2009; Lenton, 2011). In brief, the concept of a tipping point may be rather ill-defined, but is meant to illustrate the point where the global climate changes from one steady state to another. A popular metaphor is that of a glass of wine tipping over – standing the glass up will not put the wine back. In the same way, if we pass the tipping point, climate changes may be irreversible regardless of the measures taken after this point is reached ("Tipping point (climatology)," 2012).

The main way in which mankind is affecting climate changes is through the release of GHGs such as CO_2 from the global energy production (U.S. Department of State, 2007).

Figure 1: The relation between carbon dioxide in the atmosphere and the Antarctic temperature



Source: (Jouzel et al., 2007; Luthi et al., 2008)

[1] "A climate 'tipping point' occurs when a small change in forcing triggers a strongly nonlinear response in the internal dynamics of part of the climate system, qualitatively changing its future state" (Lenton, 2011).

1.2 The climatology of Climate Change

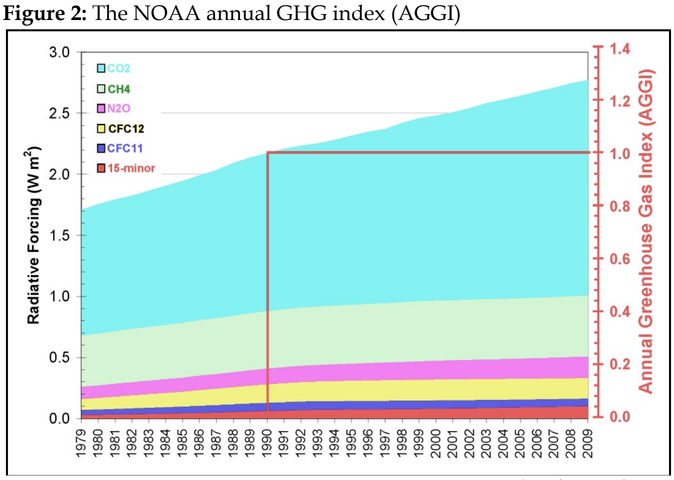
The primary reason for climate change is the greenhouse effect. The greenhouse effect is the trapping of thermal radiation by atmospheric greenhouse gases, which causes some of the thermal radiation to be reradiated back to earth. The effect is that the average surface temperature increases more than it would have if direct heating from the sun was the only source of energy. Any (significant) change in the amount of *greenhouse gases (GHGs)* in the atmosphere will affect the climate (Forster et al., 2007; Schimel et al., 1996). GHGs are gases that cause a photochemical reaction in the troposphere and the stratosphere, where they trap part of the thermal radiation from the surface of the earth. Colloquially, GHGs are understood as a product of human activity, but it is important to understand that GHGs are natural and are an important part of sustaining the conditions for much life on earth in the form of heat. A good example of a natural greenhouse gas is water vapour, which contributes between 36-72% to the greenhouse effect (Kiehl & Trenberth, 1997). The trouble is, however, that an *increase* in the amount of GHGs in the atmosphere intensifies the radiative forcing and draws us nearer to an eventual tipping point (Cook, 2009). Radiative forcing is defined as "*an externally imposed perturbation in the radiative energy budget of Earth's climate system*"(IPCC, 2001).

Climate change can briefly be described as a significant and long lasting change in the statistical properties of a climate system, among others due to "*external forcings* or *persistent anthropogenic changes in land use*" (IPCC, 2011). The main anthropogenic contribution to climate change are the burning of fossil fuels and human caused deforestation, which both contribute to an increased build-up of greenhouse gases in the atmosphere. Annually, around 6.3 Gigatons (Gt) of carbon is released from the burning of fossil fuels, whereas roughly another 1.6 Gt of carbon is released as the size of the carbon stored in the terrestrial carbon pool is taken out of storage and hence reduced due to global human caused deforestation (IPCC, 2007).

1.3 The global warming potential

While CO_2 is still the prime contributor to the radiative forcing, with approximately 63,5% according to the NOAA annual GHG index (AGGI), Methane (CH_4) is estimated to contribute roughly 18% (Butler et al., 2010). Besides contributing to global warming, CH_4 is also part of a series of chemical reactions that lead to the formation of tropospheric ozone and urban smog (Tremblay et al., 2005). Especially inland aquatic systems are thought to be a significant contributors of methane gas to the atmosphere (Bastviken et al., 2004, 2004; Caraco and Cole, 2004; Cole et al., 2007, 2007; Kosten et al., 2010). The figure below (Figure 2) shows that the radiative forcing has increased to 27.5% since 1990.

Figure 2: The NOAA annual GHG index (AGGI)



Source: (Butler et al., 2010)

Different GHGs have dissimilar impacts on global warming. In order to compare GHGs, it is therefore important to understand the correlation between them, that is, their Global Warming Potential (GWP).

Table 1: Comparison of characteristics of different GHGs over 20 to 500 years

Greenhouse Gases	*Greenhouse potential per molecule of CO2* [a]	*% increase in concentration per year* [a]	*% contribution to greenhouse effects* [b]	*Atmospheric residence time* [a]	*GWP over 20, 100 and 500 years* [c]		
					20	*100*	*500*
Carbon dioxide	1	0.5	63,5	120	1	1	1
Methane	25	1	18,1	10.5	72	25	7.6
Nitrous Oxide	320	5	6,2	132	289	198	153
Others		0.25	3,9				

Source (a): Palananthakumar 1999, (b): NOAA Earth System Research Laboratory 2010 (Butler et al. 2010), (c): (IPCC 2001)

The GWP is an expression for how much heat an equivalent mass of a specific greenhouse gases traps over time (Table 1). The GWP is understood in the Kyoto Protocol as a means to understand and convert the effect of various greenhouse gases in relation to CO_2 over a certain amount of time (Grubb et al., 1999). The term was developed in order to compensate for different GHGs' influence on the radiative forcing.

1.4 The Carbon cycle, photosynthesis and global warming

The biochemical Carbon exchange between the pedosphere (the "outer" part of the earth – primarily soil), the geosphere (the "inner" part of the earth – primarily rock), the hydrosphere (the combined mass of water on the earth), the atmosphere (the layer of gases that surround the planet) and the biosphere (that is the global sum of all ecosystems), is called the Carbon Cycle (Smith, 1997). Besides being entwined in one serious threat to human life on earth, carbon is also one of the most fundamental chemical elements supporting all of life on earth.

Under natural conditions, carbon flow between pools has both a slow and a fast component. *The slow component (*from a human perspective) concern the carbon that is stored in the biosphere (fx oil, coal and gas). This carbon storage is a result of a series of chemical reactions and tectonic activity and has a carbon-return time between 100-200 million years (Riebeek, 2011). *The fast component* of the carbon cycle can be understood as the movement of carbon through earth's forms of life. The main carbon exchange in the fast carbon cycle happens as photoautotrophs (plants, algae, and many species of bacteria) convert carbon dioxide and water into organic compounds using the energy from the sun (Smith, 1997). Basically, the photoautotrophs combine CO_2 and water to produce sugar and oxygen through photosynthesis:

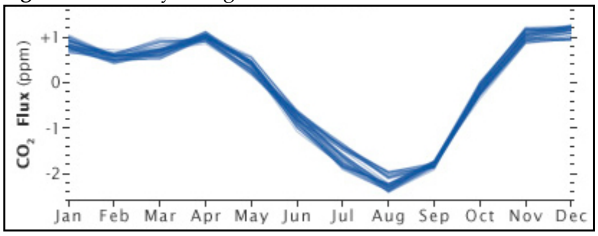
Equation 1: Photosynthesis

$$CO_2 + H_2O + Energy \rightarrow CH_2O + O_2$$

As oxygen is released as a waste product, the sugar provides the photoautotrophs with the energy, which they need to grow, and as they do so, they will continue to absorb CO_2 from the atmosphere. When the photoautotrophs later rot, are consumed by animals or burned, the organic material will be broken down into simpler forms of matter and the carbon is again returned to the atmosphere.

The photosynthesis/respiration dynamic described above is especially evident when looking at the monthly atmospheric change in carbon dioxide. Figuratively, it is almost as if the earth is breathing (Figure 3). Annually, more than 80 GtC moves through the fast cycle each year (Riebeek, 2011; Solomon et al., 2007). However when fossil fuels, for example, are extracted from the earth's geosphere and used for energy, what effectively happens is that carbon is moved from the slow to the fast component of the carbon cycle, contributing to an increase in atmospheric carbon, and ultimately, global warming.

Figure 3: Monthly change in carbon dioxide, 1959-2010



Source: (Butler et al., 2010)

Generally, all changes in a pool are balanced by changes in the other pools. This is roughly illustrated in Table 2, below. Even though an increase in atmospheric carbon is believed to have caused both the oceans and the terrestrial biosphere to absorb more carbon; changes that cause a higher concentration of carbon in the atmosphere will add to the greenhouse effect (Riebeek, 2011).

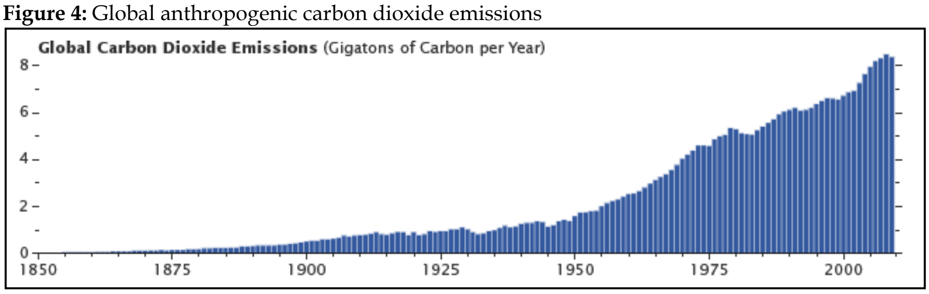
Table 2: Major carbon pools and fluxes in the carbon cycle

	Reservoir size [GtC]	*Annual discarge [GtC]*	*Annual sink [GtC]*	*Annual change [GtC/year]*
Atmosphere	750	41.1	42	+0.9
Terrestrial biosphere	2000	16	16.2	+0.2
Fossil fuels (geosphere)	5,000-10,000	1.7	-	-1.7
Oceans (hydrosphere)	93000	24.3	24.9	+0.6

Source: IPPC/Solomon et. al. 2007

This is at least true for the short term because, despite periodic fluctuations, it seems like the carbon cycle, in the long term, has had an ability to maintain a certain balance that prevents all carbon to enter the atmosphere (as it is the case on Venus) or remain stored in the earth's carbon pools (Table 2). This mechanism has helped to keep the earth's temperature relatively stable for over 2 million years and is often referred to as the earth's thermostat (Riebeek, 2011). Despite the fact that the fluctuations in the earth´s temperature are normal, the concern is that anthropogenic impacts on carbon fluxes due to especially the burning of fossil fuels and deforestation, eventually may push the natural development past aforementioned tipping point (Cook, 2009; Lenton, 2011). Figure 4 below illustrates how the annual anthropogenic emissions of carbon dioxide have increased markedly over the last 150 years.

Figure 4: Global anthropogenic carbon dioxide emissions



Source: (CDIAC, 2011)

1.5 Use of terms in GHG accounting

In general, there is a lot of confusion about the use of terms in greenhouse gas accounting. In the following, some of the fundamental terms and how they are understood here will therefore be clarified. For references, see Kirschbaum & Mueller, (2001) or Cole et al., (2007). The relationship between the terms is furthermore illustrated in Figure 5 below (p.11).

1.5.1 GPP

As discussed, the main carbon assimilation from the atmosphere to the biosphere happens through photosynthesis. The carbon that is assimilated in this process, the gross primary production (GPP), then supports the respiration (R) of all living organisms (plants, microbe and animals), as wood, roots and foliage use energy for growth and maintenance:

Equation 2: Respiration

$$CH_2O + 0_2 \rightarrow CO_2 + H_20 + Energy$$

1.5.2 NPP

The Net Primary Production (NPP) denotes the net production of organic carbon by plants after autotrophic respiration (R_a). The NPP hence represents the total annual growth increment (above and below ground) plus the amounts grown and shed in senescence, reproduction or the death of short-lived individuals in a stand plus the amounts consumed by herbivores. The majority of the NPP is attributed to biomass production in wood (branches and stems; wNPP), roots (rNPP), foliage (fNPP) and a number of components which are very difficult to measure (mNPP). These include the carbon that is invested in the understory plant growth and in the reproductive organs of flowers, seeds and fruits (Luyssaert et al., 2007a). Both the GPP and the NPP solely represents system carbon "gains" and are always positive.

Equation 3: Net Primary Production, NPP

$$NPP = GPP - R_a$$

$$NPP \approx wNPP + rNPP + fNPP + mNPP$$

1.5.3 NEP or NEE

The Net Ecosystem Production (NEP) or the Net ecosystem Exchange (NEE) is the NPP-R_h, where R_h denotes the heterotrophic respiration. While these two terms causes much confusion[2], the understanding presented above, by Kirschbaum and Mueller, (2001) and Cole et al., (2007), as well as Luyssaert et al., (2007) and others, will be adopted.

The two terms are often distinguished in that the NEE represents the immediate, or short term balance between uptakes and releases in for example gram [g] per m^2 per day (d), while the NEP on the other hand is a measurement of the net balance (gain or loss) of carbon (or energy) over a period of time and commonly expressed in flux units such as gram per. m^2 per. year (y). The NEP is most often derived from long term averages of NEE measurements.

Equation 4: Net Ecosystem Exchange, NEE (or NEP) and units

$$NEE = NPP - R_h, \text{ (usually measured in } g \cdot m^2 \cdot d^{-1})$$

$$NEP = NPP - R_h, \text{ (usually measured in } g \cdot m^2 \cdot y^{-1})$$

Both NEE and NEP focuses on vertical uptakes and releases in and out of the system, thereby ignoring lateral fluxes. Both are usually measured using Eddy-flux towers[3] in order to determine the simultaneous amount of CO_2 that is entering, and the amount of carbon that is being lost, from the ecosystem.

1.5.4 NBE and NBP

The Net Biome Exchange (NBE) and the Net Biome Production (NBP) represents the exchange in carbon stocks when episodic carbon losses due to anthropogenic or natural disturbances, are included (L_d). In systems which are not affected by major episodic losses the NBE=NEE or NBP=NEP.

Equation 5: Net Biome Exchange, NBE (or NBP)

$$NBE = NEE - L_d$$

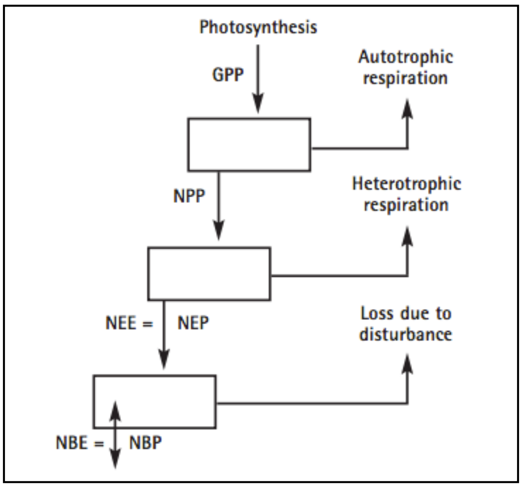
$$NBP = NEE - L_d$$

[2]For example, Tremblay et al. (2005) include in his understanding of NEP, carbon losses other than local respiration. In the case of forests, this means in effect that riverine export of dissolved organic carbon, volatile organic carbon emissions and carbon emitted through forest fires and insect outbreaks are included in NEP measurements.

[3] See description in chapter 3.1, p. 35

The relationship between GPP, NPP, NEE or NEP and NBE or NBP is represented in Figure 5 below:

Figure 5: Diagrammatic representation of the main terms describing system carbon balances



Source: (Kirschbaum and Mueller, 2001)

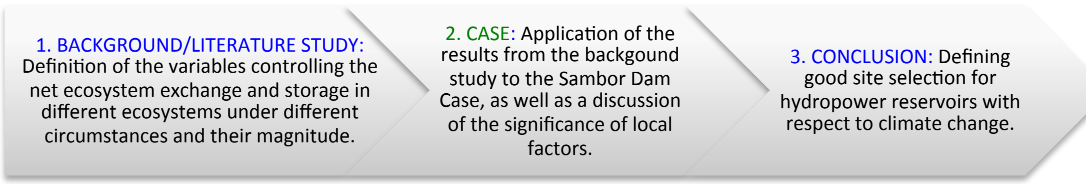
METHODOLOGY

Chapter 2: Method

The report is basically divided into three parts:

1) A thorough discussion of the controlling mechanisms that affect the role of hydropower reservoirs as sources or sinks of atmospheric greenhouse gases, including changes in carbon pools, and their magnitude (*background/literature study*)
2) The application of the results to the Sambor Dam hydropower Project, including a discussion of the role of local factors (*case*), and finally
3) A discussion of the project findings in regard to good site selection (*conclusion*):

Figure 6: Flow diagram illustrating the flow of the report



2.1 Land use, land-use change and forestry

To understand the effect land-use changes has on the carbon pools and fluxes in and beyond the reservoir area (RA), the UN concept of Land Use, Land-Use Change and Forestry (LULUCF) is introduced. The concept is defined by the United Nations Framework Convention on Climate Change (UNFCCC) as a "*gas inventory sector that covers emissions and removals of greenhouse gases resulting from direct human-induced land use, land-use change and forestry activities*" (UNFCCC, 2012a).

2.1.1 Defining the unit of study

Basically, the concept of LULUCF is meant as a tool for annex 1 countries[4] to live up to their obligations agreed upon in the Kyoto Protocol. The Kyoto Protocol is a protocol adopted at the United Nations Framework Convention on Climate Change (UNFCCC or FCCC) which set binding obligations on the industrialized countries to reduce their emissions of greenhouse gases. Among other things, the parties agreed that *GHG removals and emissions from certain activities* should be accounted for in estimating a country's progress to meet their emission obligations. Since 1997, measures such as afforestation and reforestation have been included in the range of options a country could undertake to meet their certified reduction goals. Conversely, consequences of *land-use changes* such as deforestation should also be subtracted from the emissions that annex 1 countries are allowed to emit over their commitment period (UNFCCC, 2012b). The budget seeks to account for (UNFCCC, 2012c):

1) Changes in the affected systems uptakes and releases of GHGs (the NEE balance)
2) Changes in the affected systems carbon pools (storage changes).

In December 2003, a number of good practice guidelines for LULUCF were welcomed at the COP9 in Milan, and this constitutes the way the good LULUCF practices are understood today (Penman et al., 2003). The good practice guidelines (GPG) for LULUCF (defined by the IPPC upon request of the COP7 in Morocco), described six broad land-use categories for reporting national inventories under the convention (UNFCCC, 2012c). These are:

1) Forestlands
2) Croplands
3) Grasslands
4) Wetlands
5) Settlements

[4] Industrialized countries and economies in transition

6) Other lands (fx infrastructure)

2.1.1.a Adapting the land-use categories vis-à-vis the background chapter

The following paragraph will define areas of interest, land-use categories and methodological considerations vis-à-vis the background chapters.

In estimating the effect of land-use changes consequent to hydropower development croplands, grasslands and settlements need only little consideration. Primarily, as the role of *grasslands* in carbon budgets, in general, is quite insignificant (Jaksic et al., 2006). Both the storage *in*, and the NEE of GHG *over* grasslands are in other words expected to be zero (or close to zero).

Croplands and *settlements* can be excluded from NEE estimates, due to the expectation that when these land-uses are flooded for hydroelectric reservoirs, they are likely to be established elsewhere to support whatever need or purpose they were supporting before inundation. Conversely, re-establishment of croplands and resettlement of populations will of cause need to be included in the LULUCF to the extent that this happens at the expense of for example forest land, as such would cause a proportional reduction in the carbon pools and the NEE over these implicated lands (IL).

The remaining land-use categories are understood according to the hierarchy defined by Tremblay et al. (2005), and are hence divided as such:

1) The terrestrial biosphere, including
    a. Forests
    b. Inland wetlands
        i. Peatlands
        ii. Marshes
        iii. Swamps
        iv. (Ricelands)[5]
2) The aquatic ecosystems, including
    a. Lakes
    b. Reservoirs
    c. Rivers.

Each of these ecosystem categories will be elaborated upon in the relevant chapters.

It is however necessary to apply some curtailment to carbon storage estimates:

For the *terrestrial biosphere*, little is regrettably understood of the fate of the carbon which is stored in the *terrestrial soils* of forests and wetlands[6] upon reservoir filling (Cole & Caraco, 2001; McCully, 2006; Tremblay et al., 2005). Most of it is expected to be stored at the bottom of the reservoir and will hence only be discussed in peripheral in the following.

The aquatic ecosystems, on the other hand have traditionally been understood as pipes transporting carbon from the terrestrial land to the ocean. While this might largely be true for lentic ecosystems (here; *rivers)*, recent research has shown that lotic ecosystems[7] (here; *lakes and reservoirs)* must also be included in carbon storage budgets (Cole et al., 2007).

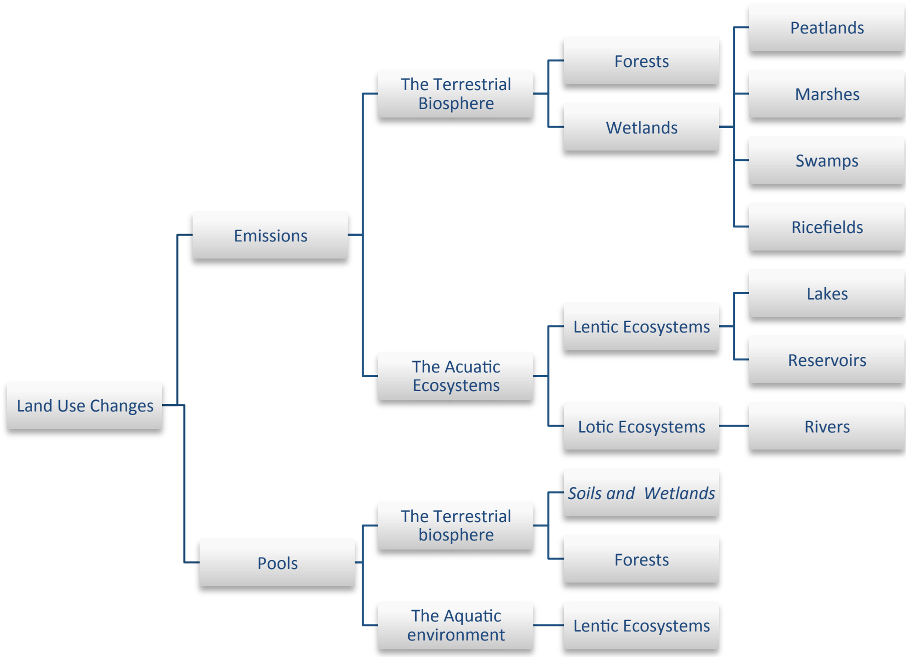
[5] Ricelands are maintained in the wetland definition despite other croplands that are excluded. This happens, as a discussion on riceland methane emissions will function as a good means to discuss the mechanisms, which affects GHG emissions from wetlands in general.
[6] Of all the aboveground terrestrial carbon, approximately 80% is stored in forest ecosystems and of all belowground terrestrial carbon, roughly 40% is stored in forest soils (Pregitzer & Euskirchen, 2004).
[7]A lentic ecosystem is the ecosystem of a lake, pond or swamp. Included in the environment are the biotic interactions (amongst plants, animals and micro-organisms) and the abiotic interactions (physical and chemical). Lentic ecosystems are most often characterized by slow moving water, compared to lotic ecosystems (such as rivers), where water movement are much more rapid (Kalff, 2001), see chapter 6.4, p. 66.

The main carbon pools are hence understood as the carbon, which is stored in:

1) Forests, and
2) Lentic ecosystems:
    a. Lakes
    b. Reservoirs.

A hierarchy of the areas of interest in the background chapter can be defined as depicted here:

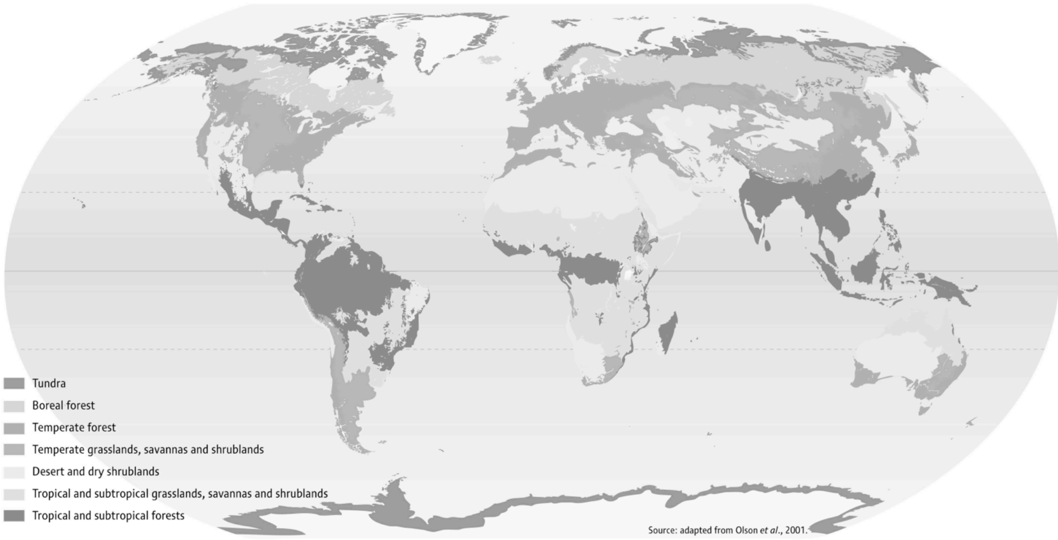
Figure 7: Diagram showing the hierarchy of the background chapter



To comprehend the vast amount of data, and to be able to understand the results from different climates in comparison to one another, the data is divided according to forest biomes. In general, biomes are somewhat loosely defined, but are often understood as *ecosystems that share abiotic*[8] *and biotic*[9] *factors*. Biomes are often identified through particular patterns of ecological succession and climax vegetation[10], and is therefore believed to share many of the variables which might show as significant in carbon budgets of certain land-use categories (eg. climate, vegetation type, precipitation etc.). The forest biomes are geographically defined as shown on Map 1:

[8] Physical rather than biological; not derived from living organisms.
[9] Of, relating to, or resulting from living things, esp. in their ecological relations.
[10] Climax vegetation is the vegetation that establishes itself on a given site for the given climatic conditions in the absence of anthropic action after a long time (it is the asymptotic or quasi-equilibrium state of the local ecosystem).

Map 1: The forest biomes



Source: (Olson et al., 2001)

Below is a rough overview of the mean temperature, precipitation and net radiation sum of various forest biomes. What is especially evident is the weak seasonality of the tropical regions, besides the higher temperatures, more precipitation, a higher net radiation sum and a lengthier growing season. The effect of these will be discussed in relation to the various ecosystems and biomes in the relevant chapters, but the table below does demonstrate a significant distinction between the biomes with regard to a number of climate variables.

Table 3: Mean temperature, precipitation and net radiation of various forest biomes

Biome	*Mean winter temperature [C]*	*Mean summer temperature [C]*	*Mean precipitation sum winter [mm]*	*Mean precipitation sum summer [mm]*	*Net radiation sum winter [W/m2]*	*Net radiation sum summer [W/m2]*	*Length of growing season [days]*
BOREAL forest							
- Humid evergreen	-9	13	205	144	46	216	130
- Semiarid evergreen	-18	13	52	183	46	359	130
- Semiarid deciduous	-20	13	47	156	33	348	130
TEMPERATE forest							
- Humid evergreen	4	17	499	194	147	473	140-200
- Semiarid evergreen	2	20	183	356	150	425	140-200
- Semiarid deciduous	0	14	356	81	152	502	140-200
TROPICAL forest							
- Humid evergreen	23	24	685	469	361	437	365

Source: (Luyssaert et al., 2007; "the forest biome", 2012)

2.1.1.b Defining the unit of study

The following paragraph will narrow down the unit of study and the focus of the present research paper to the findings in chapter 2.1.1, above.

Generally:

> *"An ecosystem, as a unit of study, must be a bounded system, yet the scale can range from a puddle, to a lake, to a watershed, to a biome. Indeed, ecosystem scale is defined more by the functioning of the system than by any checklist of constituent parts, and the scale of analysis should be determined by the problem being addressed"* (Jørgensen, 2009).

The *unit of study* can be understood bounded by the spatial extend to which ecosystems change character in a way which will alter their role in carbon budgets. The role of hydropower dams in carbon budgets are however not fully understood, but are primarily believed to be (Graham-Rowe, 2005; International Rivers, 2007; Tremblay et al., 2005) :

- The direct impact of land-use changes; geographically bordered by the RA
  - Changes in carbon fluxes
  - Changes in carbon pools
- The indirect impact of land-use change; primarily downstream of the dam
  - Emissions at dam turbines and spillways during dam operation
  - Changes in downstream river emissions.

The scope of the present paper is limited solely to focus on the direct impact of LULUCF; elaborated as the balance between carbon pools and fluxes in present land-uses:

1) NEE of, and storage in, terrestrial lands of the RA
2) NEE of, and storage in, aquatic systems of the RA
3) NEE of, and storage in, IL

- and after reservoir filling:

4) NEE of, and storage in, the hydropower reservoir.

2.1.2 Study design and implementation

In order to define an apt method, the LULUCF GPG put forward by the IPCC and agreed upon by the parties at COP9 in Milan, will be adopted. Basically, the LULUCF GPG states that inventories consistent with good practice are those which do not contain neither over- nor underestimates, so far as can be judged, and in which uncertainties are reduced as far as practicable[11] in order to ensure that carbon stock changes, emissions by sources and removals by sinks, even if uncertain, are *bona fide*[12] estimates (IPCC, 2003; Penman et al., 2003). Subsequently, the basic idea of the IPCC GPG for LULUCF follows a similar mind-set by Pannucci and Wilkins (2010), which generally states that bias is prevented best through proper study design and implementation and that estimates must not "*contain any bias that could have been identified and eliminated, and that uncertainties therefore must be reduced as far as practicable given national circumstances*" (IPCC, 2003).

The IPPC furthermore developed a rather comprehensive method to identify *key categories*[13] and subsequently to identify the appropriate *tier level*[14] for *land converted to other land-use categories* (IPCC, 2003) (Appendix 2). What the method essentially emphasizes is a sort of a hierarchy based upon the expected significance of the specific land-use changes, which recognizes that national factors play a role both in the available data and the possibilities to obtain it. Additionally, some emission factors are more complex to understand and obtain than others (IPCC, 2003; Penman et al., 2003).

Finally, the GPG for LULUCF encourages that studies showing extreme estimates are to be excluded (IPCC, 2003) and that LULUCF estimates should be done over at least 100 years (UNESCO and IHA, 2009), which essentially necessitates attention both to current land uses and the expected development.

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[11] Understood here as able to be done - or put into practice – successfully.
[12] Understood here as estimates done without the intention to deceive.
[13] A key source category has a significant influence on a country's total inventory of direct greenhouse gases in terms of absolute level of emissions, the trend in emissions, or both.
[14] The IPCC methods for estimating emissions and removals are divided into 'Tiers' encompassing different levels of activity and technology detail. Tier 1 methods are generally straightforward (activity multiplied by default emissions factor) and require less data and expertise than the most complicated Tier 3 methods. Tier 2 and 3 methods have higher levels of complexity and require more detailed country-specific information on things such as technology type or livestock characteristics. The concept of Tiers is also used to describe different levels of key source analysis, uncertainty analysis, and quality assurance and quality control activities (Australian Greenhouse Office, 2012).

2.1.2.a Adapting the conceptual framework and study design vis-à-vis the case

The following paragraph will define the conceptual framework and an appropriate study design according to the selected case. The study design is relative to knowledge obtained through the land-use mapping and the knowledge obtained throughout the background chapters.

While the GPG for LULUCF encourages that both under- and over estimations are avoided, this must be understood in the context, that the LULUCF GPGs are designed for countries to use in their national GHG accounting. The IPCC in other words encourages countries not to 'take chances' or not to choose the more 'convenient' variable (Penman et al., 2003). In the present research paper, the researcher has the opportunity to acknowledge that bias is neither a dichotomous variable, nor something one can be entirely aware of (Pannucci and Wilkins, 2010) in another way. Consequently:

> *When the obtained knowledge fits with the variables identified through the background chapters, these will, along with average biome-specific values, constitute the offset for the discussion of the Sambor GHG effect; where in doubt, estimates will however be preferred conservative. This is believed to render the overall estimates conservative, without rendering it a vast underestimate.*

Defining the IPPC concept of *key categories* relative to the knowledge obtained through the initial mapping will identify the following as the land-uses subject to the largest areal change, and the land-uses which are expected to contribute the most to LULUCF budgets (the key categories):

1) The reservoir
2) The existing forests
3) The existing river.

Identifying appropriate tier levels can be done using the IPPC decision tree on each land-use category identified (see appendix 2). The tier levels represent the methods by which data should be obtained with reference to:

1) The Existing knowledge
2) The opportunity/difficulty in obtaining new knowledge.

Basically, the appropriate method for each of the 3 IPPC tier-levels, are defined as:

Tier level 1: Activity multiplied by default emission factor
Tier level 2: Activity multiplied by country specific data
Tier level 3: Use advanced methods and detailed country specific data.

The appropriate tier-level is identified below for each land-use category included in the tailored LULUCF budgets for hydropower development. The identification takes offset in the IPCC "decision tree for identification of appropriate tier-level for land converted to other land-use category" (appendix 2), the knowledge obtained through the background chapters of the report and the land-use mapping. References to the relevant chapters will be stated in the table.

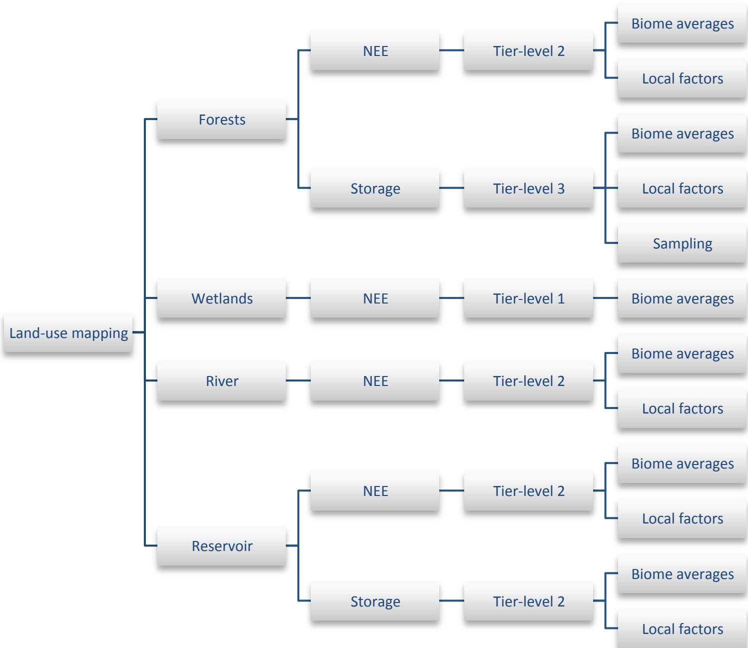
Table 4: Identifying appropriate tier-level

Category?	*Type?*	*Key?*	*Form*	*Additional background for tier-level decision*	*Tier*
Forests	Flux	Yes	CO_2, CH_4 and N_2O	Sampling not possible (security, resources)– chapter 2.1.3/12.3	2
	Pools	Yes	*SOC**	Sampling possible (see method chapter 2.2)	3
Wetlands	Flux	No	CO_2 and CH_4	Not significant due to small area – chapter 12.1	1
Lakes*	Flux	-	CO_2 and CH_4	No lakes in RA – chapter 12.1	-
	Pools	-	*SOC**	No lakes in RA – chapter 12.1	-
Rivers	Flux	Yes	CO_2 and CH_4	Sampling not possible (time, security) – chapter 2.1.3/12.3	2
Reservoirs	Flux	Yes	CO_2 and CH_4	Sampling not possible (reservoir not yet build)	2
	Pools	Yes	*SOC**	Sampling not possible (reservoir not yet build)	2

** Soil Organic Carbon*

Wetland fluxes will hence be calculated according to country/biome-specific *averages*, land-uses identified as tier-level two will be calculated according to country/biome-specific *averages* and country-specific *data* and forest carbon pools will be calculated on the basis of forest *sampling* backed up by country/biome-specific *averages* and country-specific *data* (see Figure 8). Here biome/country-specific averages and data are distinguished in that, country specific *data* will show special regard to local factors when predicting the likely role of the ecosystems in LULUCF budgets.

Figure 8: Diagram showing the hierarchy of the case chapter



Good practice guidelines (GPG) for LULUCF prescribes that LULUCF for hydropower dams should be estimated over 100 years (UNESCO and IHA, 2009). This effectively necessitates attention to:

1) Current uses
2) Expected site development.

2.1.3 Discussion of the study design

A general critique on the NEE estimates for all ecosystems is that a relatively limited amount of data exists from tropical regions, and that a large part of the data, which is available, has not been conducted over a period of more than one year. This is problematic, as NEE values for all ecosystems are known to be extremely dependent on a long range of spatio-temporal factors (Bastviken et al., 2011, 2008, 2004; Beaulieu et al., 2012; Christensen et al., 2003; Jang et al., 2006; Tremblay et al., 2005; Ullah and Moore, 2012), as it will also be demonstrated throughout the coming chapters. Consequently, research that has not been conducted over more than one year is not considered in average biome-specific calculations in the background chapters. The lack of data will contribute to the obvious uncertainties coupled with assessing the NEE over the defined land-uses.

Belowground terrestrial carbon is expected to be stored in the reservoir ecosystem upon reservoir filling (chapter 2.1.1.a, p. 17). Little knowledge exists of the fate of the belowground terrestrial carbon in reservoirs, but it is recognized that it might constitute an important factor that requires more attention in future studies.

Accordingly, the NEE over rivers are only vaguely understood, and data on river carbon fluxes are extremely sparse (chapter 6.2, p.66). As the existing river constitutes a significant proportion of the flooded land, and hence probably an important part of the pre-impoundment emissions; measuring the NEE over the Mekong river would have been preferable. Generally, estimates should be conducted over more than one year, as discussed above, but measuring the NEE over the Mekong during the field study would have fostered the opportunity to compare results obtained here with results from earlier studies. However, at location, a number of security issues emerged which precluded the possibility to carry out the field research of the NEE over the Mekong. Most significantly, strong government wishes to conceal the Sambor Dam plans, which during the time of the field trip apparently even resulted in the murder of teenage girl by government troops (see fx BBC, 2012, chapter 12.3, p.118)

Picture 1: Newspaper article posted in the Cambodia Daily during the weeks of the field study

Two youths pose as Khmer Rouge soldiers carrying out acts of violence during the annual Day of Anger at the Choeung Ek killing fields yesterday. Story page 21

As Soldiers Leave Kratie Village, Problems Remain

By Abby Seiff and Lor Chandara
The Cambodia Daily

After a three-day blockade, soldiers pulled out over the weekend from the Kratie province village where a teenage girl was shot dead last week by government security forces, officials said yesterday. However, human rights workers denied a report by a provincial official that freedom of movement had been restored to the area.

On Wednesday, 14-year-old Heng Chantha was gunned down when 200 soldiers, police and military police swept into Chhlong district's Broma village with the stated aim of routing a so-called "secessionist movement." Following the raid, hundreds of families deemed "newcomers" were evicted from the area and told to return to their original homes in Kompong Cham, Prey Veng and Kandal provinces.

The area was sealed off by units of the Royal Cambodian Armed Forces and military police, who kept human rights workers and journalists from entering the village where the teenager was shot dead.

Kratie Provincial Governor Sar Chamrong said the withdrawal of troops started on Saturday and that freedom of movement was now permitted in the area.

"The armed forces have withdrawn already from the village.

Continued on page 2

Source: (The Cambodia Daily, 2012a)

Also, measuring the NEE over the forests in the RA was not possible of similar reasons - but also due to a lack of resources, as the building and maintaining of EC towers (see chapter 3.1, p. 36) are extremely cost intensive (UNESCO and IHA, 2009). Time and resources are obviously always general concerns and a limiting factor when conducting studies like this.

Each part of the report will conclude with a discussion on chapter specific uncertainties and generalizability.

2.2 Case

The purpose of including the Sambor Dam case in the project is first and foremost to elaborate on the findings in the background chapter.

The case will demonstrate their applicability, but will also reveal the importance of ground-truthing, as well as how local factors might play an important role in understanding the LULUCF effect over the lifetime of the reservoir. To collect the necessary data, a field trip to Cambodia was carried out between the end of May and end of July 2012:

Prior to going to Cambodia, land-uses and the areal extend of these in the flooded area (FA) were mapped using QGis. These findings were subsequently verified and adjusted concurrent to groundtruthing[15] on location. During the fieldtrip, visits were made to the Sambor and the Stung Treng villages, as well as villages along the riverbank in the area that would be flooded as a consequence of the Sambor Dam reservoir. During the time in the RA, a number of samples were taken so as to estimate forest carbon density, species, species diversity and more. Finally, a number of interviews were carried out in order to comprehend present and future development and challenges.

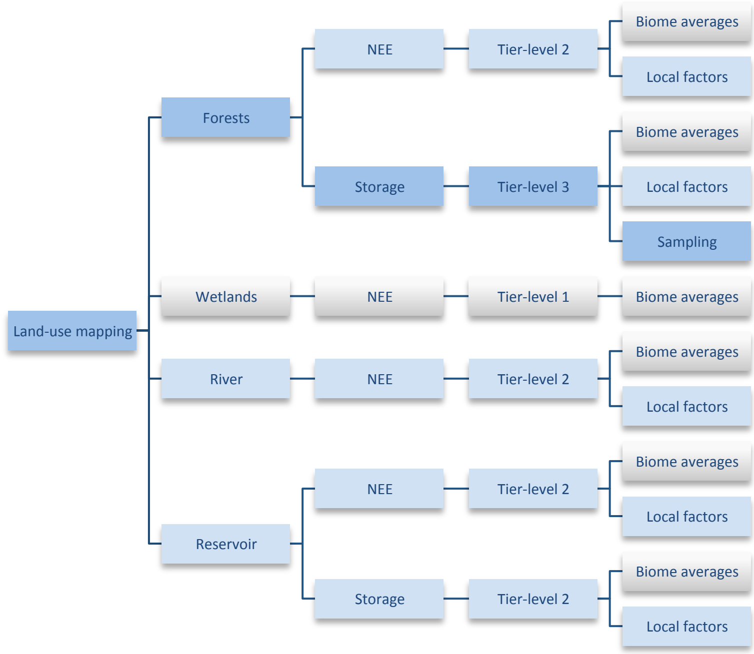
While *tier 1* estimates primarily will be based on the findings in the background chapters, both *tier 2* and *tier 3* estimates require more thorough attention to local factors. During the field trip and during interviews, information was collected relative to understanding these land-uses in a local context. Finally, the *tier 3* estimates require sampling on location. The sampling methods will further be elaborated upon in the following paragraphs.

While the background chapters will function as a tool to predict approximate carbon stocks of a certain area, local knowledge, groundtruthing and on the spot measurements are also a valuable means to appropriately assess the carbon stocks of forested areas, as most available data on forest ecosystem dynamics, especially with regards to carbon storage in the tropics, comes from coarse resolution (>4km) high temporal frequency satellite measurements (Huete et al., 2008). Despite new methods to estimate the global forest biomass using 3D imagery of the earth are being developed and improved constantly these years; researchers are still limited to "*systematically measure forests from the ground, and venture into the woods to count trees and measure trunks…*" (Carlowicz, 2012; NASA, 2012). Satellites have been used to collect regional and global measurements of the "greenness" of land surfaces, but problems still persist in finding signals to distinguish trees and shrubs from ground cover (Carlowicz, 2012). To assess forest biomass, researchers are therefore still limited to groundtruthing and relatively simple biometric methods (BMs), as those described in the following.

The following pages will outline the BM and discuss good sampling practices. The method presented here is based on a number of acknowledged techniques developed by, among others; Kevin Zobrist (2008) from the Washington State University forest education program, who established a number of guidelines to conduct forest inventories; Peter Stephens who wrote the Handbook for the Australian Master TreeGrower Program by (2001) as well a number of recommendations on assessing tree biomass presented by the Alabama Forestry Commission (2012).

[15]The process of gathering data to test the accuracy or otherwise, of a scientific model. Here primarily the preliminary mapping.

Figure 9: Diagram illustrating the data collection of the field trip according to tier-level



2.2.1 Keep it simple

The importance of spending time and resources in ensuring a good sample design cannot be underestimated. No matter how thorough and sophisticated the analysis techniques are, when poor data have been used, the result will - nonetheless - be bad.

Sampling in forestry methods have developed from simple plot or point sampling (e.g. Marty, 1999) to more sophisticated surveys with design based on stratification (Hunt and Tyrrell, 2004), optimal allocation (Weinschenck et al., 1969) as well as effort among strata multistage designs, systematic sampling, and designs with partial replacement of permanent plots (Brown, nd). However, as argued by Head of the Mathematics and Statistics department at the University of Canterbury, professor Jennifer Brown: "*for large-scale surveys the humble, but simple fixed-area plots or point sampling seem to be the most widely recommended method for forests sampling*" (Brown, nd).

The main argument is that the best method is developed using the KIS principal – Keep it Simple. Brown fundamentally argues that the advantages of a reduction in sample variance from using a complicated survey design are outweighed by the disadvantages of extra error from poor use of the design in the field. With a simple design, there is less error in the data collection phase and it supports and unburdens the fundamentally important consistency in the method for large-scale surveys. The fewer decisions that are made in the field, the less chance that things will go wrong (especially when more research teams are used), and it heightens the chance that protocol will be followed.

Finally, it is also pledged that researchers use *systematic* compared to *random sampling*, which will also limit the bias factor, as researchers for example would tend to avoid standing in the denser side of the sample. With this understanding, applying the KIS principal, the *plot* and the *point* sampling seem to be the best methods. The first step in conducting these are however to establish the *systematic plan of sampling*.

2.2.2 Identifying forests stands and project design

Forested lands are defined by the Food and agriculture organization of the UN (FAO) as:

1) Land spanning more than 0.5 hectares
2) Which support trees taller than five meters, and
3) Has a canopy cover of more than 10%

4) As well as trees able to reach these thresholds *in situ*.

It does not include:

1) Land that is predominantly under agricultural or urban land use.

In general, this also means that forest is determined both by the presence of trees and the absence of other predominant land uses (FAO, 2006). Included are areas under reforestation that have not yet reached (but are expected to reach) a canopy cover of 10% and a tree height of five meters are included, as are temporarily unstocked areas, resulting from human intervention or natural causes, which are expected to regenerate (FAO, 2006).

> *Includes*: areas with bamboo and palms provided that height and canopy cover criteria are met; forest roads, firebreaks and other small open areas; forest in national parks, nature reserves and other protected areas such as those of specific scientific, historical, cultural or spiritual interest; windbreaks, shelterbelts and corridors of trees with an area of more than 0.5 ha and width of more than 20 m; plantations primarily used for forestry or protective purposes, such as rubber-wood plantations and cork oak stands.
>
> *Excluded:* are tree stands in agricultural production systems, for example in fruit plantations and agroforestry systems. The term also excludes trees in urban parks and gardens(FAO, 2006).

A forest stand is a distinct, recognizable unit of the forest.

Typically, variables such as density, age and species compositions will differentiate stands and the identification most often happens using aerial images and subsequent validation through on the spot observations, to avoid "stand bias". Upon the preliminary mapping, the researcher must establish a plan to systematically sample the stands in the forest - to avoid "sample bias" (Brown, nd). A typical way of doing this is to establish a grid on your stand map. The intersections between the lines of the grid then become the location of your plots, which will then be evenly distributed throughout the stand, avoiding a situation where plots are based on preferred or convenient locations. The number of plots per stand will naturally determine the accuracy of the inventory, but will also be a balance that needs to be established between (Zobrist, 2008):

1) Resources
2) The uniformity of the stand
3) Desired representation

And, ultimately;

4) Accuracy

2.2.3 Fixed Area Plot and Point sampling

Fixed Area Plot sampling is described thoroughly in the guidelines to conduct forest inventories presented by Kevin Zobrist (2008). It follows the basic principle stated below. *A fixed area plot is a plot with a known area, the plot size must be uniform throughout the stand to avoid "plot size bias", and the plot should on average give at least 5 to 10 tress pr. plot or more if the tree species diversity is high*

By applying these rules, the boarder of a plot stand can finally be established relative to the plot centre. The trees that are "in" are the trees where the centre of the tree is inside the fixed area.

Picture 2: Establishing the boarders of the fixed area plot

Photo: Lasse Jesper Pedersen

Point Sampling is described thoroughly in "Aids to Professional Forestry Practice: Point Sampling" by Robert Marty from the Department of Forestry at Michigan State University (Marty, 1999), but the basic principle is this: Point sampling is sampling with probability proportional to size, and is especially interesting when estimating volumes. Large trees have large volumes and their importance is therefore equally larger. The procedure for laying out a variable plot may be faster and easier than a fixed plot, especially when working alone on a steep slope or with lots of bush. First, a count is made of all the trees that can be seen from a certain point over 360° that have a diameter larger than a constant projected angle. Usually this is done with a prism, a relascope or with a simple angle gauge made from rods. The estimate of the volume is calculated from the probability of selection of each tree. The probability is hence proportional to its basal area[16].

2.2.4 Developing a BM for estimating the carbon sequestered in one tree

When the trees to be included in the sample are found, it is time to do the final measurements. When making forest inventories, these include:

1) Measuring the tree diameter at breast height (DBH), which is defined as: 54 inches above the ground on the uphill side of the tree;
2) The total tree height[17]

- and if possible:

3) The live crown ratio, and;
4) Tree age.

The latter two are also useful when trying to predict the significance of the forest sink. The methods for estimating these are various, and described in both of the articles mentioned above.

When the DBH and the height of the tree are known, the weight of the carbon sequestered in the tree can be estimated. No standard method currently exists, which makes estimates hard to compare (Jia and Akiyama, 2005). The method presented in the Handbook for the Australian Master TreeGrower Program (Stephen, 2001) and the Alabama Forestry Commission (2012) provides as a good means which is in compliance with the KIS principal as well as other most common practices (NASA, 2012). The method for estimating the carbon storage in *one*

---

[16]The area of a given section of land that is occupied by the cross-section of tree trunks and stems at their base.
[17] Usually measured with a Biltmore Stick

tree, as well as a few easy to consider adjustments to the methods discussed, is described in the following:

First, a conservative measurement of the aboveground weight of a tree can be found using the following formula:

Equation 6: Total green above ground weight of one tree

$$W_a = \frac{\pi}{12} \cdot di^2 \cdot h \cdot sg \cdot W_s$$

Where W_a is the total (green) aboveground weight[18] of the tree in *[kg]*, *di* is the DBH in *[cm]*, *h* is the height of the tree in *[cm]* and W_s is a conversion factor to include boughs and twigs that is dependent on species group, hence 1.12 for softwood and 1.33 for hardwood (for mixed areas an average of 1.19 can be applied) (Alabama Forestry Commission, 2012). Finally, *sg* expresses the specific gravity (or the wood density) of the tree usually measured in *[g/cm³]*. If it is not possible to find the accurate wood density values, biome specific mean values ranges from 0.5 in boreal and temperate regions to about 0.7 in tropical regions. The mean region specific values can also be found in Table 5, below:

Table 5: Region specific wood densities

Region	*n*	*Wood density*	*Standard deviation*	*Min*	*Max*
Africa (extratropical)	351	0.648	0.159	0.234	1.076
Africa (tropical)	2482	0.598	0.160	0.150	1.200
Australia	678	0.725	0.173	0.300	1.137
Australia/PNG (tropical)	1560	0.636	0.181	0.164	1.227
Central America (tropical)	420	0.560	0.208	0.120	1.350
China	1010	0.541	0.144	0.200	0.996
Europe	77	0.525	0.119	0.284	0.840
India	289	0.652	0.186	0.232	1.280
Madagascar	244	0.662	0.172	0.320	1.164
Mexico	228	0.676	0.231	0.160	1.390
North America	216	0.540	0.153	0.289	1.250
Oceania	110	0.604	0.154	0.270	1.026
South America (extratropical)	744	0.715	0.210	0.120	1.331
South America (tropical)	4191	0.632	0.178	0.100	1.210
South-East Asia	219	0.559	0.154	0.100	0.930
South-East Asia (tropical)	3648	0.574	0.151	0.080	1.095
Average	16468	0.613	0.171	0.080	1.390

Source: (Chave et al., 2009)

To the aboveground weight of the tree, the root system must be added. Generally, the root system of trees is estimated to compose of 20% of W_a (ESA21, 2005).

Of the total weight of the tree, the dry weight percentage (DWP), D_w, in hardwood and softwood[19] tree species on average comprises 52.9% and 46.3% respectively (Alabama Forestry Commission, 2012; Reyes et al., 1992), but can also be measured on the spot with a moisture meter. The total weight of the carbon in the tree, W_{tc}, can finally be calculated (Alabama Forestry Commission, 2012; ESA21, 2005; Martin & Thomas, 2011; Trees for the future, 2005).

The final formula for estimating the total carbon content of the tree is then:

Equation 7: Total carbon pr. tree

$$W_{tc} = \frac{\pi}{12} \cdot di^2 \cdot h \cdot sg \cdot W_s \cdot 1.2 \cdot D_w$$

[18]The term green weight specifically refers to the weight of freshly harvested wood that has the same moisture content (MC) as the standing tree.
[19] Trees with broad, flat leaves as opposed to coniferous or needled trees. Wood hardness varies among the hardwood species, and some are actually softer than some softwoods. Both broad-leaved and deciduous trees are usually hardwoods (Nix, 2012).

2.2.5 Scaling up from one tree to find the total forest biomass of the FA

When these estimates over a number of representative stands have been done, which preliminary have been selected, both through mapping of stands from aerial images and through observation on site, the findings can be scaled up. There are however a few additional considerations to make:

Knowing that large trees (DBH≥10cm) makes up the main part (>80%) of the total forest carbon pool (Clark and Clark, 1996), a further simplification to the method presented can be made; excluding trees with a DBH below 10cm. For example, studies from an old growth tropical forests in Xishuangbanna, Southwest China, have depicted large trees to account for 86.70% of the total biomass in trees, although only compromising 13.84% of the total number of trees (Tan et al., 2010). If time is limited, leaving out the smaller trees for sampling a larger proportion of the large trees in the area will also give a more precise result (FAO, 2006).

Additionally, Cummings et al., (2002), found that the combined biomass of coarse wood debris, forest floor (litter/root mat), and standing dead plants (trees, palms and vines) [W_{tpv}] averaged 12% of the total above ground biomass (TAGB) in natural tropical forests. For boreal and temperate forests, this amount is expected to be significantly lower. This corresponds with Goodale et al., (2002) and Tremblay et al., (2005) who argue that the understory usually comprises an insignificant part of the total forest biomass, while acknowledging that some tropical low density forests have shown that this is not always the case. Also, the forest structure and biomass distribution are not uniform among sites or forest types and show rather large variability. For example, Cummings et al., (2002) made estimates of the TAGB in the South-western Brazilian Amazon, where they found that the non-tree components ranged from 41% of the TAGB in one ecotone[20] forest site, to as low as 7% in a dense forest site.

The final formula for estimating the total carbon storage [T_c] of a specific forest area that is going to be flooded looks like this:

Equation 8: Forest total carbon storage

$$T_c = \frac{T_{ts}}{T_{sa}} \cdot T_a \cdot W_{tpy} \ (\cdot\ 1.1)$$

Where [T_{ts}] is the total weight of the trees in the sampled area, [T_{sa}] is the total size of the sample area, [T_a] is the total area (that is going to be flooded) and [W_{tpy}] is the expected contribution to [T_c] of the understory, suggested to be between 0% to 7% depending on the biome. If trees with a DBH≥10cm have been excluded for convenience, these should of course also be added (conservatively by multiplying with 1.1).

2.2.6 Converting C to CO_{2eq}

In order to include these figures in the final picture of the role of lakes and reservoirs in carbon budgets, some kind of conversion from C to CO_{2eq} is necessary:

> *Since the carbon to molecule ratio is one for each molecule of CO_2 (3:1), the molar weight of CO_2 is 44.0095, the atomic weight for C and O are 12.0107and 15.9994 respectively. We also know that the C-2O ratio is 1:3.667.*

Therefore to understand the results in comparison to other results throughout the paper and to convert the total C of the tree to CO_2-equivalents, the results can be multiplied with 3.667.

2.2.7 Interviews

Throughout the field study, a series of interviews with a number of people who in one way or the other were related to the Sambor Dam were conducted. The intention primarily was to get a clear picture of the otherwise opaque plans to dam the Mekong River. Additionally, the focus was to broaden the understanding of the proposed Sambor dam, in a so-

[20]An ecotone is a transition area between two adjacent but different plant communities, such as forest and grassland.

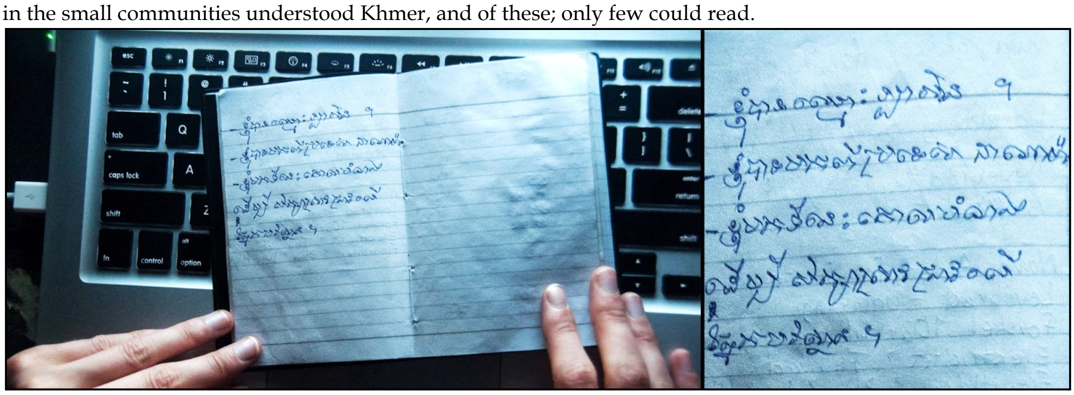
cial/environmental context. The case will demonstrate that there can be a close link between some social and environmental impacts – and the climate.

Most interviews were carried out as informal explorative interviews, which are defined by Catharina Juul Kristensen (2007) as interviews with professionals or key individuals, with the intention to procure information in an area in which little knowledge exists. According to the aforementioned recommendations, semi-structured interview guides were prepared before the (planned) interviews. The semi-structured interview is a balance between the open-interview (where the narrative of the informant yields considerable influence on the direction of the interview) and the structured interview (where the researcher strictly has decided upon the subject of the interview beforehand) (Kristensen, 2007).

> First of all, interviews were carried out with *Chhoun La* at the Oxfam Office in Phnom Penh. Mr. Chhoun is the Cambodian Advocacy Coordinator for *Oxfam Australia* and has been responsible for community development implementation in Cambodia since 1993. He has been the leader of a number of projects related to the Sambor area, deforestation and lately to the proposed Sambor Dam.
>
> In Kratie, interviews were conducted with the Executive Director of the Cambodian River Development Team (CRDT), *Sun Mao*. Besides supporting the project with valuable information, the CRDT facilitated much of the practical preparations in any way possible. When in Sambor, the CRDT office functioned as a base for the study, which provided the opportunity to participate in the daily work of the organization, which also facilitated the opportunity to conduct numerous informal ad-hoc interviews with the employees when working on in their office. During the tour around the area, the CRDT provided staff, which accompanied the research through the villages of Koh Phdao Island and on the western bank of the Mekong River where they also functioned as translators during interviews with local chiefs and tribe members.
>
> When we returned to Kratie, a final interview was conducted with *Gordon Congdon* who is the Freshwater Conservation Manager for WWF-Cambodia based in the Kratie Field Office. Mr. Congdon has been involved in several projects and reports on the impact of the proposed Sambor Dam on the regions fisheries and wildlife.

During the travels along the river, and during the time spent in the CRDT office, several ad-hoc interviews with local tribe members, tribe chiefs and CRDT staff were conducted. Before initiating the field study, both the CRDT and Oxfam professionals kindly recommended not talking to local populations about the damming plans - both in the light of recent events, but also as several communities were still to hear about the dam plans.

Picture 3: Explanation of the field study; in Khmer (without mentioning the dam). Unfortunately only few people in the small communities understood Khmer, and of these; only few could read.



Picture: Lasse Jesper Pedersen

Contacts with the interviewees and the CRDT office have been maintained upon leaving Cambodia. This has provided the project with continued support and information after homecoming. It was unfortunately not possible to undertake meetings with government officials due to reasons that are elaborated on, in the case chapter 12.3.

2.2.8 Discussion

Besides a large spatial heterogeneity, uncertainty related to bias, the necessity of scaling up when assessing very large areas and the inflexibility and simplification inherited in the algometric equations used to estimate wood volumes, there are an additional number of uncertainties related to tropical regions. For one, tropical evergreen trees develop deeper roots to maintain leaves and transpiration through dry conditions (Huete et al., 2008). Hence, the weight of the root system might be higher in some tropical areas. Conversely, the large buttresses of some tropical trees pose a need for algometric equations to be adjusted in the future so DBH is measured at a height where buttresses have disappeared (Cummings et al., 2002; Jia& Akiyama, 2005).

An additional uncertainty comes from the capability of trees to respond plastically to resource availability. As has been discussed in the variables above, nutrient scarceness on the one side causes trees to allocate more carbon to the roots, while soil resource abundance on the other side causes trees to allocate more carbon to the aboveground tissue. Further, the stand age also seems to cause a shift in the relationship between carbon stored in roots and carbon stored in the aboveground tissue.

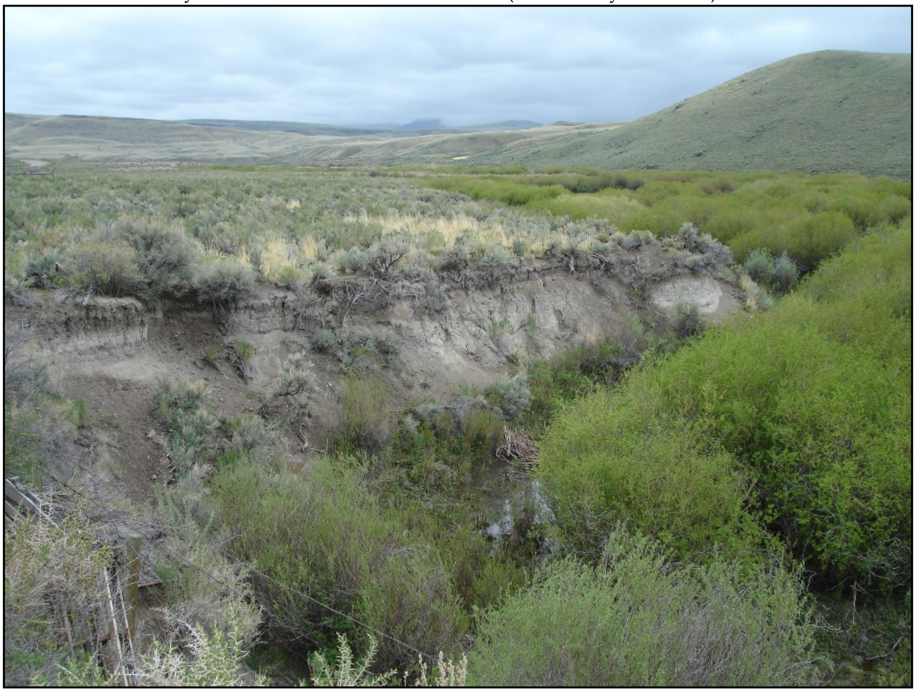
Variables affecting carbon stocks will be discussed in details in the background chapters.

Finally, interviews with local tribes provided the study with much valuable information, but some of the local people might have understood my person as coming from one of the development organizations operating in the area, even though a great deal was done to explain the purpose of the study. A misunderstanding like this might have influenced their assertions. The people living in rural Cambodia are well aware what good contacts to NGO’s can bring.

BACKGROUND/LITERATURE STUDY

Chapter 3: THE TERRESTRIAL BIOSPHERE

Picture 4: The terrestrial biosphere is a collective term for all organisms living on land, including animals, fungus, microorganisms and plants. Because carbon uptake in the terrestrial biosphere is dependent on biotic[21] factors, it follows a diurnal and seasonal cycle (see figure **Figure 3**). In CO_2 measurements, this cycle is often called a Keeling curve. It is strongest in the northern hemisphere because this hemisphere has more land mass than the southern hemisphere and thus more room for ecosystems to absorb and emit carbon ("Carbon cycle," 2012).



Picture: (CERG, 2010)

The terrestrial biosphere is understood as forests and wetlands; peatlands, swamps, and marshes - and to some extent, rice-lands (see footnote 5, p.17). All are key components in global CO_2, CH_4 and Nitrous Oxide (N_2O) budgets. However, accurately assessing their impact on the climate is extremely difficult and research results are often intimately linked to local environmental conditions and spatio-temporal factors (Tremblay et al., 2005). Consequently, much investigation on the subject is far from comparable. The following chapter will however try to gather some of the most recent information in order to give a rough overview of the carbon balance in various boreal, temperate and tropical forests and wetlands.

3.1 Methods for estimating the NEE of GHGs in the terrestrial ecosystem

Most research on the terrestrial biosphere has been gathered using the Eddy Covariance (EC) method. A large part of this is presented and publicly available through the FLUXNET-network[22]. The EC method (or technique) is used to directly measure the *vertical* turbulent fluxes within atmospheric boundary layers (ABL)[23] by means of flux towers. Some research have criticized the method for underestimating night-time respiration, as the air is often still at night (Clark, 2004). Tan et al. (2010) have recently conducted a 4year research in a primary seasonal tropical rainforest in Xishuangbanna, Southwest China, where results from using

[21] Of, relating to, or resulting from living things

[22] "FLUXNET is a global network of micrometeorological tower sites that use eddy covariance methods to measure the exchanges of carbon dioxide, water vapour, and energy between terrestrial ecosystems and the atmosphere. More than 500 tower sites from about 30 regional networks across five continents are currently operating on a long-term basis." (FLUXNET, 2012)

[23] The planetary boundary layer (PBL), also known as the atmospheric boundary layer (ABL), is the part of the atmosphere which is closest to the earth. Its behaviour is directly influenced by its contact with the planetary surface. On Earth it usually responds to changes in surface forcing in an hour or less ("Planetary boundary layer," 2012).

this method compared to the BM[24], was three times lower. The authors did not attribute the cause of this dissimilarity solely to the inability of the EC methods to correctly account for night-time advection, but rather uncertainties related to the geographical location of their flux towers, and the fact that there is a significant time lag between photosynthetic carbon uptake and tree growth (Tan et al., 2010).

Picture 5: The eddy covariance method is an atmospheric monitoring technique for CO_2 detection, comprising an infrared gas analyser, mounted on a tower together with a sensitive anemometer[25] to measure wind speed and direction.

Picture: (Anderson and Farrar, 2001)

The uncertainties related to the EC method during calm nights is related to CO_2 storage beneath the canopy of the trees, advective losses of CO_2 and higher random uncertainties during calm nights (Kruijt et al., 2004). Most sources presented in this chapter have used one or more methods to counterbalance this uncertainty, and in almost all cases, research has been done in a way which (according to the authors) renders estimates of the total flux conservative.

3.2 Critique of data

In this section, a short discussion of the data will be provided for both forests and wetlands.

In general all available data have been included. The distribution of data does hence not represent a normal distribution of data, which renders averages unrepresentative. The averages presented must hence not be understood as such, and the data included should rather be considered as individual cases, many of which is discussed in the text. Optimally a representative segment of each biome would have been included, but has not been possible due to the scarcity of data as well as the many variables, which would have had to be included. After each section the generalizability of the data will receive more attention, but this is done with respect to the offset outlined here.

3.2.1 Forests

Data on forests from Luyssaert et al. (2007) may be one of the most comprehensive collections of data combined to date. Regretfully, the report lacks a great deal of transparency. Among others, it fails to mention the number of sites that accounts for the respective average value in each forest biome, statistical significance, the geographical location of the studies (except for their forest biome), the year, number of years or periods the studies have been conducted over etc. This precludes the possibility of combining the results with other results and to understand the results in relation to one another. The data from the Luyssaert et al. (2007) report

[24] The biometric method is a way of estimating above- and belowground NPP based on algometric relationships and DBH census. Algometric relationships are often based on size parameters between the dry weight of stems, branches, leaves and roots. (Kominami et al., 2008; Peichl et al., 2010).

[25] An instrument for measuring and indicating the force or speed and the direction of the wind.

is therefore primarily used as a means to support the overall findings from the remaining research discussed in the following.

3.2.2 Wetlands

The balance between CO_2, CH_4 and N_2O uptake and releases determines the carbon balance of wetlands. While some studies on GHG from wetlands are acknowledging a possible importance of N_2O in wetland GHG budgets, most choose to ignore it due to the generally unfavourable conditions for N_2O production in the anoxic[26] and water saturated soils of wetlands (Bridgham et al., 2001) - or finds N_2O emissions to be negligible (Couwenberg et al., 2010; Kayranli et al., 2010; Tremblay et al., 2005). Consequently, there is no presentation on N_2O from wetlands in the following.

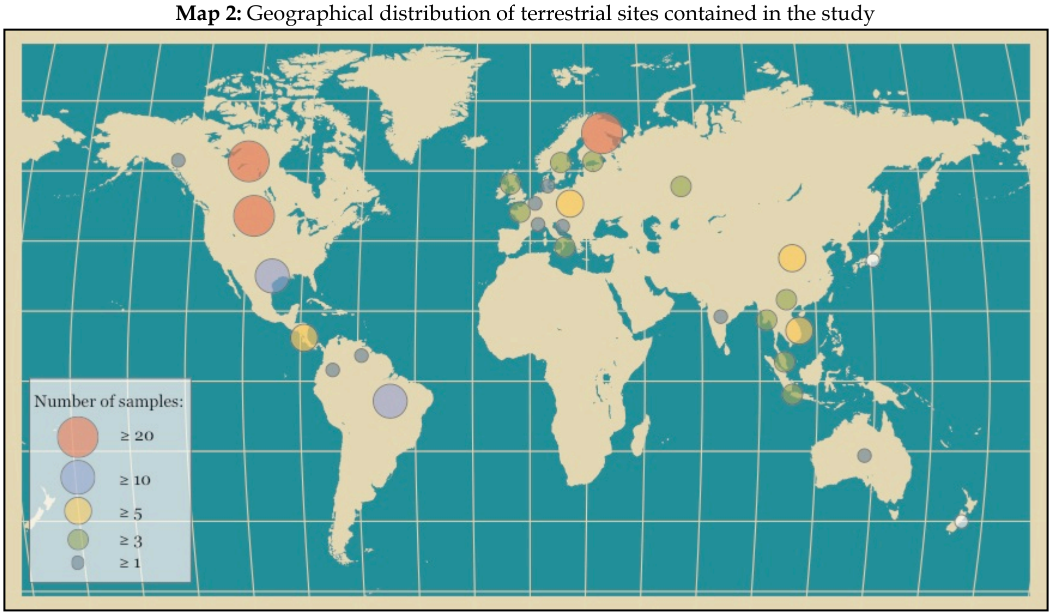
It is striking that much research of carbon fluxes in wetlands has not been conducted over more than one year. Tremblay et al. (2005) for example collected data from more than 40 studies in this category. Of these only 3 fulfilled this criteria. Taking into consideration the extremely high temporal variability of these areas, this is quite peculiar. Regretfully, data on the NEE of CO_2 from some types of wetlands, consequent to this screening, becomes somewhat limited.

Another concern is that some studies of methane emissions only include diffusive fluxes, whereas ebullition fluxes in several studies have been found to comprise over two thirds of the total fluxes (Bastviken et al., 2004; Casper et al., 2000; McCully, 2006). These have obviously been excluded too, bringing the total number of wetlands which qualify to be included in the study, further down.

3.3 Geographical distribution of samples

The map below (Map 2) illustrates the geographical distribution of the *terrestrial sites* contained in the background study (except Luyssaert et al., (2007)). The map underlines an overrepresentation of boreal and temperate sites, and highlights the need to focus more on tropical sites (especially Africa) in future studies.

Map 2: Geographical distribution of terrestrial sites contained in the study



[26] Areas depleted of dissolved oxygen, which are generally found in areas that have restricted water exchange (Kalff, 2001).

3.4 Terrestrial ecosystem definitions used

3.4.1 Forest

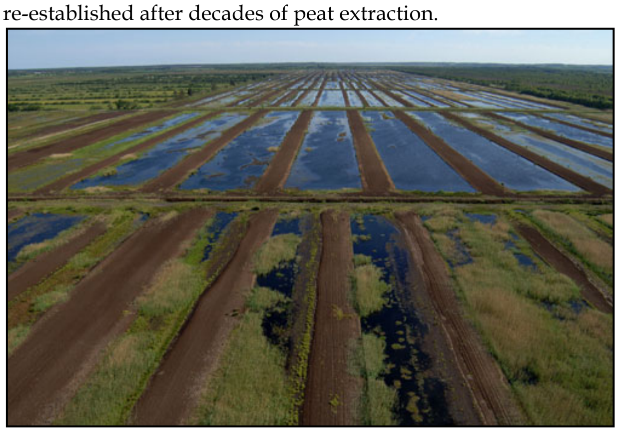
In this report, a forest is defined as land spanning more than 0.5 hectares, which supports trees taller than five meters, and has a canopy cover of more than 10% (for a further elaboration, see 2.2.2, p. 25). A typical tree forest is composed of the overstorey (canopy or upper tree layer) and the understory (FAO, 2006). The understorey is further subdivided into the shrub layer, herb layer, the moss layer and soil microbes.

3.4.2 Wetlands

Wetlands are characterized by being saturated with water on either an annual or a seasonal basis. Wetlands are understood as peatlands, marshes and swamps. Roughly half of all wetlands are found in arctic and boreal regions (~50-70°N). These are typically peat-rich bogs[27] and fens[28]. Another 35% of all wetlands are found between ~20°N to 30°S and are typically forested and non-forested swamps, marshes and floodplain formations (Whalen, 2005).

Peatlands are wetlands that accumulate partially decayed vegetation, usually as sphagnum moss. Peatlands include bogs and fens, and emerge as flooding hinders flow of oxygen from the atmosphere, hence reducing rates of decomposition. Wetlands are as far as possible distinguished from swamps for convenience, but in reality swamps can accumulate peat too. Peatlands are however usually flooded year round, whereas swamps most often are only seasonally flooded.

Picture 6: Lille Vildmose in Denmark comprises of 7.600 ha, and is the biggest raised bog in the deciduous forest belt in Northern Europe. The height is at some places, up to 5 meters. Today the bog has been announced a protected area and is being re-established after decades of peat extraction.



Picture: (Dansk OrnitologiskForening, n.d.)

Swamps are wetlands dominated by trees and are usually found along large rivers and on the shores of large lakes. In some areas, swamps can cover thousands of square kilometres, as the 30.000km^2 large Asmat Swamp in Indonesia pictured below. The ecology of swamps along rivers is especially vulnerable to change in water level fluctuations (Keddy, 2010).

[27] A bog is a peatland which receives water solely from rain and/or snow falling on its surface (NIEA, 2011)

[28] A fen is a peatland which receives water and nutrients from the soil, rock and groundwater as well as rain and/or snow (NIEA, 2011)

Picture 7: The Asmat Swamp in Indonesia is believed to cover an area of up to 30.000km^2. Besides being the biggest alluvial swamp in the world, it is also home to the famous Komodo Dragon, which is endemic to the region. A large proportion of the swamp is peatland.

Source: (Indo-Pacific Conservation Alliance., n.d.)

Marshes mainly consist of seasonal herbaceous species, such as grasses, rushes and reeds, rather than woody plant species, which will only be found as low-growing scrubs. Marshes are most often found in the transition between aquatic and terrestrial ecosystems (Keddy, 2010).

Picture 8: The Kiramashiya Marsh in Iraq is part of the Iraq central marshes, which used to cover an area of more than 3000 km^2. Due to a number of reasons, among others the 1991 uprisings, the area was drained in the 90's causing more than 90% of the marshlands to disappear in a few years. Subsequent to the U.S. invasion, the area is being re-flooded. While some areas are slowly recovering, other areas show no signs of regeneration.

Source: (Kate Day, 2010)

Ricelands can in general terms be divided into irrigated-, rain-fed-, deep-water-and upland ricelands. Upland ricelands differ in that they are neither flooded, nor does the top soil become water saturated for any significant period of time (Neue, 1993). Other ricelands share characteristics with wetlands in that they are flooded for a part of the year. In deep-water rice-fields, floating rice can develop elongated stems capable of coping with water depths exceeding 2 meters (Neue, 1993).

Picture 9: Riceland in the Northern Mekong Delta, Vietnam. While flooding of ricelands provide ideal conditions for rice cultivation, it also discourages the growth of weeds and the presence of disease-carrying pests, such as rats. Most ricelands are found in Asia where they represent the main source of nourishment for many. Not only does rice itself provide most of the calories in the rural diet, but rice deep-water paddies are often also an important source of wild and cultivated fish.

Photo: Lasse Jesper Pedersen

Chapter 4: Net ecosystem exchange in forests

Theoretically, mature forests are in balance with the atmospheric CO_2 concentrations, however, recently, scientist have discovered that the increase in the atmospheric concentration of GHG's (Riebeek, 2011) might have transformed many ecosystems into carbon sinks (Clark, 2004). The following pages will present NEE estimates and a discussion of more than 230 forests.

4.1 NEE of CO_2 in forests

In forests, the NEE of CO_2 expresses the balance between plant uptake of CO_2 through photosynthesis and autotrophic as wells as heterotrophic releases (Randerson et al., 2002).

In total, 26 northern *boreal forests* in Canada, Russia, Sweden, Alaska (U.S.), Scotland and Finland is included in the study (see Table 6, p. 44). Here the annual mean NEE of CO_2 varies between 5230 $mgCO_2 \cdot m^{-2} \cdot d^{-1}$ - estimated in a 37 year old plantation in Sweden (Valentini et al., 2000), and -271 $mgCO_2 \cdot m^{-2} \cdot d^{-1}$ - estimated in a 90 year old natural forest in Canada (Goulden et al., 1998). In general, the majority of the boreal forests in this study (24 of 26) consume CO_2, with the trend being that plantations and young stands generally are larger sinks than natural old growth forests. One of the more interesting studies were done by Fan et al., (1995) who made a noteworthy discovery as they found that the light use efficiency (LUE) (and consequently the NEE of CO_2) in a Canadian black spruce forest increased markedly during overcast periods (under certain conditions up to 50%). On average, the NEE of CO_2 over *boreal forests* is estimated to be 1305 $mgCO_2 \cdot m^{-2} \cdot d^{-1}$ (n=26). The NEE of CO_2 over the Swedish plantation measured by Valentini et al. (2000) stands significantly out and is therefore considered to be a overestimate. This forest has therefore been excluded[29].

> *The average NEE of CO_2 over the boreal forest biome is calculated to be 1147±783 $mgCO_2 \cdot m^{-2} \cdot d^{-1}$ (n=25)[30]. These results are akin to results presented by Luyssaert et al., (2007) who divide the boreal forests into; boreal humid evergreen-, boreal semiarid evergreen- and boreal semiarid deciduous forests. With average fluxes of 1315, 401 and 1787 $mgCO_2 \cdot m^{-2} \cdot d^{-1}$ respectively.*

Of the data collected on the 31 *temperate forests* in Canada, USA, Denmark, Netherlands, Germany, Belgium, France, Italy, China, Australia, Japan and New Zealand, only one 70-year-old mixed forest in Belgium was emitting CO_2. The measured values in the temperate forests ranged from 16605 $mgCO_2 \cdot m^{-2} \cdot d^{-1}$ - measured in a very young Monterey Pine plantation in New Zealand (Arneth et al., 1998) to -1115 $mgCO_2 \cdot m^{-2} \cdot d^{-1}$ in the old-growth Belgium forest (Carrara et al., 2003) mentioned above. Also in the temperate biome there was a marked difference between young and old stands. Granier et al. (2002) i.e. compared an 80-year-old beach stand in Denmark (1405.6 $mgCO_2 \cdot m^{-2} \cdot d^{-1}$) that otherwise shared characteristics with a 32-year-old beach forest in Northern France (2078.3 $mgCO_2 \cdot m^{-2} \cdot d^{-1}$). While this is according to theory, other results demonstrate that this must be understood more as tendency than a rule. For example, Law B.E. et al., (2002) measured the NEE of CO_2 over two temperate pine forests in U.S., which apart from age (15 and 50 to 250 years) shared the same characteristics (elevation, mean annual photo-synthetically active radiation, temperature and precipitation). While the young stand had a NEE of CO_2 of 2670 $mgCO_2 \cdot m^{-2} \cdot d^{-1}$, the old stand had a NEE of CO_2 of 3252 $mgCO_2 \cdot m^{-2} \cdot d^{-1}$. Finally, Kirschbaum et al., (2007) did a 4 year study on a 60 year old secondary growth Eucalyptus Delegatensis forest in Australia. While the forest was a large carbon sink for the first two years (4016 and 3514 $mgCO_2 \cdot m^{-2} \cdot d^{-1}$), the sink was reduced to less than half in the third year (1506 $mgCO_2 \cdot m^{-2} \cdot d^{-1}$) and by the forth year - the forest had turned into a carbon source (-402 $mgCO_2 \cdot m^{-2} \cdot d^{-1}$). The third and fourth year were different from the first two in having very low-average rainfall, elevat-

[29] In accordance with LULUCF GPGs, see chapter 2.1.2, p. 19.

[30] An overview of the data on boreal forests and references is presented in Table 6, p.43.

ed temperature, lower relative humidity and observations of substantial insect damage. Kirschbaum et al., (2007) concluded that the first two factors had little (if any) influence on the reduction in the net carbon gain, and attributed the primary reason to be a severe insect outbreak, which can be indirectly linked to water stress (Kirschbaum et al., 2007). On average, temperate forests fluxes are estimated to be 3250 $mgCO_2 \cdot m^{-2} \cdot d^{-1}$ (n=31) if the young Monterey Pine plantation in New Zealand which was consuming unprecedentedly large amount of carbon dioxide, is excluded from the results[31].

> *The average NEE of CO_2 over the temperate forest biome is calculated to be 2792.6±1621 $mgCO_2 \cdot m^{-2} \cdot d^{-1}$ (n=30)*[32]*. Luyssaert et al.,(2007) divide the temperate forests into; temperate humid evergreen, temperate humid deciduous and temperate semiarid evergreen, and they calculate the average flux rates to be 3995, 3121 and 1335 $mgCO_2 \cdot m^{-2} \cdot d^{-1}$ respectively. As with boreal forests, these data are akin.*

The available data on *tropical forest* NEE is extremely sparse and quite uncertain (Houghton, 2003; Huete et al., 2008; Tremblay et al., 2005). Factors that contribute to the limited knowledge of tropical forest ecosystems is in general attributed to a weak seasonality and an extremely high tree species diversity at the landscape level[33], which results in a wide variety of phonological responses to common environmental factors, such as temperature, rainfall and photoperiod (Huete et al., 2008). As mentioned earlier, it is tremendously difficult to understand, generalize and not at least, make general estimations on these data, but for tropical forests the limited amount of data significantly adds to this factor. Almost all sources however agree that tropical forests on overall are significant carbon sinks (Abril, 2005; Cavaleri et al., 2008; Clark, 2004; Huete et al., 2008; Luyssaert et al., 2007a; Tan et al., 2010; Tremblay et al., 2005). Based on a number of reports, Clark (2004) estimates the global carbon balance of tropical ecosystems to be between 3.0 and -0.4 $PgCO_2 \cdot yr^{-1}$, with three out of four of the reports showing high positive values. On average, Clark's results depict tropical ecosystems to sequester approximately 1.475 $PgCO_2 \cdot yr^{-1}$. The picture of the tropical forests as a large carbon sink correlates with available data presented here.

Overall, it has only been possible to find estimates for 11 tropical forests. In general, the numbers are equal, or only slightly higher than those found for the temperate biome. The largest sink of 6781$mgCO_2 \cdot m^{-2} \cdot d^{-1}$ was found in a young natural/managed slash pine forest in Gainesville, USA (Clark, 2004) and the smallest sink of 402 $mgCO_2 \cdot m^{-2} \cdot d^{-1}$was found in a mature Brazilian rainforest (Miller et al., 2004). Based on these results:

> *The average NEE of CO_2 over the tropical forest biome is calculated to be 3310±1989 $mgCO_2 \cdot m^{-2} \cdot d^{-1}$ (n=11)*[34]. These values are only slightly lower than values presented by Luyssaert et al. (2007), who reported an average NEE value of 4045 $mgCO_2 \cdot m^{-2} \cdot d^{-1}$ for this biome.

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[31] In accordance with LULUCF GPGs, see chapter 2.1.2, p. 19.

[32] An overview of the data on temperate forests and references is presented in Table 6, p.43.

[33] Traditional land-use planning is restricted by jurisdictional boundaries, such as municipal or state lines, land and water flow across those boundaries. Planning at landscape level is anchored in ecological principles and sets boundaries defined by a landscape or watershed.

[34] An overview of the data on tropical forests and references is presented in Table 6, p.43.

Table 6: NEE of CO_2 in boreal, temperate and tropical forests

Biome		*Country*	*n*	*NEE of CO_2*	*Min*	*Max*	Type[1]	Age[2]	*Source*
BOREAL Forest		Canada	5	865.0	321.2	1877.0	n	m	Yuan et. al. (2008)
		Canda	3	931.7	523.0	1488.0	n	80-150	Griffis et. al. (2003)
		Canada	1	1507.0			n	m	Fan et. al. (1995)
		Canada	1	1566.2			sg	74	McCaughey et. al. (2006)
		Canada	1	1576.3			n	73	Ju. et. al. (2006)
		Canada	1	329.0			n	m	Lafleur (1999)
		Canada	1	2345.0			n	30	Joiner et. al. (1999)
		Canada	1	-271.0			n	90	Goulden et. al. (1998)
		Canada	1	1539.5			sg	70	Barr et. al. (2002)
		Canada	3	705.9	281.0	1033.8	sg	74-124	Gaumont-Guay (2009)
		Alaska	1	813.2			sg	m	Bonan et. al. (1991)
		Scotland	3	2481.0	1919.0	3004.0	n	50	Zha et. al. (2007)
		Russia	1	-52.0			n	52	Hollilnger et. al. (1995)
		Finland	1	2301.0			p	31	Markkanen et. al. (2001)
		Sweden	1	351.0			sg	80	Lindroth et. al. (1998)
		Sweden	1	5230.0			p	37	Valentini et. al. (2000)
	Total/Average/Range		26	1304	-271.0	5230.0			
	- Excluding SW results		25	**1147**					
	- Standard Deviation			*783*					
	Luyssart et. al. (2007)								
	- Boreal Humid Evergreen		?	1315					
	- Boreal Semiarid Evergreen		?	401					
	- Boreal Semiarid Decidious		?	1787					
TEMPERATE Forest		Canada	1	1578.0			sg	90	Barr et. al. (2002)
		Canada	4	2068.4	504.9	4075.1	n	m	Yuan et. al. (2008)
		U.S.	2	2961.8	2670.6	3252.9	nm	14-250	Law et. al. (2001)
		U.S.	1	2099.0			n	65-75	Barford et. al. (2001)
		U.S.	1	693.0			n	m	Monson et. al. (2002)
		U.S.	1	5762.9			sg	50-120	Wilson and Baldocchi (2000)
		U.S.	1	2562.0			n	60-80	Ehman et. al. (2002)
		U.S.	1	2110.0			nm	m	Hollinger et. al. (1999)
		Denmark	1	1405.6			nm	80	Granier et. al. (2002)
		France	1	4320.0			p	m	Valentini et. al. (2000)
		France	1	2078.3			nm	32	Granier et. al. (2002)
		Germany	3	3090.7	733.0	4520.0	nm	45-110	Valentini et. al. (2000)
		Netherlands	1	2110.0			p	80	Valentini et. al. (2000)
		Belgium	1	-1115.0			p	70	Carrara et. al. (2003)
		Belgium	1	319.2			nm	70-77	Nagy et. al. (2006)
		Belgium	1	4320.0			p	70	Valentini et. al. (2000)
		Italy	3	5609.0	4520.0	6630.0	nm	50-98	Valentini et. al. (2000)
		China	2	3477.9	2599.6	4356.1	nm	100-200	Zhang et. al. (2010)
		Japan	1	4446.5			sg	90	Kitamura et. al. (2012)
		Japan	1	1677.0			-	m	Saigusa et. al. (2002)
		Australia	1	2158.6	-420.0	4016.0	sg	67	Kirshbaum et. al. (2007)
		New Zealand	1	16967.6			p	10	Arneth et. al. (1998)
	Total/Average/Range		31	3250	-1115.0	16967.6			
	- Excluding NZ results		*30*	***2793***					
	- Standard Deviation			*1621*					
	Luyssart et. al. (2007)								
	- Temperate Humid Evergreen		?	3995					
	- Temperate Humid Decidious		?	3121					
	- Temperate Semiarid Evergreen		?	1335					
TROPICAL Forest		USA	1	6781.0			nm	24	Clark et. al. (1999)
		Costa Rica	3	2939.4	1002.1	5611.6	n	m	Loescher et. al. (2003)
		Brazil	1	5926.0			n	m	Malhi et. al. (1998)
		Brazil	1	1025.0			n	m	Grace et. al. (1995)
		Brazil	1	401.6			n	m	Miller et. al.(2004)
		Brazil	1	2595.4			n	m	Lopez et. al. (2005)
		South China	1	4898.1			n	100	Li et. al. (2012)
		South China	1	4268.4			n	m	Tan et. al. (2010)
		South China	1	1694.6			n	m	Zhang et. al. (2011)
	Total/Average/Range		11	**3310**	401.6	6781.0			
	- Standard Deviation			*1989*					
	Luyssart et. al. (2007)								
	- Tropical		?	4045					

[1] n=natural forest, nm=natural managed forest, sg=secondary growth forests, p=plantation
[2] m=mature

4.2 NEE of CH_4 in forests

The well-oxygenated forest soils favour the conversion of methane into CO_2 through methane oxidation:

Equation 9: Methane Oxidation

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$$

Methane (CH_4) fluxes from forests are therefore rather insignificant on a global scale[35]. For example, Tremblay et al., have estimated boreal forests on average to consume 0.39 $mgCH_4 \cdot m^{-2} \cdot d^{-1}$ ($n = 6$), temperate forests 1.4 $mgCH_4 \cdot m^{-2} \cdot d^{-1}$($n = 14$) and tropical forests 0.30 $mgCH_4 \cdot m^{-2} \cdot d^{-1}$ (n=9) (Tremblay et al., 2005). Other studies, such as Jang et al., (2006), have collected data from a number of temperate studies and estimate a slightly higher average sink of boreal and temperate forests (1.59 $mgCH_4 \cdot m^{-2} \cdot d^{-1}$), which however does not paint a more cumbersome picture despite the higher GWP of methane.

Table 7: Average NEE of CH4 in various forest biomes

	n	*mgCH4/m2/day*
BOREAL forests	6	0.39
TEMPERATE forests	14	1.40-1.59
TROPICAL forests	9	0.30

Source: (Tremblay et. al., 2005)

4.3 NEE of N_2O in forests

As with methane, nitrous oxide (N_2O) fluxes from forests are a minor factor in the global carbon budget[36], even though the GWP of nitrous oxide is 198 times that of CO_2 over 100 years.

The N_2O is produced in forests soils through nitrification and denitrification. In the presence of oxygen, nitrifying microbes in the soil transform ammonium (NH_4) to nitrate (NO_3). During this process, some of the N is lost as N_2O, just as some of the NO_3 subsequently is reduced by denitrifying bacteria, into N_2O and nitrogen (N_2) gases under anaerobe conditions (Megonigal et al., 2007). The balance between the relative amounts of N_2O and N_2 produced depend on the availability of organic carbon substrate, NO_3 content, and soil moisture. "*When soils are saturated with moisture, N_2O diffusion into the atmosphere is slow, thereby allowing more time for the denitrification to reduce N_2O to N_2 gas before it escapes into the atmosphere*" (Ullah et al., 2009).

Globally, the nitrous oxide concentrations over tropical forests are the highest on earth, and tropical rainforest have long been considered the main contributor of N_2O to the atmosphere. Research collected by Tremblay et al. (2005) suggests that tropical rainforest N_2O emissions, are equal to those of temperate forests, but higher than boreal forests with values of -0.73 $mgN_2O \cdot m^{-2} \cdot d^{-1}$ (n=7), -0.84 $mgN_2O \cdot m^{-2} \cdot d^{-1}$ (n=16) and -0.05 $mgN_2O \cdot m^{-2} \cdot d^{-1}$ (n=3) respectively.

Table 8: Average NEE of N_2O in various forest biomes

	n	*mgCH4/m2/day*
BOREAL forests	3	0.05
TEMPERATE forests	16	0.84
TROPICAL forests	7	0.73

Source: (Tremblay et. al., 2005)

As can be seen, the amount of data is also extremely sparse on forest nitrogen releases. This is not only due to limited research, but also due to the fact that many forests have very low N_2O flux (Tremblay et al., 2005). Since the Tremblay report was written, more research has been

[35] In the final estimates (Chapter 14,p.119), the methane sink in forests is estimated to contribute less than 0.09% to the final result.
[36] In the final estimates (Chapter 14,p.119), the nitrous oxide flux from forests is estimated to contribute less than 1% to the final result.

conducted, but with similar values. (Colls, 2007; Kellman & Kavanaugh, 2008; Ullah & Moore, 2012; Ullah et al., 2009).

4.4 Discussion

Climate Change is believed to influence carbon balance of forests, as rising temperatures on the one hand is believed to exponentially influence respiration in plants and microbes, while photosynthesis on the other hand increases with rising temperatures to a peak rate, and then declines rapidly. Other research shows that the forest biomes are changing due to climate change, which might also affect forest uptakes or releases. The effect of Climate Change on NEE in forests will not be discussed in detail (see fx Clark, 2004) but might be an important consideration to investigate in future studies.

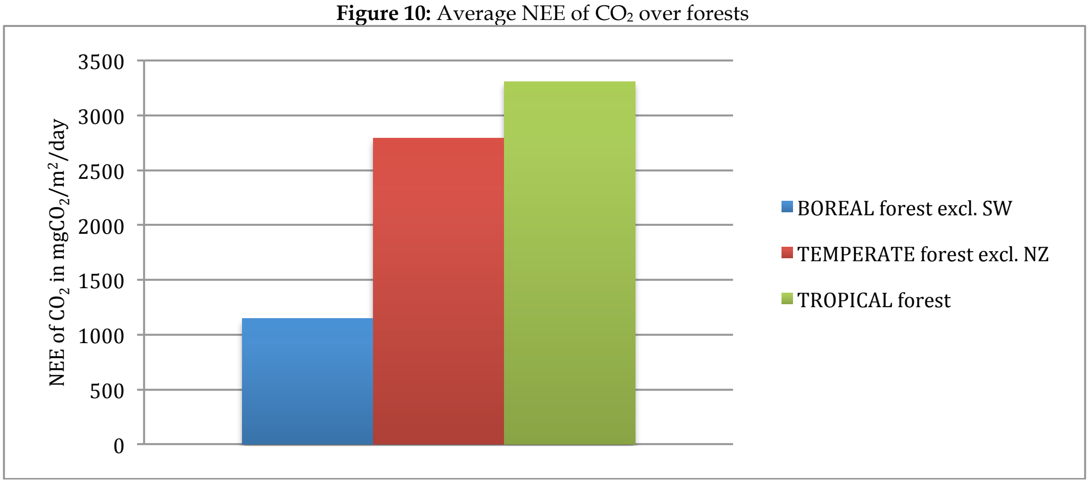
According to the results presented, the average NEE of CO_2 for boreal stands (n=25) amounts to 1147±783 $mgCO_2 \cdot m^{-2} \cdot d^{-1}$, while the NEE for temperate forests (n=30) accounts for 2793±1621 $mgCO_2 \cdot m^{-2} \cdot d^{-1}$. The increased uptake in temperate forests, are likely to be a result of:

1) A higher proportion of deciduous tree species with larger productivity, than evergreen species found in boreal regions;
2) A lengthier growing season, and;
3) A generally higher light intensity in the more southern latitudes.

(For reference please see Fan et al. (1995); Lafleur (1999); Tremblay et al. (2005) and Luyssaert et al., (2007b)).

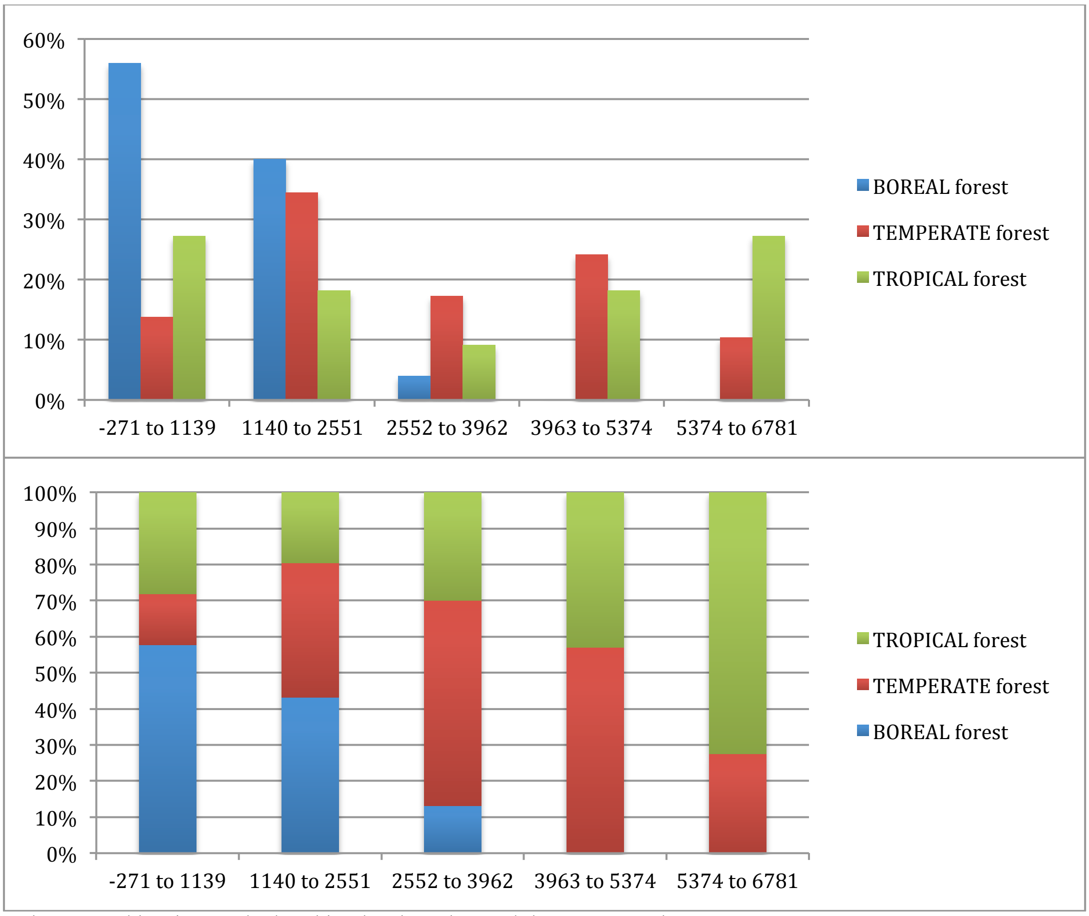
What is common for the variables mentioned above is that, they yield influence on photosynthetic processes, without directly affecting the degradation rate of organic matter. It is however peculiar in this respect that the average NEE for the tropical forests are fairly similar to that of temperate forests, in the sense that the average sink of tropical forests only amounts to 3310 (to 4045) $mgCO_2 \cdot m^{-2} \cdot d^{-1}$ (n=11). This could be the result of the very few sources for tropical forests, that the data is un-representative, some of the variables discussed hereafter such as maximum photosynthetic uptake, or the overrepresentation of managed forests in the cases included for the temperate regions.

Figure 10: Average NEE of CO_2 over forests



Looking at the distribution of the catalogued data (Figure 11, below), however, both supports the impression that all forests generally are carbon sinks, and that tropical and temperate humid forests are accounting for the majority of the total terrestrial carbon sink in forests.

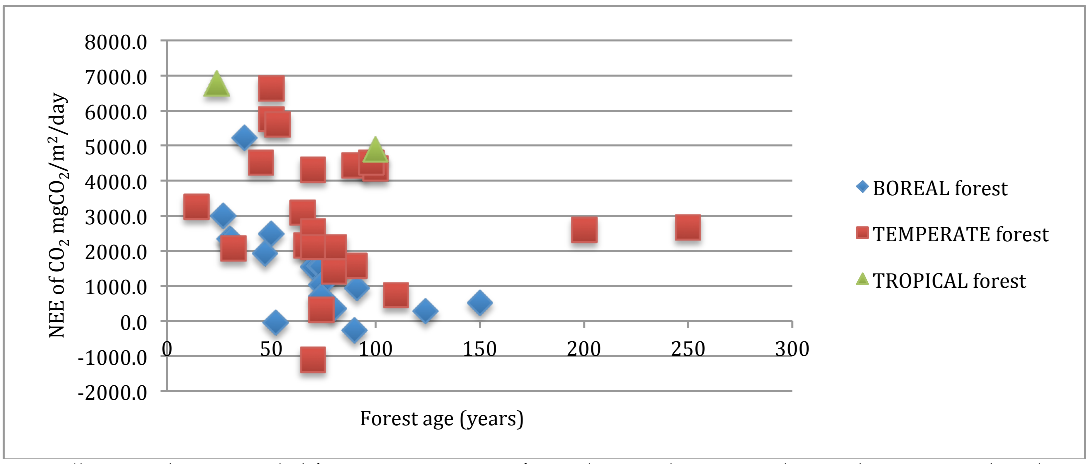
Figure 11: Percentage distribution of the catalogued data on NEE of CO_2 over forests



* The interval has been calculated by dividing the total data range with 5

Theoretically there is a relationship between forest age and carbon sink (see chapter 4.5, below). The catalogued data supports this to some degree (especially for the boreal region), but it also demonstrates that the relationship between age and NEE for all biomes, alone, is far from significant ($p<0.05$).

Figure 12: NEE of CO_2 and forest age



* Not all sources have provided forest age, some are of mixed age and some is only stated as mature. These have naturally been excluded from the figure above.

The data presented by Luyssaert et al. (2007) does not allow for a lot of interpretation, but the number does in general seem to be consistent with the data found here. However, due to the opaqueness of the report, it is difficult to figure out if some of the data is derived from the same sources.

All the stands that emitted CO_2 were mature stands (52 to 90 years), which in theory should be in equilibrium with the atmospheric CO_2 concentrations. While some were found to emit CO_2 due to a number of disturbances, it is also likely that carbon losses at these sites is an expression of the dynamic equilibrium between NEE and the climate, which might as well be compensated in years with more favourable weather conditions.

4.5 Variables effecting NEE of CO_2 forests

This paragraph will discuss which variables affect the role of forests in carbon budgets.

Stem density:	Low stem density may enhance the resource availability and reduce inner-species and interspecies competition. This means that trees in low stem density areas are likely to have higher biomass increment than trees in high density areas (Tan et al., 2010).
Mean annual temperature:	Even though early research have pointed to a link, where forests sequestered more carbon with higher temperatures, there does not seem to be a direct relation between *mean annual* temperature and NEE (Luyssaert et al., 2007a), and research have shown that cold temperatures do not necessarily constrain photosynthesis, and conversely, that it is rather the warm temperatures during mid-summer and its effect on ecosystem respiration, that affects the forests potential for carbon sequestration (Clark et al., 2003; Huxman et al., 2003).
Mean annual precipitation:	There does not seem to be a direct relationship between *mean annual* precipitation and NEE (Luyssaert et al., 2007a). Obviously, there is a connection between water availability and growth, but that will be discussed elsewhere.
Forest management:	Thinning and harvesting in managed forests results in a higher wNPP and a lower heterogenic respiration (R_h) as forest biomass is often removed before it dies and decomposes *in situ* (Luyssaert et al., 2007a; Pedroni, 1997). The fact that the highest singular values of NEE of CO_2 from terrestrial forests in this study are found in temperate humid plantations supports this theory.
Forest age/ successional stage:	Young forests are naturally the most significant consumers of atmospheric carbon (Pregitzer & Euskirchen, 2004), but, as demonstrated recent research has shown that the majority of old growth forests are carbon sinks as well (Knohl et al., 2003). The EPA of Canada conducted a 75-year research on 42 boreal forests between 1920 and 1995. The research indicated that boreal forests in general reach their maximum carbon sink between the ages of 40-60 years. The study also showed that forests with a high leaf area index (LAI) grew rapidly until canopy closure, from which point the growth would decline rather dramatically (Government of Canada, 2003). The Australian Greenhouse Office have however, conducted a similar research in Australia, that suggested a general maximum carbon sequestration over boreal, temperate and tropical biomes, of stands between 10 and 20-30 years respectively (Australian Greenhouse Office, 2006). Due to the opaqueness of the report, it is unclear if the difference between the two reports is due to the inclusion of temperate and tropical forests.
Disturbances:	Forest disturbances include forest fires, insect outbursts and diseases. Disturbances are natural, and in most cases forests will grow back or regain its former characteristics over a number of years. When the forests recover, they will sequester large amounts of carbon from the atmosphere (Liu et al., 2011b), much of which in proportion would be similar to pre-disturbance ecosystem states. Thus, in the long term, this factor is with little or no importance if the forests have the opportunity to grow back to their former state. Disturbances can furthermore be an important factor in understanding some larger fluctuations between forests that share similar characteristics.

Growing season:	Factors such as climate and elevation (affecting rainfall, temperature, and the photoperiod) are important factors influencing the growing season of a specific area. All of these are discussed separately elsewhere in this table. However, in general, the length of the growing season in itself naturally influences the carbon uptake of forests, and lengthier growing seasons will cause increased carbon uptake without effecting the degradation rate of organic matter directly (Tremblay et al., 2005).
Net radiation sum:	There seems to be a relationship between the net radiation sum and the forest carbon balance, as there seems to be a positive relationship between net radiation sum and the forest carbon sink until a certain point where the light use efficiency (LUE) starts to decrease (Luyssaert et al., 2007a) . This correlates with other research, such as Fan et al. (1995) and Taufarová et al. (2008). Additionally, Zhang et al. (2010, 2011) have conducted an extensive study in different forest biomes of China and South Korea where they found that the NEE appeared to increase on cloudy days. This seemingly happened as the diffuse radiation received by the ecosystems had increased more than the global radiation had decreased. It seemed that where the canopy photosynthesis is supersaturated with light in sunny days, cloudy days bring with them more diffuse radiation which reaches the shaded leaves more easily in areas with high LAI. Additionally Zhang et al. (2010, 2011), found this effect to be more evident in temperate than tropical forests, presumably due to the fact that the non-saturating light conditions and the increase of diffuse radiation were more beneficial to photosynthesis, and the reduced temperature was more conducive to decreasing the ecosystem respiration in temperate forest ecosystems under cloudy sky conditions. Correspondingly, the results showed that very high temperature and strong solar radiation could even cause photosynthetic rates to decrease (Zhang et al., 2010).
Water availability:	In areas or periods of water deficiency, trees will close their stomata, which will either cause tree growth to decrease or cause the trees to cease growing entirely for a period (Taufarová et al., 2008). This is important as the building of large dams do not only cause flooding of large areas above the dam, but often also diversion of water from tributaries and wet areas. Reduced (or increased) water availability might affect tree growth dramatically, and thus, the NEE. Additionally, it has been found that water stress indirectly can cause insect outbursts, which can decrease the carbon increment in water stressed areas (Kirschbaum et al., 2007).
GPP:	Where the global GPP seems to be highly related to climatic conditions, and very insensitive to non-climatic conditions, the case is the opposite for NEE according to Luyssaert et al., (2007). However, earlier studies have in fact reported a linear relationship between GPP and NEE (e.g. Law et al., 2002). This also seems to be true for the results presented in the Luyssaert et al. report, if the same GPP values as used in Law et al. report (600-2200 $gC \cdot m^{-2} \cdot y^{-1}$) are employed. When the GPP exceeds 2200 $gC \cdot m^{-2} \cdot y^{-1}$, this relationship however discontinues.
Deciduous/Evergreen:	The results presented in the Luyssaert et al., paper, does not suggest an obvious relationship between NEE and forest seasonality across biomes (Luyssaert et al., 2007a), but they however suggest that semiarid evergreen forests have the lowest biome-specific biomass increment. This partly correlates with Tremblay et al. (2005) who also attribute temperate and tropical deciduous tree species to have much larger productivity than evergreen species in boreal regions.
Semi-arid/Humid:	CO_2 fluxes are in general lower in semi-arid ecosystems compared to humid systems, when the forest species share the same seasonal characteristics (Luyssaert et al., 2007a; Tremblay et al., 2005).

Elevation: The notion of a tree line is extremely dependent on local environmental conditions. Most often, the tree line is defined by the lack of water in higher altitudes, lower temperatures and the fact that snow covers a certain area for a certain amount of the year, that makes is unable to sustain trees. In most places, the tree line is rather a gradual transition, where the last trees are stunted and form low, densely matted bushes (Körner, 1998). Furthermore, species diversity most often declines from low to high elevation (Chapin (III.) et al., 2002). Effectively this naturally means that the NEE of forests approximates zero, as the trees start to disappear close to the tree line. The transition rarely happens over more than 100 meters of elevation.

Picture 10: Boreal mixed wetland of Canada

Picture: Chad Delany, **Source**: ("Pew Environmental Group," n.d.)

Chapter 5: Net ecosystem exchange in wetlands

In the water saturated soils of wetlands, the decomposition of organic matter often follows an anaerobic pathway, which results in large quantities of both CO_2 and CH_4 releases.

In theoretical terms, one would think that the vast amount of peat found in wetlands would sequester large amounts of atmospheric carbon. In reality there are, despite heavy research especially on wetland methane emissions, no consensus as to whether wetlands in general are sources or sinks of atmospheric carbon (Kayranli et al., 2010). Besides disagreement on the interpretation of variables, their reactions, the size of their impact and the role of environmental conditions (Kayranli et al., 2010) this might partly be derived from the fact that whether a wetland is a source or a sink is very much related to a number of spatio-temporal conditions, which is even more pronounced here, than is in any other biome. In wetlands, this can for the most part be attributed to the significant micro-topographic variability, created by depressions, pools, hummocks and hollows (Keddy, 2010). Additionally, research in wetlands, and especially peatlands have shown that these areas have the capability to change from a carbon sink to a carbon source from season to season (and sometimes from day to day) (Keddy, 2010). The high temporal variability have by several authors mainly been linked with water availability (e.g. Bubier et al., 2003 and Kayranli et al., 2010). In reality, these factors might also be the reason why several studies of the same area have showed weighty results, but with different operational signs (Couwenberg et al., 2010; Tremblay et al., 2005).

Under pristine conditions, peatland plants would absorb carbon dioxide through photosynthesis and as the plants later die and decay, they would build up the wetlands' soil, where parts of the carbon would be stored. Of the remaining carbon, parts would leave the system again as CH_4 and parts would leave the system as CO_2. Peatland ecosystems have however, as already mentioned, demonstrated extremely high sensitivity to water level fluctuations (Belger et al., 2011; Couwenberg et al., 2010; Hirano et al., 2009; Keddy, 2010). The consequence of drier conditions created by changing climates, direct or indirect human caused drainage, deforestation and so on, is therefore believed to have led to cessation of the peat accumulation and ultimately a collapse of the peat structure in many wetlands (Furukawa et al., 2005; Hirano et al., 2009). Many tropical peatlands in developing countries have in recent years for example, come under immense pressure due to drainage caused degradation, and as a consequence, research now show that these ecosystems are shifting from being net carbon sinks - to carbon sources (Canadell et al., 2007; Furukawa et al., 2005).

5.1 NEE of CO_2 in wetlands

Generally, wetlands have both an anaerobic and an aerobic zone. In the anaerobic zone, methanogenic bacteria produce methane gas of which parts, when it leaves the anaerobic zone, will be oxidized by methanotrophic bacteria, and transformed into CO_2 on the way to the surface (see Equation 9, p. 45). It has not been possible to find any data on the NEE of CO_2 in swamps, except the few peat-swamps included, which were all sequestrating very large amount of atmospheric carbon (Belger et al., 2011; Whiting & Chanton, 2001). The large numbers demonstrated in the following urges for more research in this area to better understand the role of swamps in global carbon budgets and in LULUCF budgets.

In total, data has been collected from 29 boreal and 14 temperate peatlands. For the boreal region, the values of NEE extend from 2750 $mgCO_2 \cdot m^{-2} \cdot d^{-1}$ in Alberta, Canada to -502 $mgCO_2 \cdot m^{-2} \cdot d^{-1}$ in the Hudson Bay Lowlands, Canada. For the temperate region, the range of the NEE of CO_2 stretches from -540 $mgCO_2 \cdot m^{-2} \cdot d^{-1}$ in a slightly raised bog in Mer Bleue, Canada to -4944 $mgCO_2 \cdot m^{-2} \cdot d^{-1}$ in a drained fen south of Ljubljana, Slovenia.

> *The average NEE of CO_2 over boreal peatlands is calculated to be -189.6±571 $mgCO_2 \cdot m^{-2} \cdot d^{-1}$ (n=29) and -1649.9±1357$mgCO_2 \cdot m^{-2} \cdot d^{-1}$ (n=14) for the temperate peatlands*[37].

For tropical SEA, Couwenberg et al. (2010) collected data from a number of researches on tropical peat swamps in Vietnam, Thailand, Malaysia and Indonesia. In general, these peatlands were emitting substantially large amounts of CO_2. The results, however, showed a clear distinction, where one natural peatland was found to consume as much as 5205 $mgCO_2 \cdot m^{-2} \cdot d^{-1}$, one near-natural but selectively logged site was in near equilibrium and all drained peatlands were large emitters of CO_2. On average, the peat swamps released -2163$mgCO_2 \cdot m^{-2} \cdot d^{-1}$(n=6), with values spanning between 5205 and -5967 $mgCO_2 \cdot m^{-2} \cdot d^{-1}$. Tremblay et al., (2005) also collected data from two tropical peat-swamps, which showed very different values. One was a cypress swamp in Florida with an average NEE of CO_2 of 609 $mgCO_2 \cdot m^{-2} \cdot d^{-1}$, and the other was a seasonally flooded forest of the Amazon Basin where the average NEE of CO_2 was estimated to as much as -3443 $mgCO_2 \cdot m^{-2} \cdot d^{-1}$.

> *The average NEE of CO_2 over tropical peatlands and tropical peat-swamps is estimated to be -2343.2±1369 $mgCO_2 \cdot m^{-2} \cdot d^{-1}$ (n=14)*[38].

[37] An overview of the data on boreal and temperate peatlands is presented in Table 9, p. 52

[38] An overview of the data on tropical peatlands is presented in Table 9, p. 52

Table 9: NEE of CO_2 in peatlands and swamps

Biome	*Country*	*n*	*NEE of CO_2*	*Min*	*Max*	*Source*
BOREAL Peatlands	Canada	5	1401.8	-491	2,750.0	Tremblay et. al. (2005)
	Canada	3	-192.0	-502	142.0	Whiting et. al. (1994)
	Canada	1	900.0			Griffis et. al. (2000)
	Sweden	1	111.0			Waddington and Roulet (2000)
	Finland	1	-427.4			Rinne et. al. (2007)
	Finland	14	-737.0	-1693	-142.5	Sivola et. al. (1996)
	Estonia	4	-549.1	-779.5	-413.4	Salm et. al. (2012)
Total/Average/Range		*29*	***-189.6***	*-502.0*	*2,750.0*	
- Standard Deviation			*571.6*			
TEMPERATE Peatlands	Canada	1	540.0			La Fleur et. al. (2003)
	U.S.	5	-967.1	-1570	-630.1	Chimner et. al. (2003)
	U.S.	1	-2400.0			Carroll and Crill (1997)
	U.S.	3	-2329.0			Bridgham et. al. (1992)
	U.S.	1	-1351.0			Miller et. al. (1999)
	Sweden	1	215.3			Lund et. al. (2007)
	Slovenia	2	-4140.0	-4944	-3,336.0	Danevcic et. al. (2010)
Total/Average/Range		*14*	***-1649.9***	*-4944.0*	*540.0*	
- Standard Deviation			*1357.6*			
TROPICAL Peatlands/Peat Swamps	U.S.	1	609.0			Tremblay et. al. (2005)
	Brazil	1	-3443.0			Tremblay et. al. (2005)
	SEA	6	-2163.0	-5967	5,205.0	Couwenberg et. al. (2010)
	Indonesia	2	-4664.9	-5527.83	-3,802.0	Hadi et. al. (2005)
	Indonesia	1	-370.0			Hirano et. al. (2007)
	Thailand	2	-1900.0			Suzuki et. al. (1999)
	Thailand	1	-3493.0			Jauhiainen et. al. (2005)
Total/Average/Range		*14*	***-2343.2***	*-5967.0*	*5,205.0*	
- Standard Deviation			*1369.4*			

Whiting and Chanton (2001) collected data from three subtropical marshes; two in Florida, and one in Virginia, which all consumed unprecedentedly high amounts of carbon dioxide. Accordingly, the mean NEE of CO_2 in the marshes were 9005, 11634 and 10633 $mgCO_2 \cdot m^{-2} \cdot d^{-1}$ respectively. Belger et al. (2011), on the other hand, investigated CO_2 emissions from 3 tropical marshes within the Brazilian Negro River basin over one year and found them to be extreme large emitters of CO_2. The average NEE of CO_2 for the three sites was -8041 $mgCO_2 \cdot m^{-2} \cdot d^{-1}$, which renders the average NEE of CO_2 of marshes in this biome to 1191.5±10220 $mgCO_2 \cdot m^{-2} \cdot d^{-1}$, (n=6) - and the understanding of GHG from marshes in GHG budgets somewhat blurred. What can be concluded is that marshes, large emitters or large sinks, can play a very significant role in GHG budgets, which is why much more research is needed in this field.

Table 10: NEE of CO_2 in marshes

Biome	*Country*	*n*	*NEE of CO_2*	*Min*	*Max*	*Source*
TROPICAL Marshes	U.S.	3	10424.0	11634	9,005.0	Whiting et. al. (2001)
	Brazil	3	-8041.0	-5907	-10,266.7	Belger et. al. (2011)
Total/Average/Range		*6*	***1191.5***	*-10266.7*	*11,634.0*	
- Standard Deviation			*10220.0*			

5.2 NEE of CH_4 in wetlands

The main emission pathways of methane are ebullition, diffusion and transport through aerenchymous[39] and/or vascular[40] plants (Whalen, 2005). As with CO_2 emissions, wetlands have been found to be both sources and sinks of methane. In general, most wetlands are however emitting extremely high amounts of CH_4 compared to other land-use categories. Overall, wetlands are thus believed to be responsible for 20-24% of annual CH_4 emissions to the atmosphere from all sources (Bastviken et al., 2011, 2004; Kayranli et al., 2010; Whalen, 2005).

5.2.1 NEE of CH_4 in peatlands

Nykänen et al. (1998) estimated the average fluxes from 17 connected boreal natural and drained peatlands of the southern and middle boreal regions of Finland over 2 years. All of the areas were on average covered with snow for more than half of the year. Interestingly, the authors found a strong positive relation between the annual precipitation and average NEE of CH_4 for the region. Additionally, they also found that this relationship was much more pronounced in fens than bogs. Through a number of experiments in situ, it was furthermore found that lowering the water table with 10cm reduced CH_4 emissions from the fens with 70% and the bogs with 45%. The report finally separated natural and drained wetlands, with a similar and unambiguous pattern similar to that presented by Couwenberg et al., (2010) in the previous chapter. The Nykänen et al., (1998) report thus estimates the average NEE of CH_4 from the boreal peatlands in Finland to -21.92, -52.05, -10.7 and -0.0822 $mgCH_4 \cdot m^{-2} \cdot d^{-1}$, for natural bogs and fens, and drained bog and fens, respectively. Interestingly, this result also suggests that there could be a distinction between bogs and fens, which are interesting to investigate in future studies. Finally, these findings suggest that fens are much more sensitive to fluctuations than bogs. Other Finnish studies include Alm et al. (1999) who studied a number of Finnish wetlands over an exceptionally dry summer, with similar results. The big difference between drained and natural wetlands as well as dry and wet conditions, confirm the significance of the water level on methane emissions, which will be discussed in detail later.

The average NEE of CH_4 over boreal peatlands is calculated to be -46.6±43.5 $mgCH_4 \cdot m^{-2} \cdot d^{-1}$ (n=32)[41], with values spanning from 0.7 to -509 $mgCH_4 \cdot m^{-2} \cdot d^{-1}$. These values are similar, slightly lower, to those found in temperate peatlands, which are averaging -65.9±41.5$mgCH_4 \cdot m^{-2} \cdot d^{-1}$ (n=17)[42], ranging from 0.9 to -190 $mgCH_4 \cdot m^{-2} \cdot d^{-1}$. These results comply with early reviews on the matter done by Bartlett and Harriss (1993), who found these areas on average to emit between -87 and -96 $mgCH_4 \cdot m^{-2} \cdot d^{-1}$ respectively.

With respect to NEE of CH_4 in tropical wetlands, Couwenberg et al. (2010) recently reviewed 8 tropical peatlands in Southeast Asia over 2 years (in Vietnam, Thailand, Malaysia, Indonesia and Borneo). The character of the peatland sites ranged from pristine wetlands to heavily managed agricultural peatlands. Overall, the authors found the tropical peatlands to emit relatively small amounts of methane compared to boreal and temperate peatlands, and one of the reviewed sites was even found to consume small amounts of methane. The Couwenberg et al., (2010) report finds the NEE of CH_4 to be -35 $mgCH_4 \cdot m^{-2} \cdot d^{-1}$ for natural tropical peatlands, and -6.4 $mgCH_4 \cdot m^{-2} \cdot d^{-1}$ for *drained* tropical peatlands.

The average NEE of CH_4 over tropical peatlands is calculated to be -7.7±13.7$mgCH_4 \cdot m^{-2} \cdot d^{-1}$, (n=9)[43].

[39] A type of plant tissue in which cells are unusually large, resulting in large air spaces in the plant organ, such tissues are often referred to as spongy and usually provide increased buoyancy

[40] Vascular plants are those plants that have lignified tissues for conducting water, minerals, and photosynthetic products through the plant.

[41] An overview of the data on boreal peatland CH_4 emissions is presented in Table 11, p. 54

[42] An overview of the data on temperate peatland CH_4 emissions is presented in Table 11, p. 54

[43] An overview of the data on tropical peatland CH_4 emissions is presented in Table 11, p. 54

Table 11: NEE of CH_4 in peatlands

Biome		*Country*	*n*	*NEE of CH_4*	*min*	*max*	*Source*
BOREAL peatlands		Finland	5	-53.9	-118.6	-13.1	Alm et. al. (1999)
		Finland	17	-24.0	-144.19	0.7	Nykänen (1998)
		Finland	1	-34.5			Rinne et. al. (2007)
		Sweden	1	-74.0			Jackowicz-Korczyński et. al. (2010)
		Russia	2	-254.9	-509	-0.8	Panikov et. al. (1999)
		Canada	2	-81.5	-84.3	-78.6	Roulet et. al. (1994)
		Estonia	4	-8.0	-23.34	-0.1	Salm et. al. (2012)
	Total/Average/Range		*32*	***-46.6***	*-509.0*	*0.7*	
	- Standard deviation			*43.5*			
	Bartlett and Harriss (1993)			*-87*			
TEMPERATE peatlands		U.S.	5	-69.6	-167.1	-24.7	Chimner et. al. (2003)
		U.S.	3	-59.7	-140.4	-9.8	Koh et. al. (2009)
		U.S.	4	-89.3	-180	-24.0	Dise et. al. (1993)
		U.S.	1	-190.0			Frolking et. al. (1994)
		U.S.	1	-25.8			Teh et. al. (2011)
		Germany	1	-21.0			Fiedler et. al. (2000)
		Slovenia	2	0.0	-0.8	0.9	Danevcic et. al. (2010)
	Total/Average/Range		17	**-65.9**	-190.0	-9.8	
	- Standard deviation			41.5			
	Bartlett and Harriss (1993)			*-96*			
TROPICAL peatlands		SEA	6	-2.8	-32.9	0.1	Couwenberg et. al. (2010)
		Indonesia	1	-53.7			Hadi et. al.
		Indonesia	1	-1.4			Jauhiainen et. al. (2005)
		Malaysia	1	0.5			Melling et. al. (2005)
	Total/Average/Range		9	**-7.7**	-53.7	0.5	
	- Standard deviation			13.7			

5.2.2 NEE of CH_4 in marshes

All 12 temperate marshes included here emit CH_4, and values range from near neutral (-2 $mgCH_4 \cdot m^{-2} \cdot d^{-1}$ to as much as -583.2 $mgCH_4 \cdot m^{-2} \cdot d^{-1}$.

The average NEE of CH_4 over <u>*temperate marshes*</u> *is calculated to be -144.9*±161.5 $mgCH_4 \cdot m^{-2} \cdot d^{-1}$ *(n=12)*[44].

For tropical marshes, the available research include Smith et al. (2000) who measured the NEE of CH_4 in a Venezuelan macrophyte mat to be -114 $mgCH_4 \cdot m^{-2} \cdot d^{-1}$. These values are contrasted by Devol et al. (1988) who measured the NEE of CH_4 from a number of Amazonian macrophyte mats. Despite that their research shared more of the same characteristics (such as average temperature and annual precipitation), the NEE of CH_4 in the Amazonian floodplains of Columbia were more than 4 times as high, namely -590 $mgCH_4 \cdot m^{-2} \cdot d^{-1}$. Other research has also demonstrated substantially high methane emissions in the tropics. For example Nahlik and Mitsch (2011) who did a 29 month research on two tropical marshes of Costa Rica between 2006 and 2009. One of the study sites was a heavy managed alluvial marsh in Paulo Verde, which was found to emit as much as -959.9 $mgCH_4 \cdot m^{-2} \cdot d^{-1}$. The other tropical marsh in this study was located in a humid tropical forest in the north east of Costa Rica, were natural, and had similar values compared with what other research had been found for this biome (-120.5 $mgCH_4 \cdot m^{-2} \cdot d^{-1}$).

[44] An overview of the data on temperate marshes CH_4 emissions is presented in Table 12, p. 55

The average NEE of CH_4 over <u>tropical marshes</u> is calculated to be -235.8±304.4 $mgCH_4 \cdot m^{-2} \cdot d^{-1}$, (n=10)[45]. In comparison, based on an unknown number of reports, Bartlett and Harriss (1993) found tropical marshes on average to emit from -49 to -202 $mgCH_4 \cdot m^{-2} \cdot d^{-1}$.

Table 12: NEE of CH_4 in Marshes

Biome	*Country*	*n*	*NEE of CH_4*	*min*	*max*	*Source*
TEMPERATE Marshes	Germany	2	-64.5	-127	-2.0	Fiedler et. al. (2000)
	U.S.	1	-390.0			Whiting et. al. (2001)
	U.S.	1	-119.0			Wilson et. al. (1989)
	U.S.	1	-583.2			DeLaune et. al. (1983)
	U.S.	1	-262.8			Neubauer et. al. (2000)
	U.S.	4	-61.6			Kelly et. al. (1995)
	U.S.	2	-4.2			Megonigal and Schlesinger (2002)
Total/Average/Range		*12*	***-144.9***	*-583.2*	*-2.0*	
- Standard deviation			*161.5*			
TROPICAL Marshes	U.S.	1	-130.0			Whiting et. al. (2001)
	U.S.	2	-166.5	-226.0	-107.0	Tremblay et. al. (2005)
	Costa Rica	2	-540.2	-959.9	-120.5	Nahlik and Mitch et. al. (2011)
	Brazil	3	-36.9	-60	4.8	Belger et. al. (2011)
	Venezuela	1	-114.0			Smith et. al. (2000)
	Columbia	1	-590.0			Devol et. al. (1988)
Total/Average/Range		*10*	***-235.8***	*-959.9*	*4.8*	
- Standard deviation			*304.4*			
Bartlett and Harriss (1993)			*-49 to -202*			

5.2.3 NEE of CH_4 in swamps

For swamps in the boreal region, it has not been possible to find data on swamps that do not accumulate peat. Supposedly this is because the cool climate in the boreal regions supports low rates of plant productivity and decomposition, which provides ideal conditions for peat accumulation in the soil (Keddy, 2010). The occurrence of swamps (as defined here) in the boreal region is hence unknown, but accordingly, expected to be minimal. For both the temperate and the tropical biome, research is also quite limited.

For the temperate biome, early research by Bartlett and Harris (1993) on a undefined number temperate swamps, came to the conclusion that swamps in temperate areas emitted between -70 and -75 $mgCH_4 \cdot m^{-2} \cdot d^{-1}$, which is slightly lower than average values found in this study. Purvaja et al. (2004) and Mukhophadhya et al. (2001) for example measured methane emissions from two temperate mangrove swamps in South India, and found them to emit -27.4 and -117.7 $mgCH_4 \cdot m^{-2} \cdot d^{-1}$ respectively. Additionally, Wilson et al. (1989) collected research on two temperate swamps in Virginia, USA, over one year. The two sites were calculated to emit similar values; namely -117 and -152 $mgCH_4 \cdot m^{-2} \cdot d^{-1}$.

The average NEE of CH_4 over <u>temperate swamps</u> is calculated to be -120.6±59.9 $mgCH_4 \cdot m^{-2} \cdot d^{-1}$, (n=5)[46], which resembles NEE of CH_4 in temperate Marshes.

With respect to tropical swamps, the available data have unfortunately also been very scarce. Tremblay et al. (2005) reviewed the research from two studies done in Georgia, USA which were comparable to those of temperate swamps (-55 and -149 $mgCH_4 \cdot m^{-2} \cdot d^{-1}$). In contrast,

[45] An overview of the data on tropical marshes CH_4 emissions is presented in Table 12, p. 55

[46] An overview of the data on temperate swamp CH_4 emissions is presented in Table 13, p. 56

Nahlik and Mitsch (2011) did a 2 year research on a tropical swamp in Costa Rica which had an average NEE of CH_4 of -802.2 $mgCH_4 \cdot m^{-2} \cdot d^{-1}$.

The average NEE of CH_4 over tropical swamps is calculated to be -279.2±351 $mgCH_4 \cdot m^{-2} \cdot d^{-1}$, (n=4)[47].

Table 13: NEE of CH_4 in swamps

Biome	*Country*	*n*	*NEE of CH_4*	*min*	*max*	*Source*
TEMPERATE Swamps	India	1	-27.4			Purvaja et. al. (2004)
	India	1	-117.7			Mukhophadhya et. al. (2001)
	U.S.	2	-134.5	-152.0	-117.0	Wilson et. al. (1989)
	U.S.	1	-189.0			Miller et. al. (1999)
Total/Average/Range		*5*	***-120.6***	*-189.0*	*-27.4*	
- Standard deviation			*59.9*			
Bartlett and Harriss (1993)			*-70 to -75*			
TROPICAL Swamps	United States	2	-102.0	-149.0	-55.0	Tremblay et. al. (2005)
	Costa Rica	1	-802.7			Nahlik and Mitsch (2011)
	Columbia	1	-110.0			Devol et. al. (1988)
Total/Average/Range		*4*	***-279.2***	*-802.7*	*-55.0*	
- Standard deviation			*351.1*			

5.2.4 NEE of CH_4 in ricelands

The main emission pathway of methane in ricelands happens through the aerenchymnia of the plants. In total 70-90% of the total methane releases from ricelands are estimated to be released this way (Neue, 1993). The number of growing seasons varies from field to field, and from location to location, and is thus an important factor in estimating approximate carbon budgets of ricelands. All but one of the studies presented here is made over one growing season[48].

Irrigated ricelands comprises about 50% of all ricelands and produces roughly 70% of the rice harvested (Yan et al., 2009). In irrigated rice fields, rice production enjoys benign conditions by assured water supply and control, which also favors methane production. The drought prone conditions and poorer growth in rain fed rice production makes methane emissions lower and more variable here. In deep-water rice fields, sediment methane emissions may be high, but emission pathways are limited, as large parts of the methane that escapes the soil will be oxidized before reaching the surface (Neue, 1993). The majority of the methane emitting rice fields is concentrated in the tropical and warm temperate regions of Southern China and South East Asia (Yan et al., 2009). However warm temperate and tropical South America, some parts of Africa, Spain, Central America and some parts of North America (especially Texas, Louisiana and Mississippi) are also supporting large ricelands (Yan et al., 2009).

Neue (1993) investigated methane emissions from 10 irrigated rice fields in Texas. On average, the NEE of CH_4 from the rice fields were -270 $mgCH_4 \cdot m^{-2} \cdot d^{-1}$ estimated over one growing season. Peng (1995) similarly did research on four Chinese rice fields; two Andosol rice fields in Tsukuba and Mite, which were found to emit very low amounts of methane (-3.1 and -34.5 $mgCH_4 \cdot m^{-2} \cdot d^{-1}$ respectively), one estimate from a gley[49] soil rice field in Ryugasaki and one from a peat soil rice field in Kawachi, which also showed fairly lower values than those identified by Neue (1993) (-74 and -122 $mgCH_4 \cdot m^{-2} \cdot d^{-1}$). As did research by Hadi et al. (2005) in Indonesia (-71.2 $mgCH_4 \cdot m^{-2} \cdot d^{-1}$).

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[47] An overview of the data on tropical swamp CH_4 emissions is presented in Table 13, p. 56

[48] Preparation, planting and harvesting

[49] A type of hydric soil, sticky, greenish-blue-grey in colour and low in oxygen

Finally, Banker et al. (1995) did measurements on one rice paddy in Louisiana, USA, in an area that supported two growing seasons (one normal season, and one with ratooning – see discussion hereafter). Interestingly, the report found that the average NEE of CH_4 for the first crops were fairly similar to those found by Neue (1993) (-301.2 $mgCH_4 \cdot m^{-2} \cdot d^{-1}$), while the NEE of CH_4 during the second crop period were almost three times higher, and the highest for the entire study (-826 $mgCH_4 \cdot m^{-2} \cdot d^{-1}$). It is believed that the cultivation method might hold a large part of the reason for this. Ratooning is a method used for both sugar and rice cultivation. The basic principle is that the lower parts of the plants and the roots are left uncut. Normally rice is an annual monocarpic[50] plant, but in the warmer regions it can often survive as a perennial[51], supporting ratooning for one or two additional seasons. Besides advantages related to the fact that, costs for preparing and replanting the ricelands are reduced, the crops will also mature earlier in the season. The yield of the crops does however decrease after each cycle, and the plant will become more vulnerable to pests and diseases, which is why it cannot be done more than a few times, if at all (International Rice Research Institute, n.d.; Neue, 1993). The idea that rice fields (or sugar plantations) which are subject to ratooning is causing an increase in methane emissions, is supported by other research (Banker et al., 1995; van Bodegom et al., 2000), which however concludes that more knowledge is needed to understand the effect of this probably.

> *The average NEE of CH_4 over rice fields is calculated to be -243.1 $mgCH_4 \cdot m^{-2} \cdot d^{-1}$ (n=17)[52], which is fairly similar to average values found in swamps and marshes for all biomes.*

In comparison, Cao et al. (1996) did a theoretical estimation using process based models (methane emission models) and integrated GIS data sets defining the distribution of rice paddies, climate, soil conditions and rice calendar. While field measurements as those presented in the majority of cases in this study are usually made over less than 1 m^2, these model calculations have been carried out at a scale of hundreds of thousands of hectares and are naturally permeated with uncertainties. The results are pertinent to mention in that the values identified by Cao et al. (1996) are much similar to those presented here as they fluctuate between -50 and -400 $mgCH_4 \cdot m^{-2} \cdot d^{-1}$.

Table 14: NEE of CH_4 in ricelands

Biome	*Country*	*n*	*NEE of CH4*	*min*	*max*	*Source*
	U.S.	10	-270.0			Neue et. al. (1993)
	U.S.	2	-563.6	-301.17	-826.0	Banker et. al. (1995)
	China	4	-58.4	-122	-3.1	Peng et. al. (1995)
	Indonesia	1	-71.2			Hadi et. al. (2005)
Total/Average/Range		*17*	***-243.1***	*-826.0*	*-3.1*	
- Standard deviation			*175.1*			
Cao. et. al. (1996)			*-50 to -400*			

5.3 Discussion

In general, the data on NEE of GHG's for wetlands seems strangely fragmented and with little consensus to methods;

1) Several of the authors have therefore been contacted in order to comprehend their flux measurements, but only few responded, and of these most with uncertainty over their own results;

[50] Monocarpic plants are those that flower, set seeds and then die

[51] A perennial plant or simply perennial (Latin per, "through", annus, "year") is a plant that lives for more than two years.

[52] An overview of the data on rice field CH_4 emissions is presented in Table 14, p. 57

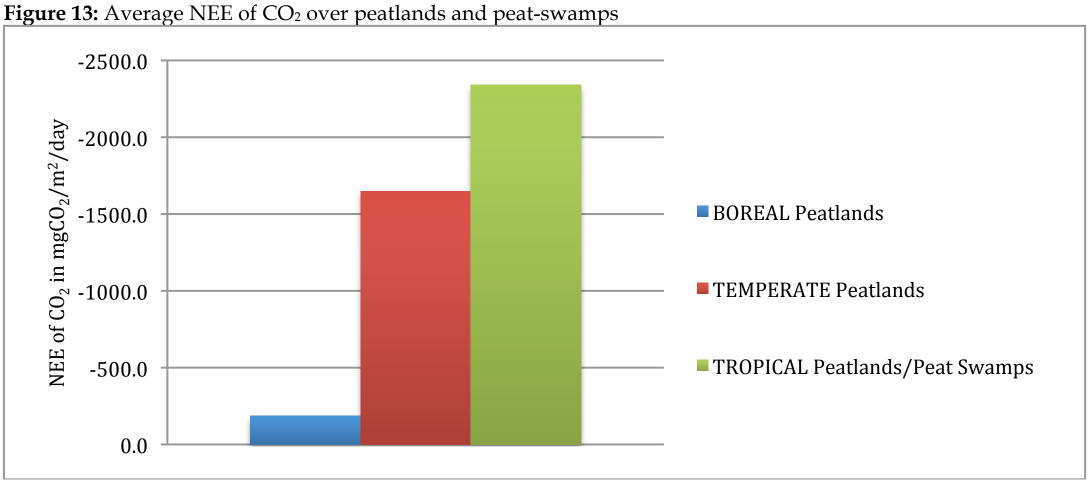
2) The data is rarely collected over more than one year, even though it seems quite obvious that this is a necessary distinction to make;
3) Others ignore the ebullition flux of carbon dioxide which might only mean a small underestimation, while some goes as far as to ignores the ebullition flux of methane, which probably means an underestimation in the 3-10 times magnitude.
4) Finally, all but very few, of the reports fail to discuss site history.

It seems like biome specific fluxes of methane gases are more uniform than biome specific fluxes of carbon dioxide. This might suggest that methane fluxes from wetlands might be less sensitive to the factors that seemed to cause large fluctuations with regard to CO_2[53]. The extremely high variability for the NEE of CO_2 within the same biome is partly expected to be a result of such variables as discussed in the introduction to this chapter. This assumption is however difficult to verify as most of the available sources regrettably have failed to comment on site history, which as it appeared, palpable in the 6 tropical swamps examined by Couwenberg et al. (2010), and as it was discussed by Hirano et al. (2009) and others, seems to be a crucial factor in understanding current behaviour of wetland ecosystems. Also, a discussion of land-use history would provide a powerful tool to interpret measurements and understand if such estimates can be used for any kind of generalization. Finally, it would also provide a means to differentiate between short- and long-term drivers in understanding the variables that drive GHG fluxes in wetlands.

While the data presented seems to give a fairly good picture of the range and averages for the NEE of CO_2 in wetlands regions, the lack of data on tropical marshes, and of marshes in general are problematic. What the results do show is that these systems apparently can be both very large sources and very large sinks. If this is a general picture of marshes within all biomes or merely a misleading figure constructed by the few sources is of cause not known. Overall, the representation of marshes is extremely dichotomous, while peatlands and swamps, share more uniform values. On average peatlands and swamps seems to be significant sources of CO_2 to the atmosphere.

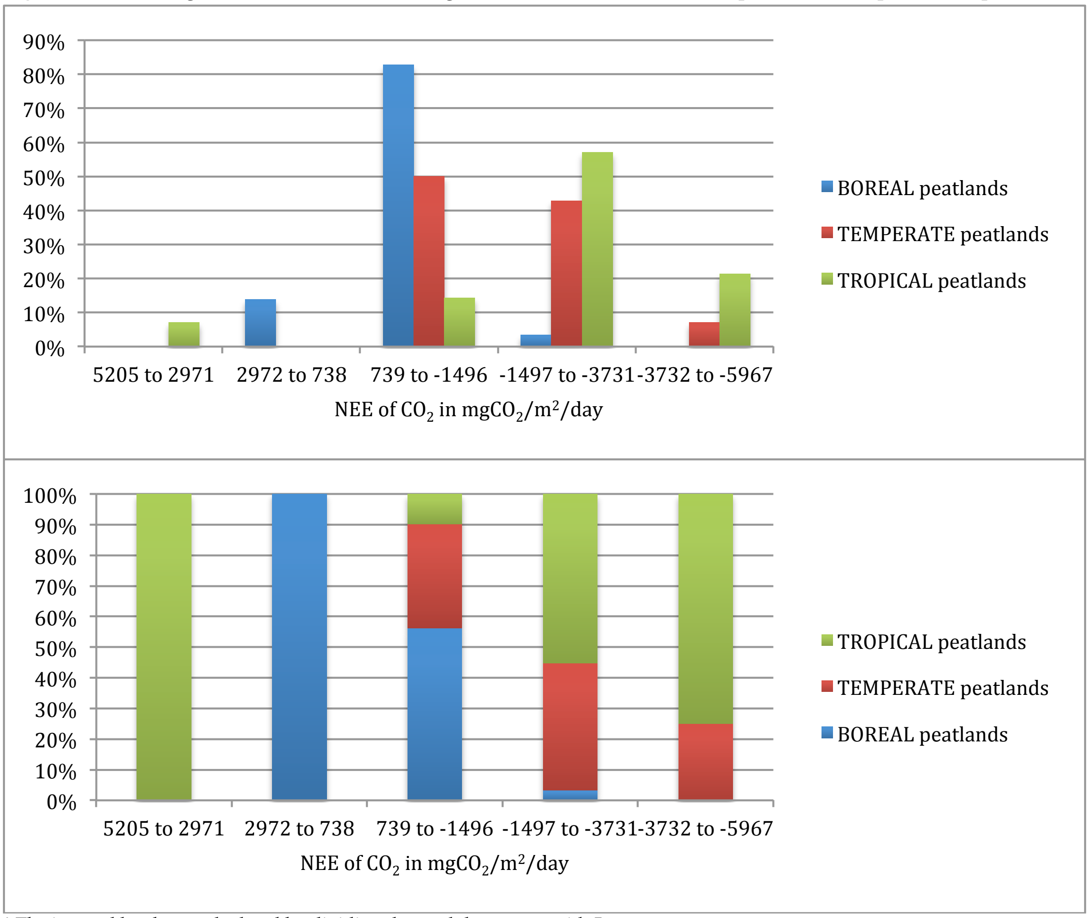
Additionally, the findings also indicates that both temperate and especially tropical peatlands and peat-swamps on average are much larger sources than the boreal peatlands, but that some peatlands in the boreal and especially the temperate regions can be as significant a source of CO_2, as tropical peatlands.

Figure 13: Average NEE of CO_2 over peatlands and peat-swamps



[53] That drier conditions created by changing climates, direct or indirect human caused drainage, deforestation and so on, may have led to cessation of the peat accumulation and ultimately a collapse of the peat structure in many wetlands, just as many tropical peatlands in developing countries in recent years have come under immense pressure due to drainage caused degradation, ultimately causing many of these ecosystems to shift from being net carbon sinks - to carbon sources.

Figure 14: Percentage distribution of the catalogued data on NEE of CO_2 over peatlands and peat-swamps



* The interval has been calculated by dividing the total data range with 5.
* Notice that the first interval in the bottom chart of the percentage distribution above is representing only one tropical peatland, and is therefore far from resembling the actual case fully. For reference see the top chart.

For CH_4 emissions in all wetlands - except for peatlands - the tropical region seem to be the largest wetland source of methane gas. In between wetlands, peatland methane emissions are much smaller than methane emissions from marshes, swamps and ricelands for which the values seem fairly similar.

Figure 15: Average NEE of CH_4 in peatlands

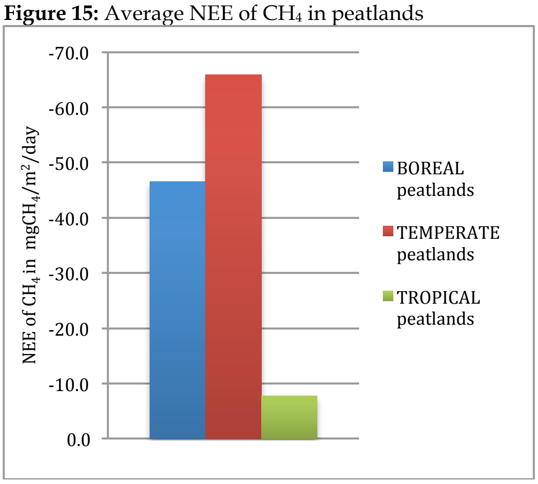


Figure 16: Average NEE of CH_4 in marshes

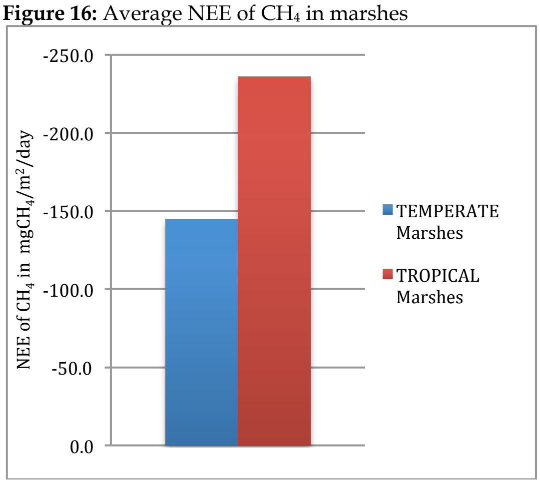


Figure 17: Average NEE of CH_4 in swamps

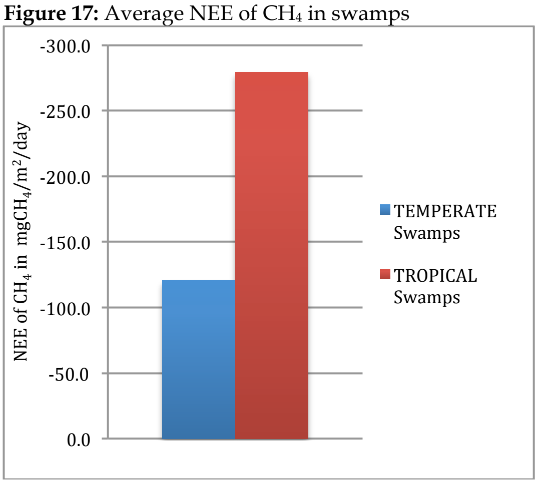
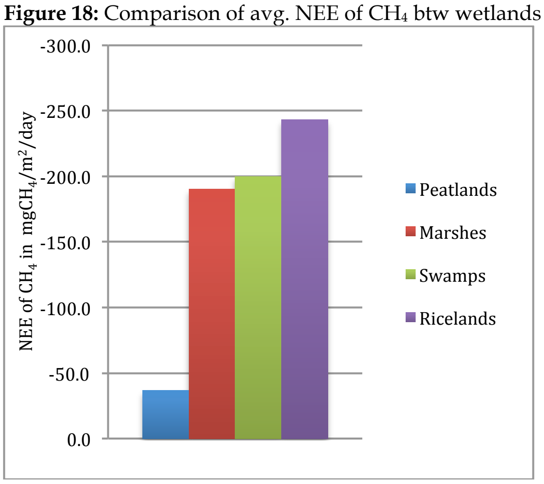
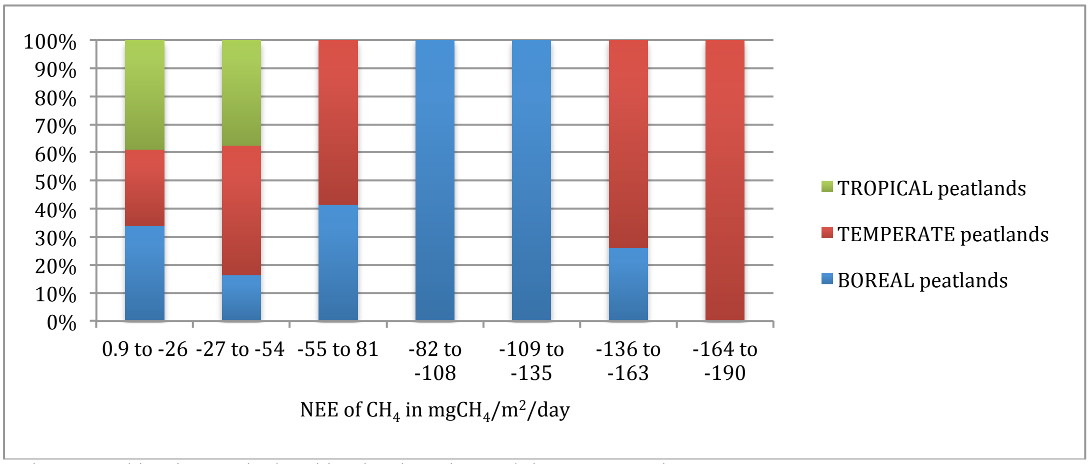


Figure 18: Comparison of avg. NEE of CH_4 btw wetlands



The generally few methane emissions from tropical wetlands is backed up by the percentage distribution of the data included in this study. Below this is illustrated for peatlands.

Figure 19: Percentage distribution of the catalogued data on NEE of CH_4 over peatlands



* The interval has been calculated by dividing the total data range with 7

The data presented on rice fields may give a general idea of the NEE of methane over ricelands today, but (as with other agricultural produces) much research is conducted to increase the yield of rice fields. Examples include experimenting with producing rice without flooding (Epule et al., 2011), low methane emitting rice varieties (Anand et al., 2005) and fertilizer amendment (Evans, 2007). In some places experiments are also conducted in order to make ricelands more resilient to intrusion of saline waters (LWA, 1997; Phogat et al., 2010). This is especially important in countries like Cambodia and Vietnam where saline water is travelling further and further upstream each year; probably as a consequence of damming of rivers on the upper Mekong in China (International Rivers, 2009; Osborne, 2007). If hydropower causes a change in cultivation methods, a discussion of cultivation methods in general is an important consideration in LULUCF budgets. Some research has shown a factor ten increase in methane releases when shifting from one cultivation method to another (Khalil et al., 2008).

In general, all wetland types with a possible exception of the tropical marshes are generally sources of both CO_2 and CH_4. Several of the cases have demonstrated that the distinction made between biomes might be more meaningful if it had been possible to distinguish between drained, natural and irrigated wetlands, and for peatlands it would furthermore probably have been advantageous also to distinguish between bogs and fens.

5.4 Variables effecting NEE of CO_2 and CH_4 in wetlands

The variables that affect the NEE of CO_2 in wetlands are by far the same variables that affects NEE of CH_4 in wetlands, and there seems to be a balance between the two (Kayranli et al., 2010). The main factors influencing net GHG flux from wetlands are the factors that control water level depth. This includes site history, precipitation (and precipitation timing), temperature (evaporation) and altitude (run-off). In general, there seems to be a reciprocal relationship between the water level and methane/carbon dioxide emissions (Kayranli et al., 2010).

This chapter for the most part revolves around the research by Christensen et al. (2003) who over 12 measurement years conducted a number of thorough research in northern wetlands. Beside the distinct relationship between water availability, the study suggested that temperature and microbial substrate availability (expressed as the organic acid concentration in peat) could explain almost entirely the variation in mean annual CH_4 emissions.

NEE/NEP/NPP of CO_2 and total plant biomass: While some early research has pointed to a strong explanatory correlation between total methane emissions from wetlands and the NEE, NEP and NPP of CO_2, as well as total plant biomass (Tremblay et al., 2005), Christensen et al. (2003) partly reject these findings and stress that the individual field studies, which have been used in these analyses', have all differed in experimental design, and have failed to explain large scale variations in CH_4 fluxes from single factors.

Temperature and methane releases: Early studies by Wilson et al. (1989) found a "step function" relationship between soil temperature and methane releases. They found methane emissions to respond most strongly to temperature changes between 10°C and 16°C, and that in sediment, methanogenesis rates were generally limited and insensitive to changes at temperatures below 10°C. This is backed up by Christensen et al. (2003) who however found the relationship to be exponential. Christensen et al. (2003) estimate in his studies that temperature explains up to 84% of the variance in methane emissions.

Species composition: Both Christensen et al. (2003) and Bubier et al. (2003) found a strong relationship between species composition and the NEE of GHGs in wetlands. These studies showed that large evergreen or deciduous scrubs generally had a larger carbon uptake than smaller scrubs and sedges. The study also showed that aerenchymatous plants facilitated some of the methane which is produced in the wetland, could escape the anaerobic conditions through the plant, without being oxidized in the oxic waters, causing these areas to emit more methane. Interestingly, the rice fields presented in this report were all but one emitting similar amounts of CH_4 compared to marshes and swamps, while the one which did emit relatively large amounts of CH_4 was the system in which ratooning had been used.

Water table, water availability and water depth:

During the wet seasons, the water table in peatlands rises above or near the surface, which slows down the aerobic decomposition in the peat soil, while favouring peat accumulation, especially if factors that in general are benign to growth are propitious (e.g. low temperatures, and the successional stage of the system). The drawdown of the water level in the dry season deepens the oxic peat profile, which causes an increase of substrate availability for CO_2-releasing decomposition. While high water levels favours methane production (which is reduced in oxic environments), Hirano et al. (2009) did a five year study on factors controlling GHG from peatlands and found that the relative significance, when the increase of the more potent greenhouse gas methane were converted into carbon dioxide equivalents and the increased carbon storage were included, were nonetheless minor to the increase in the cumulative GHG's of the ecosystem, if the water level where lowered. This is due to the consequent increase in CO_2 emissions this would otherwise trigger.

All cases investigated by Christensen et al. (2003) had relatively high water table level, and thus the research concluded that the predictive power of the water table height were more as an "on-off switch" and that as long as the water table is around or above 10 cm from the surface, other processes take over "the control on large scale variability" (Christensen et al., 2003). This is however not completely consistent with more recent research, and both Hirano et al. (2009) and Kayranli et al. (2010) finds that there seems to be a critical depth at which maximum CH_4 emissions occur. At greater depths, research have shown methane production to decrease, while methane consumption (methanotrophy) increases. Correspondingly, old research by Roulet et al. (1993) found that when the water table dropped below 25 cm from the surface of the peat, peatlands would convert from being a source to a sink of methane gas, due to increased methane oxidation, while CO_2 releases would increase significantly.

Amount and quality of decomposable substrate:

According to Christensen et al. (2003), the amount and quality of decomposable substrate seems to be an important controlling factor. Organic acids are typical fermentation products of anaerobic degradation of organic matter and a significant facilitator and important substrate for methane formation. Consequently, the organic acids are also good indicators of the availability of methanogenic substrate (Christensen et al., 2003). Additionally, most vascular plant species also exude organic acids from their roots, and as one of the main factors controlling belowground C exudation and allocation is the intensity of photosynthesis, this provides a "direct species dependent linkage between vascular plant production and the substrate availability for CH_4 for formation, and this linkage has the potential to affect methane emission rates" (Christensen et al., 2003). The research done by Christensen et al. (2003) thus showed a strong correlation between the organic acid, acetate, which made up more than half of all the organic acids measured in all cases, and methane formation. In total the acetate availability explained 92% of the methane emission rate variability.

Chapter 6: THE AQUATIC ECOSYSTEM

Picture 11: The Bon River Delta of the Mekong River south of Da Nang City in Vietnam, is one of the places in SEA which today is severely affected by decreasing river flows as a consequence of hydropower development on the Upper Mekong River. In recent years, this has caused increasing saltwater intrusion, as reduced river flows allows saline waters to travel further upstream (Osborne, 2004).

Picture: (ICEM, 2012)

Carbon storage and exchange in the biosphere is still traditionally understood as an activity that predominantly takes place between:

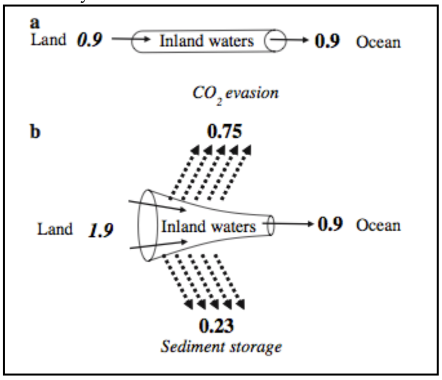
1) The terrestrial biosphere;
2) The oceans, and;
3) The atmosphere.

(For reference please see: IPCC (2001) and Solomon et al. (2007))

To this comes the anthropogenic contribution from the burning of fossil fuels (IPCC, 2001; Solomon et al., 2007).

When riverine systems are included, it is still most often simply as "pipes" transporting carbon from the terrestrial land to the ocean, when, in fact, the carbon drainage through this system is only the end result of a number of losses and transformations in the aquatic system *en route* (see Figure 20, p.65). Of the total amount of carbon that enters the freshwater aquatic ecosystem (1.9 PgC y^{-1}), Cole et al. (2007) estimate that at least 0.75 PgC y^{-1}, and presumably much more, is returned to the atmosphere, 0.23 PgC is stored in the sediments while 0.9 PgC enters the ocean through "the pipe". Hence, there is an obvious need to include these ecosystems in the understanding of Carbon pools and fluxes (Bastviken et al., 2004; Cole et al., 2007; Kosten et al., 2010).

Figure 20: Simplified model describing the role of inland aquatic systems in the global carbon cycle



Unit: $pgC \cdot y^{-1}$
Source: (Cole et al., 2007)

In addition to their gross primary production (GPP), inland aquatic systems receive input of both *organic-* and *inorganic carbon* from the surrounding lands. The specific form of the imported carbon plays a determining role in the fate of the carbon dynamics in the water bodies and their ecology. Recent studies estimate the addition of imported organic carbon to the system as often being co-equal or even exceeding the aquatic GPP (Cole et al., 2007; Cole and Caraco, 2001; Kosten et al., 2010), for which reason the sum of respiration, storage and export can be significantly larger than the GPP of the system (Caraco & Cole, 2004). Consequently, lakes are commonly net sources of carbon to the atmosphere, while simultaneously storing organic carbon in their sediments (Åberg et al., 2010; Kosten et al., 2010; Sobek, 2005).

Also, rivers and streams are believed on average to be net contributors of carbon to the atmosphere, even though storage is expected to be negligible in the lotic ecosystem[54](Cole et al., 2007). The excess of CO_2 in rivers typically derived as organic inputs from the groundwater are respired into the soil system, the hyporheic zone[55] or directly into the stream or river itself. Additionally, a relatively large amount of carbon is imported into the system as bicarbonate aluminosilicate from clay minerals, or bicarbonate ions from rocks weathered by the carbonic acid in the water (Cole et al., 2007).

6.1 Methods for estimating the NEE of GHGs in aquatic ecosystems

The methods for estimating the NEE of GHG's over aquatic systems have changed several times over the years in which the results presented subsequent to this have been collected. The methods vary between:

1) The thin boundary layer (TBL) method,
2) The use of floating chambers with in situ and ex situ laboratory analysis, and finally;
3) The use of floating chambers coupled to an automated instrument (NDIR and FDIR).

The methods obviously varies in design (see for example Lambert and Fréchette(2005) for a thorough description), but also in effort of obtaining the results. Tremblay et al. (2005) estimate that using the method where floating chambers are coupled with automated instruments allows a factor five increase in collection of data, compared to methods with laboratory analysis. In general, there seems to be little variation between measurements obtained using floating chambers. Floating chambers coupled with an automated instrument, does however tend to have a slightly lower accuracy, while measurements that have been obtained through the TBL method tends to yield slightly lower overall results (Lambert & Fréchette, 2005).

[54] See definition p. 67
[55] The hyporheic zone denotes an area or ecosystem beneath the bed of a river or stream that is saturated with water and that supports invertebrate fauna which play a role in the larger ecosystem.

6.2 Critique of data

As with the terrestrial biome, there is a remarkably scarcity of data from tropical regions (Bastviken et al., 2011; Luyssaert et al., 2007b; Tremblay et al., 2005), and again, there are no estimates at all from the African continent. The critique of the data used here are by and large the same as was discussed for wetlands; much research have not been conducted over more than one year. There are extremely little data on NO_2 releases, fluxes are extremely variable and dependent on several spatio-temporal factors which makes them hard to calculate, and ultimately; some studies leave out the ebullition fluxes of methane, which in many cases are likely to contribute to the main portion of the total methane emissions (Bastviken et al., 2008; Casper et al., 2000; Ramos et al., 2006; Tremblay et al., 2005; Xing et al., 2005).

Finally, there is a certain inaccuracy in measurements taken with different methods (as described above). It has unfortunately not been possible to compensate for these inaccuracies in the following, as there is no known compensation factor between TBL measurements and methods where floating chambers have been used - probably as there is little direct correlation between the results obtained using the two methods (Lambert & Fréchette, 2005).

As with forests, all available data have been included. The distribution of data here does hence not represent a normal distribution of data, which renders averages unrepresentative. The averages presented must hence not be understood as such, and the data included should rather be considered as individual cases, many of which is discussed in the text. Optimally a representative segment of each biome would have been included, but this has not been possible due to the scarcity of data as well as the many variables, which would have had to be included. After each section the generalizability of the data will receive more attention, but this is done with respect to the offset outlined here.

6.3 Geographical distribution of samples

The map below illustrates the geographical distribution of the aquatic sites contained in the study. The map again underlines an overrepresentation of boreal and temperate sites, and highlights the need to focus more on tropical sites (especially Africa) in future studies. In total, 387 aquatic systems have been included in the study. Of these, 175 are from Canada. Included in these studies are also 66 studies presented by Bastviken et al. (2011). Not all of these studies are presented by country, but rather by latitude. Some of these are therefore not included in the map below.

Map 3: Geographical distribution of aquatic sites contained in the study

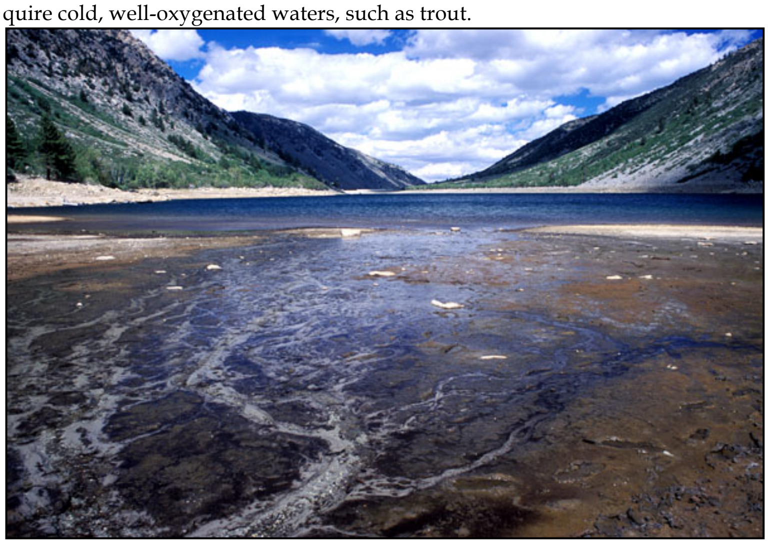
6.4 Freshwater ecosystems definitions used

The freshwater ecosystem can be divided into two categories based on the way in which they hold water; *Lentic* and *Lotic* systems (Jørgensen, 2009). Lentic systems are characterized by having slow-moving water such as lakes and reservoirs. Lotic systems on the contrary are characterized by having rapid-moving water and are here included as rivers.

6.4.1 Lentic ecosystems

Lakes are large bodies of standing water, which are either formed naturally or are man-made for amenity reasons. The water levels of especially large lakes tend not to fluctuate significantly, and their often gentle sloping boundaries, support the growth of a wide variety of flora and associated fauna (Jørgensen, 2009).

Picture 12: Opposite to *eutrophic* lakes, *oligotrophic* lakes are unproductive lakes, characterised by nutrient deficiency - like the Californian Lake Lundy hereunder. Oligotrophic lakes typically host little or no aquatic vegetation and are hence relatively clear, with little or no algal. The bottom waters of such lakes most often enjoy ample oxygen; thus supporting many fish species, which require cold, well-oxygenated waters, such as trout.



Source: (Micro*scope, 2006)

Reservoirs are either artificial lakes or the result of impoundment for dams, in order to support the storage of water, for one of more purposes. The major ecological difference between lakes and reservoirs is the force of the occasional “draw-down”, which occurs as the extraction from the dam exceeds recharge from feeder streams and rivers, causing a significant lowering of the water table (Jørgensen, 2009).

When rivers are dammed, the carbon stored in the terrestrial biosphere is usually flooded. This will inevitably cause a rapid increase in GHG emissions for a certain period, usually 10-15 years (Abril, 2005; Acharya et al., 2010; Tremblay et al., 2005) due to the augmented bacterial decomposition of the labile carbon from the newly inundated organic matter and the consequent release of nutrients (Åberg et al., 2010; Delmas et al., 2001; Tadonléké et al., 2012). In GHG accounting for large reservoirs, it is therefore crucial to distinguish between new and old impoundments.

Picture 13: The Three Gorges Dam in China is the largest hydropower project in the world. With an installed capacity of more than 22.5 GW, it is almost 11 times bigger than the famous Hoover Dam. The construction of the dam has had immense consequences for millions of people. Officially, Chinese Government sources estimate that more than 1.3 million people have had to relocate as a consequence to the dam reservoir, which inundated 13 cities, 140 towns and 1.600 villages or a total of 632 km². The total surface area of the reservoir is estimated to 1.045 km² (International Rivers, 2012a).

Picture: (NASA, 2012)

6.4.2 Lotic ecosystems

Rivers are natural watercourses flowing towards the ocean, the sea, lake or another river. The water within a river is generally collected from precipitation through a drainage basin, from surface runoff and other sources such as groundwater recharge, springs or the release of stored water in ice and snowpack's. Hence the amount of water in the river is dependent on a variety of factors such as precipitation, season, temperature and so on. Additionally, rivers often have a relative large contact per volume area compared to reservoirs and lakes.

Picture 14: The Horseshoe Bend of the Colorado river which flows 2.366 kilometres from the Rocky Mountains to the Gulf of California's Sea of Cortez. At least that was the case when the waters were more plentiful. Today, human impacts such as hydropower construction on the river are believed to have caused that the Colorado River Delta often runs dry.

Source: ("River Photos -- National Geographic," n.d.)

In general, the balance between photosynthetic uptake and respiration in aquatic systems may very well be staggered of the same reason that forests are no longer believed to be in equilibrium with atmospheric CO_2. However, the most interesting characteristic of inland aquatic systems is the relationship between CO_2 and CH_4 emissions. A variety of factors affect the rate at which methane is oxidized in the water column and transformed into CO_2, which might also, partly, be the reason why the two gases respond differently to season; so while CH_4 has the highest emission rates during summer/warmer periods (Juutinen et al., 2009; Marinho et al., 2009; Xing et al., 2005), CO_2 emissions are often absorbed from the atmosphere during the summer months, and released during winter/colder periods (Trolle et al., 2012; Xing et al., 2005).

Chapter 7: Net ecosystem exchange in lentic systems

Although lakes and reservoirs cover a relatively small proportion of the earth's surface, both are believed to play an important role; in regional carbon budgets as well as in the global carbon cycle; not at least as both have been found to sequester vast amounts of organic carbon, while simultaneously emitting large amounts of CO_2 and CH_4 to the atmosphere (Cole et al., 2007; Einola et al., 2011; Tranvik et al., 2009). The surplus in aquatic ecosystems is believed to be the result of a large allochtonous input[56]. The balance between uptake and release is hence understood differently than it was in forests, which (roughly speaking) were either sources or sinks, and where the majority of the overall balance could be determined almost alone from measuring the NEE over the forest roof. The NEE of GHGs between the water surface and the atmosphere will be discussed here. The sink in lake- and reservoir beds will be discussed in the chapter on carbon storage (Chapter 9, p. 88).

7.1 NEE of CO_2 in lakes

Schrier-Uijl et al. (2011) among others estimated the NEE of two oligotrophic and three eutrophic lakes[57] in the Netherlands. Peculiarly for this study, there did not seem to be any relationship between the amount of oxygen, or the limited amount of productivity or nutrients in the oligotrophic wasters and the NEE of CO_2 (or CH_4). The mean NEE over the lakes was -1485.12$mgCO_2 \cdot m^{-2} \cdot d^{-1}$(n=5).

> *The average NEE of CO_2 over boreal lakes is calculated to be -1078.35±283 $mgCO_2 \cdot m^{-2} \cdot d^{-1}$ (n=62)*[58].

For temperate lakes, Striegl and Michmerhuizen (1998) did a two year research on two large neighbouring Minnesota lakes; Williams Lake of which the epilimnion[59] was depleted of CO_2 and Shingobee Lake which on the contrary was supersaturated with CO_2. For both lakes, the storage was largest in the late winter, while maximum emissions happened immediately after the ice melted. For Williams Lake, the NEE of CO_2 was as could be expected measured to be near zero, while the CO_2 supersaturated Shingobee Lake had a NEE of CO_2 of -964.059 $mgCO_2 \cdot m^{-2} \cdot d^{-1}$. Casper et al. (2000) also measured the NEE of CO_2 over a very small and shallow lake in England, which they found to emit very large amounts of CO_2. In the lake, the NEE was measured to be -1760.38 $mgCO_2 \cdot m^{-2} \cdot d^{-1}$. Buffam et al. (2011) on the contrary measured the average NEE of CO_2 in the whole lake district of Wisconsin and Michigan to be -87.61 $mgCO_2 \cdot m^{-2} \cdot d^{-1}$, with the same pattern of seasonality as measured by Striegl and Michmerhuizen (1998). Finally, most recently Trolle et al. (2012) published an extensive study of the NEE of CO_2 in as much as 151 shallow lakes in Denmark (mean depth < 3m), in order to assess the influence of lake trophic status on the NEE of CO_2. Contrary to the research on the Hollandish lakes measured by Schrier-Uijl et al. (2011) this research found that CO_2 efflux generally increases as trophic status decreases. This was attributed to findings that showed seasonal CO_2 fluxes to be strongly negatively correlated with pH, which in turn was correlated with chlorophyll a (Chl a) concentrations[60]. The research largely found that lakes with low Chl a concentrations were emitting CO_2 while lakes with a high Chl a concentration served as carbon storage during the summer months. All lakes were however sources of CO_2 on an an-

[56] Material introduced into rivers from terrestrial environments. Examples include leaves or branches from trees.

[57] Oligotrophic lakes typically have high levels of oxygen, and nutrients for plant growth. Eutrophic lakes usually have a lot of minerals and organic nutrients that benefits the growth plants and algae. An oligotrophic lake is what is typically considered a 'healthy lake' since it can support a wide range of marine life. The low nutrient content and the low algal production, often renders the water very clear. Eutrophic lakes appear, conversely, often dark. Excessive amounts of nutrients and reoccurring algal blooms render the quality of the water very low. The lack of oxygen in the water makes eutrophic lakes inhabitable for fish (Kalff, 2001; "Trophic state index," 2012)

[58] An overview of the data on boreal lake CO_2 emissions is presented in Table 15, p. 70

[59] The epilimnion is the upper layer of water in a stratified lake

[60] Trophic status is usually based on the total mass of algae in a lake, which is represented by the concentration of photosynthetic pigment (chlorophyll-a) in water samples.

nual basis. The average annual NEE of CO_2 was measured to be -619 $mgCO_2 \cdot m^{-2} \cdot d^{-1}$ (n=151).

> *The average NEE of CO_2 over <u>temperate lakes</u> is calculated to be -621.17$mgCO_2 \cdot m^{-2} \cdot d^{-1}$ (n=155)[61]. An unproportionally large amount of the lakes presented in this figure is however small (area) and shallow lakes. The Trolle et al. (2012) research did not show a correlation between CO_2 efflux and lake size and depth, which correlates with research by other authors such as Bastviken et al. (2004, 2008) and Juutinen et al. (2009). However, when lakes are substantially larger, such as the two Minnesota lakes mentioned, average CO_2 efflux estimations might be substantially altered.*

Finally, the NEE of CO_2 in tropical lakes were measured by Xing et al. (2005), who found the NEE of a shallow subtropical lake in China to be -332.3 $mgCO_2 \cdot m^{-2} \cdot d^{-1}$ and Tremblay et al. (2005) who collected data from two French-Canadian reports on CO_2 from tropical lakes. The reports found the average NEE of CO_2 for a number of lakes in French Guiana to be -734 $mgCO_2 \cdot m^{-2} \cdot d^{-1}$ (n=3) with values ranging from -51 to -1232 $mgCO_2 \cdot m^{-2} \cdot d^{-1}$. The data on tropical lakes is regrettably extremely sparse, and despite intensive research, it has not been possible to find more data than what was presented here.

Table 15: NEE of CO_2 from lakes

Biome		*Country*	*n*	*NEE of CO_2*	*min*	*max*	*Source*
BOREAL Lakes		*Finland*	*1*	*-776.1*			*Huotari (2011)*
		Finland	1	-545.6			López Bellido et. al. (2011)
		Canada	12	-953.0	-2202.5	104.8	Tandoléké (2012)
		Netherlnds	5	-1485.1	-2999	240.0	Schrier-Uiji et. al.(2011)
		Canada	43	-1085.5	-3597	4,434.0	Tremblay et. al.(2005)
	Total/Average/Range		*62*	***-1078.4***	*-3597*	*4,434.0*	
	- Standard deviation			*283.0*			
TEMPERATE Lakes		US	2	-482.0	-964.059	0.0	Striegl and Michmerhuzen (1998)
		US	*1*	*-87.6*			Buffam et. al. (2011)
		England	*1*	*-1760.4*			Casper et. al. (2000)
		Denmark	151	-619.0	-3000	310.0	Trolle et. al. (2012)
	Total/Average/Range		*155*	***-621.2***	*-3000*	*310.0*	
	- Standard deviation			*636.6*			
TROPICAL Lakes		China	1	-332.3			Xing et. al. (2005)
		French Guiana	3	-734.0	-1232	-52.0	Therrien (2004) in Tremblay et. al.(2005)
	Total/Average/Range		*4*	***-633.6***	*-1232*	*-52.0*	
	- Standard deviation			*616.5*			

7.2 NEE of CH_4 in lakes

Bastviken et al. (2011) recently compiled a number of reports on methane gas from freshwater ecosystems. The report found the net ecosystem exchange of boreal (n=22), temperate (n=15) and tropical lakes (n=29) to be -52.61, -65.08 and -124.46 $mgCH_4 \cdot m^{-2} \cdot d^{-1}$, respectively. These results lack transparency, which makes them hard to verify, but the criteria match the requirements defined earlier.

Among others, Tremblay et al. (2005) conducted a number of studies in seven boreal lakes in Canada. They found the NEE to be between 0.1 and -33.0$mgCH_4 \cdot m^{-2} \cdot d^{-1}$ averaging -11.3 $mgCH_4 \cdot m^{-2} \cdot d^{-1}$ (n=7). Other studies on boreal lakes include the urban boreal lake in Fin-

[61] An overview of the data on temperate lake CO_2 emissions is presented in Table 15, p. 70

land mentioned earlier by López Bellido et al. (2011) who estimated the NEE of CH_4 to be -3.9$mgCH_4 \cdot m^{-2} \cdot d^{-1}$.

The average NEE of CH_4 over <u>boreal lakes</u> is calculated to be -41.4 $mgCH_4 \cdot m^{-2} \cdot d^{-1}$ (n=30)[62]. Other research include two oligotrophic and the three eutrophic lakes in the Netherlands mentioned earlier (Schrier-Uijl et al., 2011). The average NEE of CH_4 in these lakes were -136.32$mgCH_4 \cdot m^{-2} \cdot d^{-1}$ (n=5), and the report showed no relationship between lake trophic status and methane emissions. Interestingly, one of the oligotrophic lakes in the study was found to release substantially higher amounts of CH_4 than the others, namely -434.4 $mgCH_4 \cdot m^{-2} \cdot d^{-1}$. The literature however does not provide any possible explanation for this. Also, the results by Schrier-Uijl et al. (2011) sadly lacked CH_4 emission data from winter, and late summer, which is why they are not included above. The results witness that there might be more to the picture painted here.

For temperate lakes, the research by Bastviken et al. (2011) found the average NEE of CH_4 in temperate lakes to be -65.08 $mgCH_4 \cdot m^{-2} \cdot d^{-1}$ (n=15). Additionally, Striegl and Michmerhuizen (1998) found that the Williams Lake, which had 2-4 years of hydraulic residence time[63], had a NEE of CH_4 of -70.14 $mgCH_4 \cdot m^{-2} \cdot d^{-1}$, while the Shingobee Lake, which had a shorter hydraulic residence time (0.3-0.4 years) and a much higher input of dissolved organic carbon (DOC) (close to 13 times higher), were similar to those of the Williams Lake, and both only slightly higher than the Bastviken et al. (2011) review on NEE of CH_4 from temperate lakes, namely -83 $mgCH_4 \cdot m^{-2} \cdot d^{-1}$. Other research include Casper et al. (2000) who measured the NEE of CH_4 over a very small lake in Priest Pot, England to have a NEE of CH_4 of -192.51 $mgCH_4 \cdot m^{-2} \cdot d^{-1}$, which corresponds with Bastviken et al. (2004) who found a very strong and negative relationship between the lake area and methane emissions (as will be discussed later) and the study by Buffam et al. (2011) on the Wisconsin lake district, where the authors found the average NEE of CH_4 to -8.21 $mgCH_4 \cdot m^{-2} \cdot d^{-1}$. The research by Casper et al. (2000) also underlined the importance of including ebullition fluxes, which traditionally have often been ignored or overlooked when measuring methane emissions from lakes (Bastviken et al., 2011; McCully, 2006; Tremblay et al., 2005). In the case of the small lake in Priest Pot, England, Casper et al. (2000) estimated that 96% of the total methane emissions were lost by ebullition.

The average NEE of CH_4 over <u>temperate lakes</u> is calculated to be -70 $mgCH_4 \cdot m^{-2} \cdot d^{-1}$ (n=19)[64].

For NEE of CH_4 in tropical lakes, Xing et al. (2005) did estimate on a shallow lake in China and found the NEE of CH_4 in the lake to be-23.3 $mgCH_4 \cdot m^{-2} \cdot d^{-1}$ which is substantially lower than the average found in the literature review done by Bastviken et al. (2011) (-124.46 $mgCH_4 \cdot m^{-2} \cdot d^{-1}$) (n=29). Other research include Engle and Melack (2000) who did research on an dendritic[65] lake located in the Amazon Basin, and estimated the average NEE of CH_4 to -163 $mgCH_4 \cdot m^{-2} \cdot d^{-1}$.

The average NEE of CH_4 over <u>tropical lakes</u> is calculated to be -122.4$mgCH_4 \cdot m^{-2} \cdot d^{-1}$ (n=31)[66].

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[62] An overview of the data on boreal lake CH_4 emissions is presented in Table 22, p.84
[63] The average travel time for a particle of water through a reservoir or other bodies of water
[64] An overview of the data on temperate lake CH_4 emissions is presented in Table 22, p.84
[65] Having a branched form resembling a tree
[66] An overview of the data on tropical lake CH_4 emissions is presented in Table 22, p.84

Table 16: NEE of CH_4 from lakes

Biome	Country	n	NEE of CH_4	min	max	Source
BOREAL Lakes	Lat >54°	22	-52.6			Bastviken et. al. (2011)
	Canada	7	-11.3	-33	0.1	Tremblay et. al.(2005)
	Finland	1	-3.9	-19.09	0.0	López Bellido et. al. (2011)
Total/Average/Range		*30*	***-41.3***	*-52.61*	*0.1*	
TEMPERATE Lakes	Lat 25°-54°	15	-65.1			Bastviken et. al. (2011)
	US	*2*	*-76.6*	*-83.0*	*-70.1*	Striegl and Michmerhuzen (1998)
	US	*1*	*-192.5*			Casper et. al. (2000)
	US	1	-8.2			Buffam et. al. (2011)
Total/Average/Range		*19*	***-70.0***	*-192.5*	*-8.2*	
TROPICAL Lakes	Lat <24°	29	-124.5			Bastviken et. al. (2011)
	China	1	-23.3			Xing et. al. (2005)
	Brazil	1	-163.0			Engle and Melack (2000)
Total/Average/Range		*31*	***-122.4***	*-163.0*	*-23.3*	

7.3 NEE of CO_2 in reservoirs

A complete list of reservoirs with detailed information can be found in appendix 1.

The NEE of CO_2 in boreal reservoirs ranges from 1195 to -6703 $mgCO_2 \cdot m^{-2} \cdot d^{-1}$. In general, there is a clear relationship between reservoir age and CO_2 emissions, to a lesser degree between reservoirs, but to a large degree when looking at the same reservoirs over several years. In the aforementioned research by Tremblay et al. (2005), the authors measured the average NEE of CO_2 from three boreal Canadian reservoirs <10 years. The La Forge 1 reservoir was measured at age two where the NEE of CO_2 were almost double compared to research done by Tadonléké et al., (2012) five years later (-892 at age 7 compared to -2062 $mgCO_2 \cdot m^{-2} \cdot d^{-1}$ at age 2). Similar trends were seen with respect to the Sanite-Marguerite 3 Reservoir (-5484 at age 5 and -6703 $mgCO_2 \cdot m^{-2} \cdot d^{-1}$ at age 1). Santos et al., (2006) and Abril, (2005) both did measurements on the Samuel reservoir in the Amazon region of Brazil. The reservoirs where flooded in 1989, and measurements carried out in 1998, 1999 (Dos Santos et al., 2006) and 2004 (Abril, 2005). The results show a similar trend with those presented before. The NEE of CO_2 from the reservoir was measured to be -8087 (at 9 years), -6087 (at 10 years) and -3345 (at 15 years) $mgCO_2 \cdot m^{-2} \cdot d^{-1}$. The same pattern is furthermore evident for methane fluxes, where values for the same case respectively were -183.6, -27.2 and -24.4 $mgCH_4 \cdot m^{-2} \cdot d^{-1}$. With very few exceptions, the trends presented here correspond with the theory that reservoirs have a larger release of GHG's immediately after flooding, which will then fade out over time, eventually leveraging at values similar to those of lakes and rivers.

> *The average NEE of CO_2 over boreal reservoirs is calculated to be -1450.4 $mgCO_2 \cdot m^{-2} \cdot d^{-1}$(n=64)[67], with some reservoirs being large carbon sinks and other large sources of CO_2.*

Only very few studies have been conducted on *temperate reservoirs* (Bastviken et al., 2011; Liu et al., 2011a; Tremblay et al., 2005), and of these the youngest reservoir with regard to CO_2 emissions was 22 years old. This has undoubtedly caused the average NEE of CO_2 of this biome to appear unreasonably low. The average NEE found here also seems quite uncertain when considering the average for both the boreal and tropical reservoirs. Part of the low CO_2 can also be attributed to the fact that the (Wang et al., 2011) and (Soumis et al., 2004) studies

[67] An overview of the data on boreal reservoir CO_2 emissions is presented in Table 17, p. 73

only included diffusive fluxes of CO_2, which are however thought to attribute more than 90% of the total CO_2 flux (Borges et al., 2011; dos Santos et al., 2006).

The average NEE of CO_2 over <u>temperate reservoirs</u> is calculated to be -837 $mgCO_2 \cdot m^{-2} \cdot d^{-1}$ (n=7)[68].

The study by dosSantos et al. (2006) on tropical reservoirs is especially interesting, as they did measurements on a number of tropical reservoirs over two years. All but the 37 year old Três Marias Reservoir confirmed the notion that older reservoirs emit less GHGs, but also, it confirms that there are situations where reservoirs, like lakes and wetlands can change characteristics from one year to another. The tropical reservoirs are contrary to temperate reservoirs quite young, which will have altered the picture in a way where tropical reservoirs on average seems to emit more GHG's than they actually do. This will be discussed later.

The average NEE of CO_2 over <u>tropical reservoirs</u> is calculated to be 3159.9 $mgCO_2 \cdot m^{-2} \cdot d^{-1}$ (n=29)[69].

Table 17: NEE of CO_2 from reservoirs

Biome	*Country*	*n*	*NEE of CO_2*	*Min*	*Max*	*Source*
BOREAL Reservoirs	Canada	44	-1536.7	-5754	1032	Tremblay et. al. (2005)
	Canada	7	-796.1	-2426	-316	Demarty et. al. (2009)
	Canada	4	-2834.1	-6703	-892	Tadonléké (2011)
	Canada	2	-2425.0	-3450	-1400	Kelly et. al. (2004)
	US	3	668.7	349	1195	Suomis et. al. (2004)
	Sweden	1	-880.0			Åberg et. al. (2004)
	Finland	3	-1525.3	-660	-352	Huttunen et. al. (2003)
Total/Average/Range		64	**-1450.4**	-6703.0	1195.0	
TEMPERATE Reservoirs	US	3	-362.3	-1247	1186	Suomis et. al. (2004)
	China	4	-1192.5	-2068	-660	Wang et. al. (2011)
Total/Average/Range		*7*	***-836.7***	*-2068.0*	*1186.0*	
TROPICAL Reservoirs	Brazil	18	-4173.4	-10433	142	Santos et. al. (2006)
	Brazil	1	-3344.0			Guérin et. al. (2006)
	Brazil	1	-3345.0			Abril et. al. (2005)
	Brazil	1	-3300.0			Kemenes et. al. (2011)
	Brazil	4	-632.8	-3895	5853	Roland et. al.(2010)
	French Guiana	1	-5765.0			Abril et. al. (2005)
	Laos PDR	2	-330.6	-1365	704	Chanudet et. al. (2011)
Total/Average/Range		*28*	***-3359.5***	*-10433.0*	*5853.0*	

7.4 NEE of CH_4 in reservoirs

In general, reservoirs share many of the same characteristics as lakes, some of which has been discussed above. Hence much attention will not be given to methane emissions but will rather be discussed in comparison to lakes in the discussion on variables affecting the aquatic ecosystems in the following chapters.

The average NEE of CH_4 over <u>boreal reservoirs</u> is calculated to be -11.6 $mgCH_4 \cdot m^{-2} \cdot d^{-1}$ (n=41) the average NEE of CH_4 in <u>temperate reservoirs</u> is

[68] An overview of the data on temperate reservoir CO_2 emissions is presented in Table 17, p. 73

[69] An overview of the data on tropical reservoir CO_2 emissions is presented in Table 17, p. 73

-31 $mgCH_4 \cdot m^{-2} \cdot d^{-1}$(n=6) , and the average NEE of CH4 in tropical reservoirs is-79.4 $mgCH_4 \cdot m^{-2} \cdot d^{-1}$ (n=20) [70].

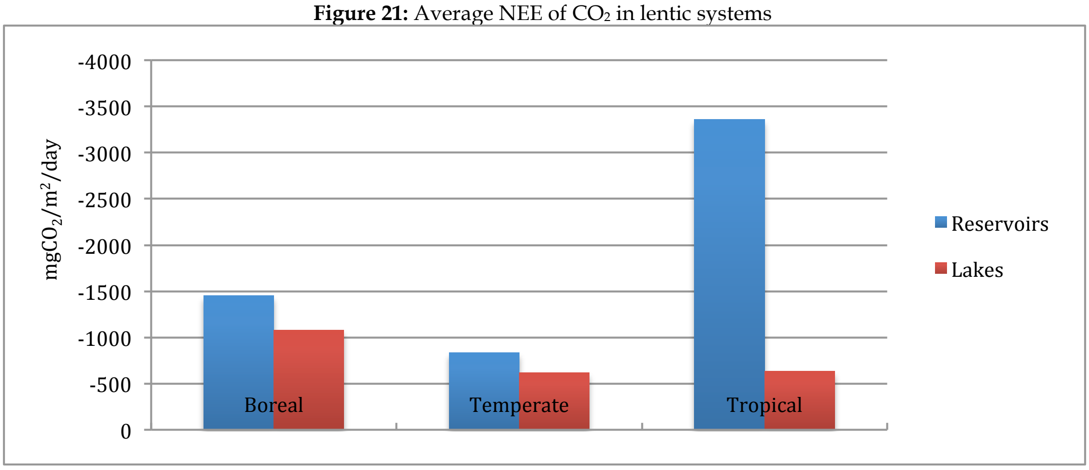
Table 18: NEE of CH_4 from reservoirs

Biome	Country	n	NEE of CH4	min	max	Source
BOREAL Reservoirs	Canada	28	-14.2	-113	5	Tremblay et. al. (2005)
	Canada	6	-0.6	-2.29	0.14	Demarty et. al. (2009)
	Canada	2	-10.5	-13	-8	Kelly et. al. (2004)
	US	3	-5.5	-9	-3.2	Suomis et. al. (2004)
	Finland	2	-18.6	-33.6	-3.5	Huttunen et. al. (2003)
Total/Average/Range		*41*	***-11.6***	*-113.0*	*5.0*	
TEMPERATE Reservoirs	US	3	-6.9	-9.5	-4.2	Suomis et. al. (2004)
	China	1	-6.2			Chen et. al. (2011)
	China	1	-2.8			Zheng et. al. (2011)
	Switzerland	1	-156.0			Eugster et. al. (2011)
Total/Average/Range		*6*	***-31.0***	*-156.0*	*-2.8*	
TROPICAL Reservoirs	Brazil	18	-84.3	-328.2	-7.9	Santos et. al. (2006)
	Brazil	1	-24.4			Abril et. al. (2005)
	Brazil	1	-33.7			Guérin et. al. (2006)
	Brazil	1	-47.0			Kemenes et. al. (2011)
	French Guiana	1	-46.0			Abril et. al. (2005)
Total/Average/Range		*22*	***-75.8***	*-328.2*	*-7.9*	

7.5 Preliminary discussion on lakes and reservoirs

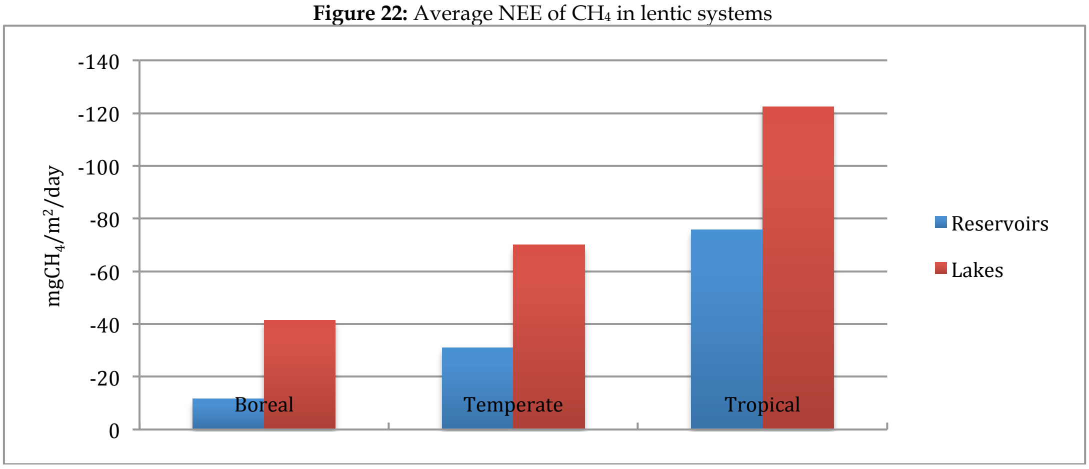
In the results presented here, CO_2 emissions have been found to be slightly higher in boreal and temperate reservoirs than lakes, and much higher in the tropical region, while the opposite is the case for CH_4 fluxes.

Figure 21: Average NEE of CO_2 in lentic systems



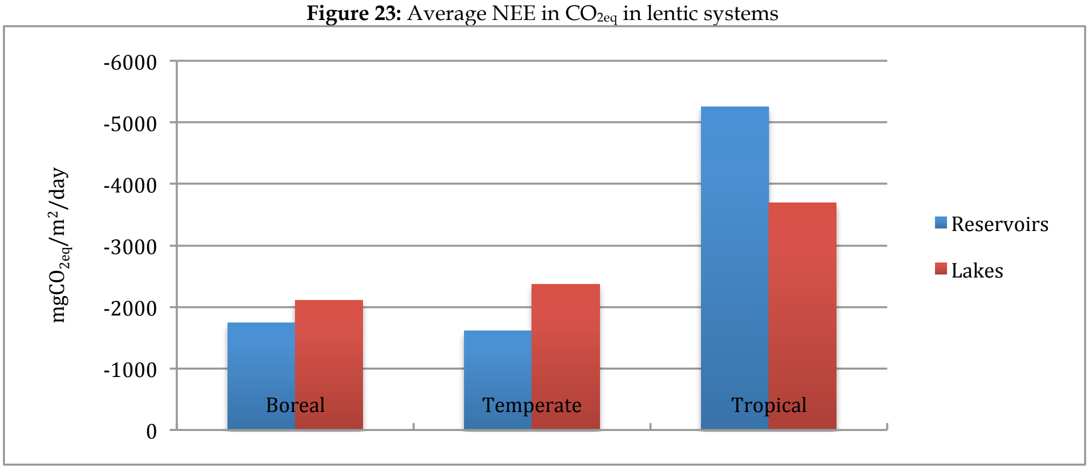
[70] An overview of the data on reservoir CH_4 emissions is presented in Table 18, p. 74

Figure 22: Average NEE of CH_4 in lentic systems



The total flux in CO_2 equivalents show that the average GWP of reservoirs, compared to lakes, are slightly lower in the boreal (-1740 vs. -2112 $mgCO_{2eq} \cdot m^2 \cdot d^{-1}$) and temperate biome (-1611 vs. -2371 $mgCO_{2eq} \cdot m^2 \cdot d^{-1}$), and substantially higher in tropical regions (-5194 vs. -3661 $mgCO_{2eq} \cdot m^2 \cdot d^{-1}$).

Figure 23: Average NEE in CO_{2eq} in lentic systems



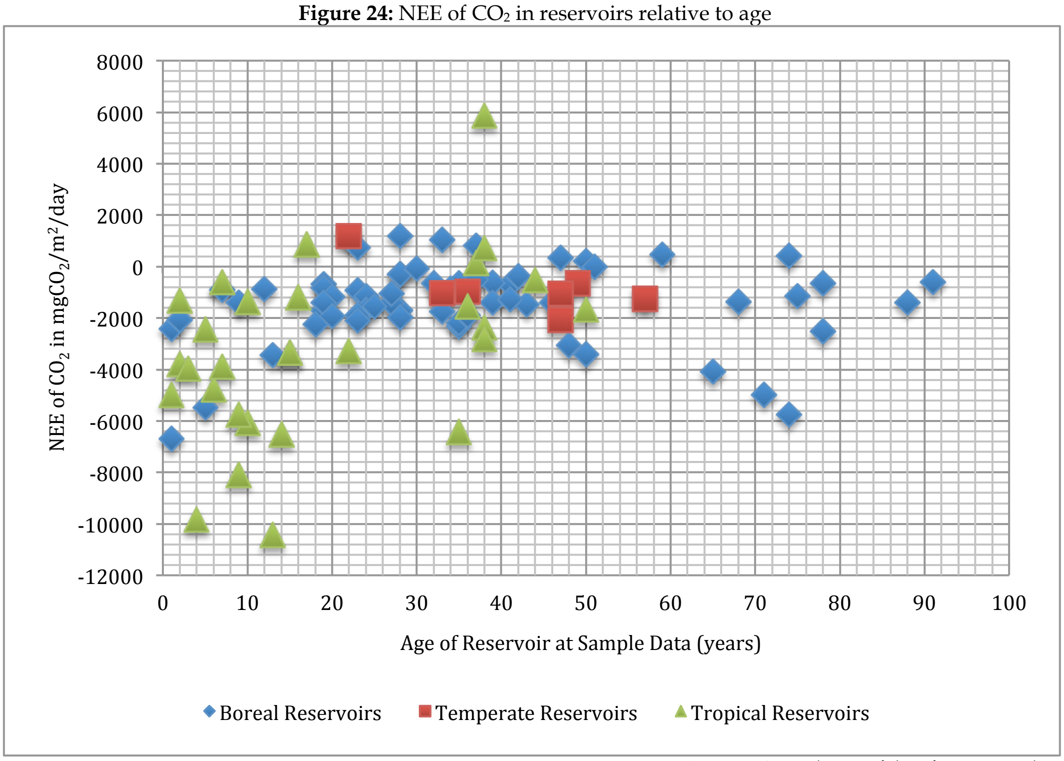
Due to the opaqueness of the Bastviken report, it has not been possible to make a percentage comparison, as it was done for the terrestrial biosphere.

Also, in the estimates, temperate reservoirs distinguish themselves in having the lowest average CO_2 emissions. This is partly expected to be the result of the relatively few cases included, but most importantly the fact that none of the temperate reservoirs included in the study of CO_2 were young reservoirs. It has been argued that age is a fundamental factor in understanding GHG emissions for hydroelectric reservoirs. It is therefore critical in understanding these averages that the age distribution is very different between the reservoirs. For the boreal biome, the age span lies between 1 and 91 years, for the temperate biome between 5 and 87 and tropical biome between 1 and 50 years, which favor the tropical regions. According to the two figures below (Figure 24 and Figure 25), it does, however still seem palpable that emissions are generally higher in the tropical biome. In these figures, the temperate biome values also seem to appear in between average NEE values for boreal and tropical reservoirs, relative to age, as is expected. Finally, to acknowledge the high age dependence of NEE values, it is obvious that some kind of compensation must be made when calculating the climate effect of a specific dam[71].

[71] This has been done in the case-chapters. For references, please see chapter 14.2.1 p. 127.

Like lakes, older reservoirs can be both sinks and sources of GHGs, while younger reservoirs (<17 years) are all sources. Indeed it also seems like– *there are both "good" dams, and "bad" dams*. While some of the very young reservoirs, such as the Eastmain-1 and the La Forge 2 reservoir in Ontario, Canada (1 and 2 years at sampling), emitted only slightly more than the average for the region - and for the biome; some of the older reservoirs, such as the 34 year old Brazilian reservoir, the Berra Bonita; and the 74 year old Canadian Great Falls reservoir, which both respectively were found to emit more than double and more than triple of the biome average (-6434 and -5754 $mgCO_2 \cdot m^{-2} \cdot d^{-1}$). This happens despite the inclusion of many very young reservoirs, for example the Tucurui, the Samuel, the Miranda and the Xingó reservoirs in Brazil (-10,433 to -4980 $mgCO_2 \cdot m^{-2} \cdot d^{-1}$), as well as the Sanite-Marguerite 3 and the Opinaca reservoirs in Canada (-6703 to -3403 $mgCO_2 \cdot m^{-2} \cdot d^{-1}$). *For references, please see appendix 1.*

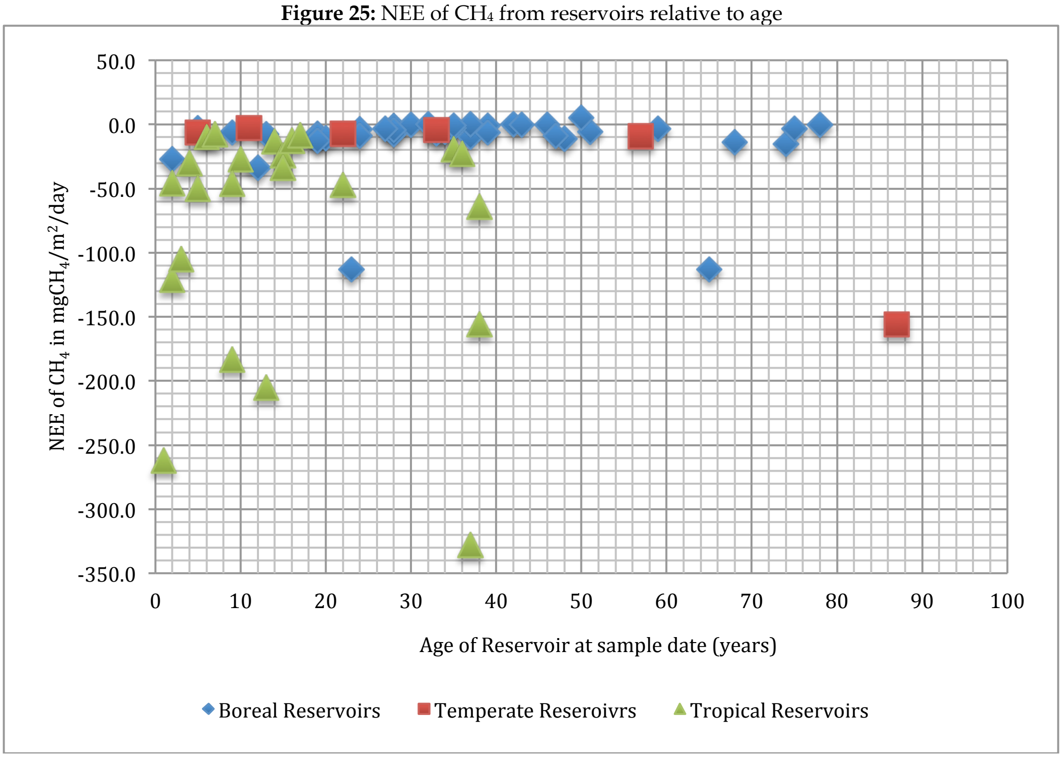
Figure 24: NEE of CO_2 in reservoirs relative to age



Sources: Compilation of data from appendix 1

For methane gas and reservoir age, the picture is the same as it was with CO_2. In general, the average release of methane from reservoirs seems significantly lower than the average releases of methane from lakes. This was to be expected as the great turnover of water in hydroelectric reservoirs probably affects the stratification of the reservoir, resulting in that more methane will be oxidized than what was otherwise the case. While the overall trend generally is as described, a few reservoirs stand out. One is the 2-year-old boreal Sante-Marguerite 3 in Canada, which was mentioned before as one of the younger reservoirs with very high releases of CO_2. With regard to CH_4, the reservoir stands out as one of the good examples with very low emissions compared to the region and the biome average (NEE of CH_4 of -2.7 $mgCH_4 \cdot m^{-2} \cdot d^{-1}$). The same is the case for 6 year old tropical Segredo reservoir in Brazil (NEE of $CH_4$of -9.9 $mgCH_4 \cdot m^{-2} \cdot d^{-1}$) and the biggest hydropower dam in the world, the 5 year old Three Gorges Reservoir in temperate China (NEE of CH_4 of -6.2 $mgCH_4 \cdot m^{-2} \cdot d^{-1}$). For the older reservoirs, especially three stand out as very bad examples. One is the 65 year old boreal Slave Falls reservoir in Canada (NEE of CH_4 of -113 $mgCH_4 \cdot m^{-2} \cdot d^{-1}$), another is the 87 year old temperate reservoir Lake Wohlen, Switzerland (NEE of CH4 of -156 $mgCH_4 \cdot m^{-2} \cdot d^{-1}$), and the last is the 37 year old tropical Brazilian reservoir, Três Marias (NEE of CH4 of -328.2 $mgCH_4 \cdot m^{-2} \cdot d^{-1}$). *For references, please see appendix 1.*

Figure 25: NEE of CH_4 from reservoirs relative to age



Sources: Compilation of data from appendix 1

Finally, Figure 24 and Figure 25 above show a relatively large spreading of the values in between the same years for the tropical biome, compared to those for the boreal and temperate biome, which are both more uniform. This might to some degree reflect the different types of managements, that some sites have been cleared prior to flooding, that this happens more often in boreal and temperate regions etc. etc. Either way, it reflects a situation, in which tropical reservoirs bears an increased risk of turning out as very bad examples.

7.6 Disparity between lakes and reservoirs

As it has been indicated, reservoirs are on average releasing higher amounts of CO_2-, and fewer methane emissions than lakes. This is consistent with the theory (i.e. Bergstrom et al. (2004) and Tadonléké et al. (2012)), which suggests that high turnover rates in reservoirs cause more methane to be oxidized before it reaches the surface compared to lakes.

While the mechanisms that control CO_2 emissions in lakes and reservoirs, have been found to be identical; the magnitude of the variables seems to vary significantly (Tadonléké et al., 2012). For methane, no comparisons between the mechanisms that control CH_4 emissions in lakes and reservoirs has (as far as is known) been made so far, but the fact that there is a relationship between methane oxidation and CO_2 emissions indicates that there must be some kind of relationship between the two. However, this relationship can not be understood as if when CO_2 emissions are high, CH_4 emissions will below – see for example 'Slave Falls', 'Tucurai', 'Trés Marias' and others in Appendix 1.

As a good measure, it must also be pointed out that not all reservoirs that share characteristics with lakes do necessarily emit more CO_2. Åberg et al. (2004) compared a reservoir and a lake in the northern part of Sweden which shared the same drainage area. While the sediments were the main source of CO_2 in the reservoir, mineralization[72] in the water column was the more pronounced contributor of CO_2 from the natural lake. For the two, the total flux was similar during the summer periods, but during winter time the mineralization continued in the natural lake, while the hydroelectric reservoir was slowly emptied for electricity produc-

[72] Mineralization refers (in biology) to a process where an organism produces an inorganic substance - such as CO_2.

tion, consequently causing a rapid decline in CO_2production rates. On an annual basis, the lake therefore released more CO_2 than did the reservoir.

Table 19: The basic difference between lakes and reservoirs

Lakes:	Reservoirs:
1. While lakes usually have higher temperatures, lower dissolved organic matter (DOM) quality (which have been known to influence the microbial metabolism more than DOC concentrations) and a larger size of daphnia and zooplankton 13C, (Tadonléké et al., 2012)…	2. … reservoirs stand out by exhibiting "a more pronounced horizontal heterogeneity in physicochemical characteristics" (Tadonléké et al., 2012) and a shorter water residence time. 3. … Also, reservoirs lack the lakes classic limnological features of especially temperate lakes, such as "persistent thermal stratification and epilimnetic nutrient depletion associated with physical structuring of the water column" (Tadonléké et al., 2012) 4 … Additionally, reservoirs because of their larger drainage ratio, may receive higher inputs of allochtonous material than lakes (Moss, 2008).

For $CO_{2,}$ the process that happens in lakes and reservoirs seems akin, but unalike in importance and magnitude, which is probably caused by the dissimilarity in horizontal water movements (Åberg et al., 2004; St Louis et al., 2000). Accordingly, Tadonléké et al. (2012) also tested the hypothesis that lakes and reservoirs are alike – and more precisely "*if the relative importance of factors explaining CO_2 emissions in reservoirs is similar to that in natural lakes*". They did so by examining four reservoirs and 11 nearby lakes in Quebec Canada, which all shared the same watersheds. What the research showed was that variations in water temperatures and/or the quality of DOM between lakes and reservoirs resulted in differences in interactions within plankton communities, and therefore the relative importance of the factors and their influences on CO_2 emissions.

With regard to lakes, variations in CO_2 emissions seemed as though they could partly be explained by lake temperature (negative relationship) and bacterial production (BP) (positive relationship), while DOM quality and the phytoplankton[73]/microheterotrophic[74] biomass ratio were of much higher explanatory value in reservoirs. Reservoirs CO_2 emissions were correspondingly positively related to former and negatively related to the latter. Generally, the temperature difference between lakes and reservoirs was the strongest explanatory factor of CO_2 variations, followed by bacterial production and phytoplankton/microheterotrophic ratio (Tadonléké et al., 2012).

7.7 Variables affecting CO_2 emissions from lentic systems

Lakes and reservoirs due to their intimate contact with the surrounding landscape can be understood as sentinels tracking changes in their catchments (Cole et al., 2007) and are despite earlier beliefs far from being in equilibrium with the atmospheric CO_2 (and CH_4) concentrations. In fact, lentic systems are most often substantial sources of GHG's to the atmosphere (they are net heterotrophs, GPP < R), which probably is because of their sizable supply and substantial degradation of allochtonous[75] organic material from the surrounding landscape (Sand-Jensen and Staehr, 2007), and for a smaller part, an additional groundwater input of CO_2, contributing to super-saturation of CO_2 in the water of most lakes and reservoirs (Furukawa et al., 2005). The fate of lakes and reservoirs as net sources or sinks of atmospheric CO_2 is connected to concentrations of total phosphorus (TP), phytoplankton biomass (Chl *a*), dissolved organic carbon (DOC) and the trophic status of the lake. These, and other, variables will be discussed here. It does however not make sense to present them in a table as it has been done hitherto, as the variables to a great extend need to be understood in relation to one another.

[73] Photosynthesizing microscopic organisms.
[74] Heterotrophs are organisms that cannot fix carbon, and use organic carbon for growth.
[75] In limnology, allochtonous sources of carbon or nutrients come from outside the aquatic system (such as plant and soil material).

For example Hanson et al. (2003) investigated the relationship between DOC concentrations and TP in 25 lakes and found that the GPP were strongly affected by TP, whereas R was strongly correlated with DOC (NEE = GPP - R). In the study, the relationship between GPP, R and DOC changed over a gradient of DOC, and showed a unimodal graph with a hump when DOC was about $10mg \cdot L^{-1}$. Below this concentration, both GPP and R rose but above this concentration R continued to increase, while GPP decreased. Overall, the study showed that when DOC concentrations were low, GPP and R were nearly equal, and when DOC concentrations were high, R uncoupled and the systems became *heterotroph*. When TP was high and DOC low, the system was on the other hand more likely to become *autotrophs* (GPP > R) as TP and hence GPP reacted slightly more strongly to low DOC concentrations, than R. As there is an almost linear relationship between TP concentration and Chl *a* concentrations in water bodies (Dillon & Rigler, 1974), this indicates a negative relationship between Chl *a* and NEE. This relationship has however been found to be much more evident in large lakes, than small lakes (Sand-Jensen and Staehr, 2007).

Sand-Jensen and Staehr (2007) looked at the pelagic[76] metabolism in 64 small lakes in North Sealand, Denmark, relative to size and forest cover. First of all, they found that light availability increased with lake size, while nutrient availability, phytoplankton biomass and DOC declined. In effect, this means that lake size might reduce the magnitude of the *areal fluxes* of CO_2 (e.g. pr. m^2). It should not be misunderstood with relation to the *total flux* pr. lake, as larger lakes are usually larger sources than smaller lakes, just not necessarily pr. unit area (Bastviken et al., 2004). With regard to forest cover, forest lakes had substantially larger net heterotrophic traits, compared to open lakes. This is attributed to a higher light attenuation (lower light availability), increased DOC (and consequent increased R) and increased incidences and strengths of CO_2 super-saturation. To exemplify, the study by Sand-Jensen and Staehr (2007) found a 20 to 30 fold CO_2 super-saturation in the smallest forest lakes, compared to the largest open lakes.

Clark and Fritz (1997) investigated the relationship between GHG's and pH, and found that pH values higher than 8 favours the formation of bicarbonate instead of dissolved CO_2 in aquatic ecosystems, which then leads to an undersaturation of dissolved CO_2 - thereby stimulating the ability of these systems to absorb more atmospheric CO_2. This corresponds with research by Tremblay et al. (2005) on a total of 1997 measurements in the aforementioned Canadian ecosystems (rivers, lakes and reservoirs) where the authors found a mean flux of CO_2 of -1684 $mgCO_2 \cdot m^{-2} \cdot d^{-1}$ for pH<7.9 (n=1744) and -15 $mgCO_2 \cdot m^{-2} \cdot d^{-1}$ for pH>7.9 (n=253). A similar relationship was found for CH_4 fluxes where the average NEE of CH_4 in samples with a pH<7.2 was-68.9 $mgCH_4 \cdot m^{-2} \cdot d^{-1}$ (n=524) and for samples with a pH>7.2, -4.5 $mgCH_4 \cdot m^{-2} \cdot d^{-1}$ (n=105).

Finally, this also correlates with the study of Trolle et al. (2012) who over a 20 year period collected data form 151 shallow (<3m) temperate lakes in Denmark partly in order to determine the influence of lake tropic status. The research found that CO_2 fluxes where strongly negatively correlated with pH, as described above. But, conversely the study also found that lake trophic status, being a proxy for pelagic production, seemed to interact with the acid neutralizing capacity (ANZ) of the lakes and consequently pH, which would then affect the equilibrium between the free CO_2 and bicarbonate production as described above. Or, in other words, the CO_2 efflux decreases as the tropic status increases.

[76] Open water, that is: not close to the bottom or close to the shore

Table 20: Trophic status relative to Chlorophyll and Phosphorus (in $\mu g \cdot L^{-1}$)

	Chl	*P*
Oligotrophic	0-2.6	0-12
Mesotrophic	2.6-20	12-24
Eutrophic	20-56	24-96
Hypereutrophic	56-155+	96-384+

Source: (Carlson and Simpson, 1996)

7.8 Variables affecting CH_4emissions from lentic systems

Basically, there are four emission pathways of methane gases from the aquatic systems;

1) Ebullition flux
2) Diffusive flux
3) Storage flux, and;
4) Flux through aquatic vegetation.

Each of these fluxed are briefly described here.

Ebullition flux is a direct flux of methane from the sediment to the atmosphere. Hence, the ebullition flux component is primarily dependent on a) the net methane production rate in the sediments and b) the hydrostatic[77] pressure, which has to be overcome for the bubbles to leave the sediment.

Diffusive flux of methane is the result of methane from anoxic sediment entering either oxic sediment or water. The methane-oxidizing bacteria will immediately oxidize a large proportion of the methane. Most of the methane that is not oxidized will reach the upper mixed layer of the water column and be emitted by diffusive flux. The magnitude of the diffusive flux is dependent on the difference in methane concentration between the atmosphere and the water, as well as the physical rate of exchange between air and water. Methane concentrations is a function of methane production, methane oxidation rates, pattern of methane fluxes within the lake as well as a piston velocity, dependent on turbulence and hence; the wind speed.

Storage flux is especially evident in stratified lakes, where a build-up of methane in the anoxic layer can cause methane storage in the water column. This methane will be emitted by diffusion in periods of Lake Overturn which for example happens in dimictic lakes[78]. The magnitude of the storage flux is a function of methane production rates, the volume of the anoxic water layer, and the losses by methane oxidation and diffusion to upper layers.

Flux through vegetation is dependent on methane production and oxidation in the sediments, and vegetation characteristics, as described in the chapter on wetlands and ricelands (chapter 5.2, p.57).

While the variables affecting the fluxes described above can be rather hard to measure, Bastviken et al. (2004) did an extensive research on the relationship between lake and reservoir characteristics and CH_4 over 49 cases, and found that most methane emissions can be fairly well predicted from a number of easily measured variables. These are included in this table:

[77] Relating to or denoting the equilibrium of liquids and the pressure exerted by liquids at rest (Citizendium, 2011).

[78] Dimictic lakes are holomictic lakes that mix from top to bottom during two mixing periods each year. During winter, they are covered by ice. During summer, they are thermally stratified, with temperature-derived density differences separating the warm surface waters (in the epilimnion), from the colder bottom waters (at the hypolimnion) (Kalff, 2001).

Surface water methane concentrations

The concentration of methane in surface waters is positively related to the size of the anoxic volume fraction and negatively related to the lake area and the DOC concentrations in the lake (Bastviken et al., 2004).

The reason why the size of anoxic volume fraction plays a significant role probably indicates that a large proportion of the methane in the surface water comes from the methane that is stored in the anoxic parts of the water column below the mixed surface layer and/or that methane export is less simply because lakes with a high anoxic volume fraction is less well mixed. The negative relation to the lake area is probably due to a higher piston velocity in large lakes, or due to a longer residence time and a generally larger volume - causing increased methane oxidation in the mixed layer. Bastviken et al. (2004) furthermore found a negative relationship between DOC concentrations and surface methane concentrations, for which they could not give a good explanation.

Ebullition flux

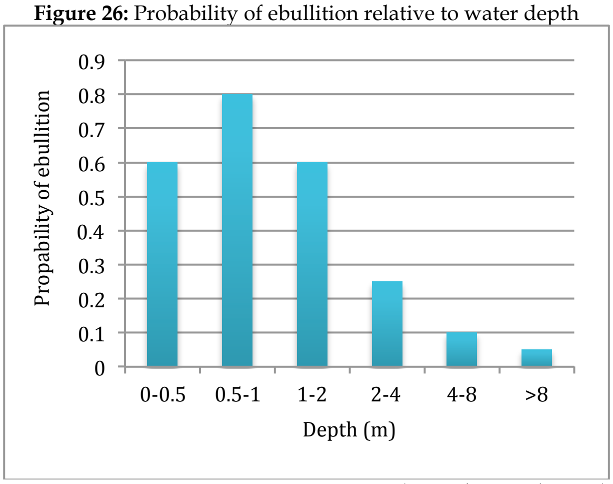
The ebullition flux is best explained from the total phosphorous concentrations, the concentration of methane in the surface waters and depth (Bastviken et al., 2004).

There seems to be a positive relationship between areal ebullition flux and the concentration of total phosphorous - probably reflecting a positive relation between nutrient load and NPP of methane in the lake. A possible explanation of the relationship between surface water methane concentration and ebullition could be that the methane concentration indirectly reflects the magnitude of the methane production and the overall methane cycling in the lake.

Finally, there is a non-linear relationship between the frequency of ebullition and water depth, with ebullition occurring in 25-80% of chambers at less than 4 meters. This depth-dependence is mainly related to air-pressure, as bubbles in the sediment under shallow waters have less hydrostatic pressure to overcome, in order to leave the sediment and be released to the atmosphere. The cooler sediments at greater depths also allows less methane to be produced than sediments in shallow waters as methanogenesis rates are sensitive to temperature (Citizendium, 2011).

Additionally, wave induced pressure changes in the littoral[79] zones, might further facilitate ebullition from shallow waters.

Figure 26: Probability of ebullition relative to water depth



Source: (Bastviken et al., 2004)

The ebullition flux is the most variable of the fluxes. *Annual ebullition flux pr. lake is best explained by total lake area.*

Diffusion flux

The diffusive flux is positively related to the storage in the pr. areal unit (Bastviken et al., 2004), again indicating that much of the methane that leaves the lake in this way comes from the deeper water layers. *The diffusive flux pr. lake pr. year is again best explained by total lake area,* (even though surface methane concentration have been found to decrease with lake size, discussed above), which is probably due to the increased gas piston velocity over larger lakes.

[79] Of, relating to, or situated on the shore of the sea or a lake

Storage flux	*The storage flux is positively related to the size of the anoxic volume fraction, however when data on the anoxic volume fraction is not available, both the concentration of methane in the surface layers and total phosphorous or dissolved organic carbon (DOC) are useful for predicting the storage flux component* (Bastviken et al., 2004), probably as the supply of substrates for microbial metabolism is important for methane gas generation. This links the storage flux to the lake area in a different manner than it was the case for the other fluxes, as larger lakes typically have a smaller catchment area (relative to its size), and therefore lower DOC concentrations (Trolle et al., 2012). The significance of the storage component however decreases with lake size, diluting the significance of this (see discussion hereafter).
Plant mediated fluxes	*Finally, the total vegetation flux is expected to decrease with lake size*, as plants primarily grow at depths less than 1.5m (Kalff, 2001).

Additional to the variables above, Xing et al. (2005) and Tadonléké et al. (2012) found a strong relationship between temperature and CH_4 flux, and a negative relationship between temperature and CO_2 flux in both lakes and reservoirs. This relationship has been refused by other research which instead have credited seasonal factors to this relationship, i.e. an increased piston velocity during winters (Bastviken et al., 2004; Trolle et al., 2012), while others again proclaim that temperature might be a minor factor in boreal and temperate regions, but possibly a significant factor contributing to increased fluxes of CH_4 in tropical regions (Tremblay et al., 2005; Xing et al., 2005).

The proportional relationship between the various methane fluxes (compared to total flux) is relative to the lake size. The storage component of CH_4 is usually a larger component in small lakes (up to 45%), compared to larger lakes where it can be somewhat insignificant (down to <5%). While the opposite is the case for diffusive fluxes (up to 50% in large lakes and down to <10% in small lakes), ebullition fluxes are relatively stable (between 40 and 60%) (Bastviken et al., 2011, 2004; Walter et al., 2001).

Finally, pH has also been found to have a strong explanatory value on methane emissions (see chapter on variables affecting NEE of CO_2 in lentic systems earlier), where a higher value of pH usually means fewer methane emissions.

Chapter 8: Net ecosystem exchange in rivers

It has been extremely difficult to find measurements of both CO_2 and CH_4 from rivers, probably partly due to the general high spatial and temporal/seasonal variability found in and along rivers. While some older research generally claim that rivers are negligible in GHG budgets (eg. Franken et al., 1992) which until recently were also in line with global GHG practices (Bastviken et al., 2011; Cole et al., 2007), more recent research have found that rivers can be significant sources of both CO_2 and CH_4 - especially when considering the total terrestrial land surface that is covered by these ecosystems (Bastviken et al., 2011). Some recent research generally find rivers to emit slightly less carbon dioxide and much less methane than lakes (Bastviken et al., 2011) while others find a much stronger similarity between both rivers, lakes and old reservoirs (Tremblay et al., 2005).

Tremblay et al. (2005) did an extensive research for Hydro Quebec covering a 5000 km transect from the west to the east coast of Canada, where the authors compared fluxes from rivers, lakes and old reservoirs. This research covered 24 boreal rivers in Canada, and is to my knowledge the most extensive continuous work on rivers over more than one year. On average, the study found the average NEE to be -1976 $mgCO_2 \cdot m^{-2} \cdot d^{-1}$ (n=24) and -3.3$mgCH_4 \cdot m^{-2} \cdot d^{-1}$ (n=24). Additionally, and confirming the picture of a relative lack of knowledge in this area, Bastviken (2011) were only able to collect data from one additional boreal river in his research on NEE of CH_4 from aquatic ecosystems besides the Tremblay et al. (2005) research. The NEE of CH_4 of the river was estimated to be -7.04 $mgCH_4 \cdot m^{-2} \cdot d^{-1}$.

The average NEE of CO_2 and CH_4 in boreal rivers is hence measured to -1976 $mgCO_2 \cdot m^{-2} \cdot d^{-1}$ (n=24) and -3.4 $mgCH_4 \cdot m^{-2} \cdot d^{-1}$ (n=25).

Other research include a literature review done by Bastviken et al. (2011) who based on research from 20 temperate rivers in the US and Europe found the NEE of CH_4 of rivers in temperate ecosystems -13.29 $mgCH_4 \cdot m^{-2} \cdot d^{-1}$ (n=20). Also, Franken et al. (1992) collected research on NEE of CH_4 from seven temperate rivers in the US. Values in this research ranged from -145 to -0.4 $mgCH_4 \cdot m^{-2} \cdot d^{-1}$, with an average NEE of -24.3 $mgCH_4 \cdot m^{-2} \cdot d^{-1}$ (n=7).

As it was the case of reservoirs, only very little data has been collected on the aquatic ecosystems in temperate regions (Bastviken et al., 2011; Liu et al., 2011a). For CO_2 in rivers, it has consequently only been possible to find data on the NEE of CO_2 from five temperate rivers. One is Telmer and Veizer (1999) who collected data from the Ottawa River, in Canada (which arguably lies in the boreal biome[80]). In their research, the NEE of CO_2 in the river was found to be -5061 $mgCO_2 \cdot m^{-2} \cdot d^{-1}$. Other research include Cole and Caraco (2001) who coupled estimates done on the partial pressure of CO_2 in the Hudson River, USA, over a number of years by Raymond et al. (1997), with hourly wind data from the meteorological station at the Institute of Ecosystem Studies. The research conservatively estimated annual NEE of CO_2 to be -1837.3 $mgCO_2 \cdot m^{-2} \cdot d^{-1}$. Additionally, the St. Lawrence River that runs from Ontario in Canada to the State of New York in the US were researched by Helie J.-F. et al. (2002), who estimated the NEE of CO_2over the river to be similar to the Ottawa River,-4621 $mgCO_2 \cdot m^{-2} \cdot d^{-1}$. Crosswell et al. (2012) estimated the air-water CO_2 flux from the microtidal[81] Neuse River Estuary, North Carolina, which due to the high inflow of saline water when the tide goes in might not pose a representative case. The research found that the NEE of CO_2 over the Neuse River Estuary were -567 $mgCO_2 \cdot m^{-2} \cdot d^{-1}$. In the study, the partial pressure of CO_2 was found to decrease with salinity, which confirms the concern that the river might not be representative in comparison with the other freshwater systems presented here. Finally, Buffam et al. (2011) conducted research on the Wisconsin lake area, mentioned earlier. The releases in these systems were substantially lower than most of those measured elsewhere.

[80] As they themselves categorize the river as temperate, so has it been done here.
[81]Microtidal estuaries are defined as estuaries having tides less than 2 meters.

The same is the case of the CO_2 efflux from the inflowing rivers. The average NEE of CO_2 of the entire river system was measured only to be -128.68 $mgCO_2 \cdot m^{-2} \cdot d^{-1}$.

The average NEE of CO_2 and CH_4 in <u>temperate rivers</u> is hence measured to be -2594.17$mgCO_2 \cdot m^{-2} \cdot d^{-1}$ (n=5) and -16.14 $mgCH_4 \cdot m^{-2} \cdot d^{-1}$ (n=27).

For the tropical biome, Bastviken et al. (2011) did a theoretical experiment to estimate the average fluxes from tropical rivers, as a consequence of the pronounced non-existence of data in this area. The measurements were based on experience from boreal and temperate rivers, as well as knowledge of the relationship between fluxes in reservoirs and lakes. Doing so, the paper estimated the NEE of CH_4 from these ecosystems to be -16.4 $mgCH_4 \cdot m^{-2} \cdot d^{-1}$. For the NEE of CO_2 from tropical rivers, it has correspondingly only been possible to find estimates on very few natural rivers. Four is presented in Wang et al. (2011), supposedly from other studies. Unfortunately, it has not been possible to find the papers which are referred to in this report, and the numbers from their own research seems unrealistically high (up to -24645 $mgCO_2 \cdot m^{-2} \cdot d^{-1}$), just as other parts of the sources used in the report seems dubious. Consequently, these have of necessity been excluded from the results presented here. The only available estimates comes from research on two subtropical rivers in Texas, North America by Zeng and Masiello (2010), who estimate the NEE of CO_2 of the two rivers to be -890 and -1454 $mgCO_2 \cdot m^{-2} \cdot d^{-1}$, and a two year measurement on the Amazon River system by Richey et al. (2002) (-2272 $mgCO_2 \cdot m^{-2} \cdot d^{-1}$).

The average NEE of CO_2 and CH_4 in <u>tropical rivers</u> is hence measured to be-1538$mgCO_2 \cdot m^{-2} \cdot d^{-1}$ (n=3) and -16.4 $mgCH_4 \cdot m^{-2} \cdot d^{-1}$ (n=0!). Victoria et al. did an extensive research in 2008 on small streams and rivers (<100m wide) which were supersaturated with CO_2 running to the Ji-Paraná basin, Brazil. These streams were emitting extremely large amounts of CO_2 (Victoria et al., 2008), but the measurements were regrettably only conducted over one day, so even though the results might have influenced the average NEE of CO_2 from large rivers substantially, they were left out. To paint a picture, the NEE of CO_2 of these systems was found in the range between -621.5 to 13087 $mgCO_2 \cdot m^{-2} \cdot d^{-1}$. Even though the results have been excluded from the study, they do nonetheless give a picture of some tropical rivers as being capable of pushing this average significantly; urging for more research on carbon fluxes from tropical rivers, and rivers in general, in order to be able to properly quantify the significance of these systems.

Table 21: NEE of CO_2 in rivers

Biome	*Country*	*n*	*NEE of CO_2*	*Min*	*Max*	*Source*
BOREAL Rivers	Canada	24	-1976.0	-2577.0	424.0	Tremblay et. al. (2005)
Total/Average/Range		*24*	***-1976.0***	*-2577.0*	*424.0*	
TEMPERATE Rivers	Canada	1	-5061.0			Telmer and Veizer (1999)
	Canada/U.S.	1	-4621.0			Helie J.-F. et. al. (2002)
	US	1	-567.0			Crosswell et. al. (2012)
	US	1	-128.7			Buffam et. al. (2011)
	US	1	-1837.3			Raymond et. el. (1997)
Total/Average/Range		*5*	***-2443.0***	*-5189.7*	*-128.7*	*Total/Average/Range*
TROPICAL Rivers	US, texas	2	-1172.0	-1454.0	-890.0	Zeng and Masiello (2010)
	Brazil	1	-2272.0			Richey et. al. (2002)
Total/Average/Range		*3*	***-1538.7***	*-2272.0*	*-128.7*	

Wang et al. (2011) also measured the NEE of CO_2 from the tropical rivers upstream of the Maotiao river, in China, on which four hydropower dams (Hongfeng, Baihua, Xiuwen and Hongyan) were built in the 60's and 70's, and downstream of the dams. The rivers were found to emit extremely large amounts of CO_2 compared to the studies presented above, indicating a possible relation with the dams, which bides the necessity to investigate this matter further in future studies. The two rivers had a NEE of CO_2 of, respectively, -15931 $mgCO_2 \cdot m^{-2} \cdot d^{-1}$ and -21521 $mgCO_2 \cdot m^{-2} \cdot d^{-1}$.

Table 22: NEE of CH_4 in rivers

Biome	*Country*	*n*	*NEE of CH_4*	*min*	*max*	*Source*
BOREAL Rivers	Canada	24	-3.3	-36.4	-0.1	Tremblay et. al. (2005)
	Lat >54°	1	-7.0			Bastviken et. al. (2011)
Total/Average/Range		*25*	***-3.4***	*-36.4*	*-0.1*	
TEMPERATE Rivers	Lat 25°-54°	20	-13.3			Bastviken et. al. (2011)
	US	7	-24.3	-145.0	-0.4	Franken et. al. (1992)
Total/Average/Range		*27*	***-16.1***	*-145.0*	*-0.4*	
TROPICAL Rivers	Lat <24°	?	-16.4			Bastviken et. al. (2011)
Total/Average/Range			***-16.4***	*-16.4*	*-16.4*	

8.1 Variables affecting the NEE of CO_2 and CH_4 from lotic systems

The large emissions of carbon dioxide from rivers might be the result of a large turnover, an increased piston velocity caused by the moving water or other factors that contribute to increased diffusive emissions from aquatic systems. These have however been discussed in the chapter on variables affecting the NEE of lentic systems earlier in this paper (p. 79f, chapter 7.7 and 7.8). Research on variables affecting the NEE from lotic systems are generally rare, but expected to be similar to those of the lentic systems (Beaulieu et al., 2012; Caraco and Cole, 2004; Crosswell et al., 2012).

8.2 Discussion

The few cases available for CO_2 in rivers (and for CH_4 in tropical rivers) is critical, especially taking into consideration the extreme values some cases have demonstrated. As discussed in the introductory chapter to aquatic systems, riverine wetlands have traditionally been understood merely as a pipe transporting carbon from the terrestrial ecosystems to ocean (Cole et al., 2007), which probably has contributed to the scarcity of data in this field. It must however also be accentuated that some of the rivers discussed are more than a thousand kilometres long, and many of the rivers are not included as only rivers, but as river systems. This includes for example Richey et al. (2002) who made estimates of various places on the Amazon river system. Buffam et al. (2011) who included all the rivers in the Wisconsin Lake area, and estimates on the nearly 1200 km long Ottawa river at which data were collected by Telmer and Veizer (1999).

The results presented leave a picture of tropical rivers as emitting slightly lower CO_2 than both boreal and temperate rivers, which is still expected partly to be a result of the very few cases from tropical regions (n=3). The low methane emissions from all river systems are expected to be the result of the well-oxidized conditions.

Figure 27: Average NEE of CO_2 from rivers

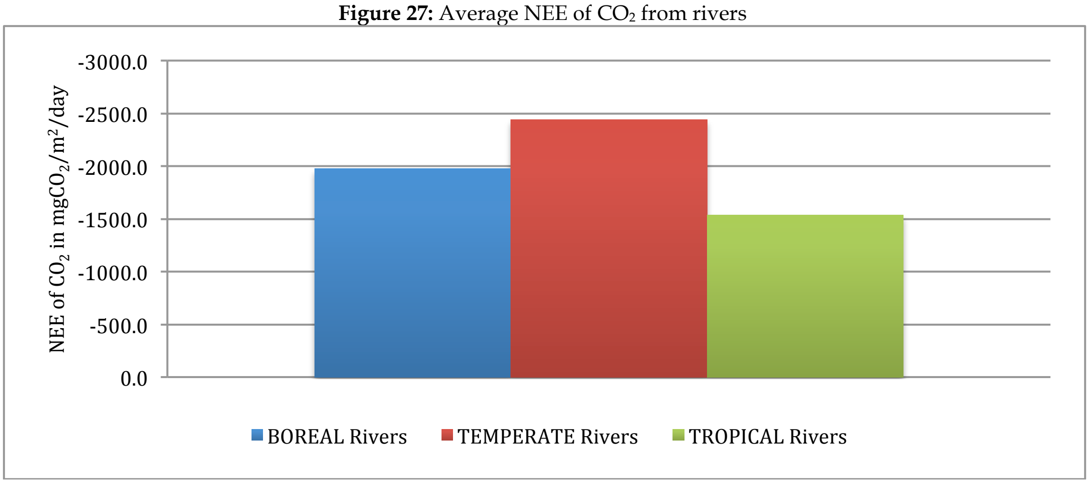
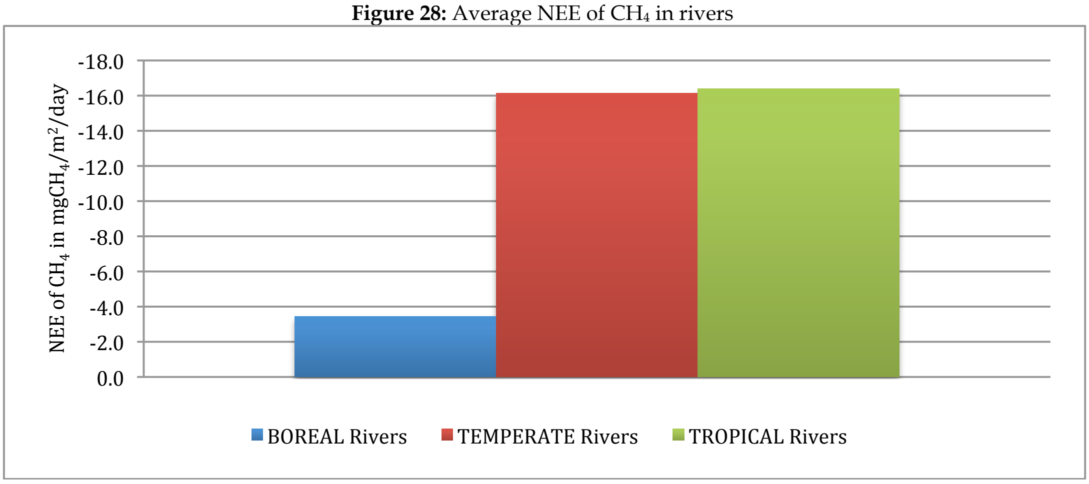


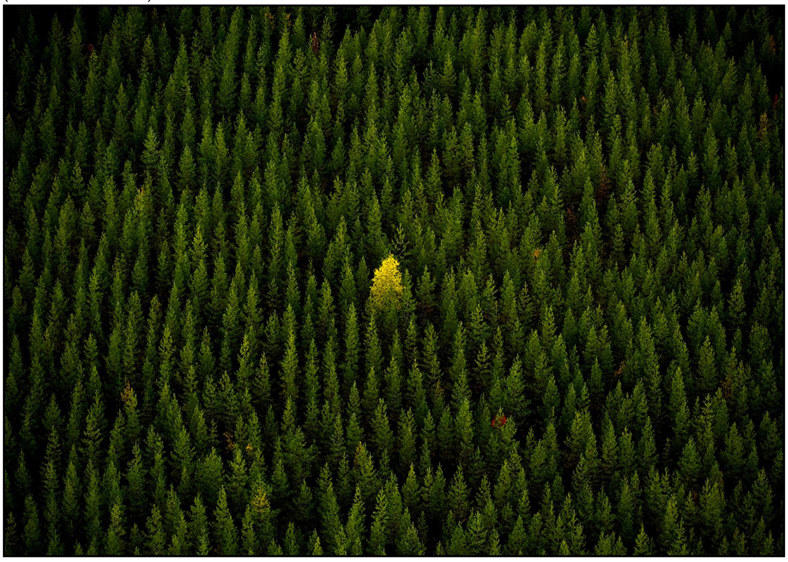
Figure 28: Average NEE of CH_4 in rivers



The scope of this paper is limited to discussing LULUCF related to the building and flooding of the reservoirs (upstream). Some research are however emerging in recent years, which advocated the investigation of the downstream effect of dams, i.e. Guérin et al. (2006), Lima et al. (2008) and Roberts (2011). This will be discussed in more detail elsewhere, but it is interesting to mention, that rivers downstream of hydroelectric reservoirs have been found to emit extremely large amounts of GHGs (Guérin et al., 2006; Li and Lu, 2012; Roberts, 2011; Wang et al., 2011) compared to all ecosystems mentioned in this paper. This was partly demonstrated in the example mentioned above by Wang et al. (2011).

Chapter 9: CARBON STORAGE

Picture 15: A carbon sink is a natural or artificial reservoir that accumulates and stores some carbon-containing chemical compound for an indefinite period. ("Carbon sink," 2012). Recent research have indicated that forests account for almost all of the world's terrestrial carbon sink (Pan et al., 2011). Disturbingly a warming climate has the potential to, among others, increase forest fires and insect outburst, theoretically causing the terrestrial biosphere to sequester less carbon in the future (Pan et al., 2011)



Picture: Mats Almöf / National Geographic

The main carbon pools of the terrestrial biosphere are forest vegetation and forest soils (Pregitzer and Euskirchen, 2004). Carbon accumulation happens due to the imbalance between photosynthetic uptake and various loss processes, such as respiration, herbivory, natural perturbations and harvesting. Especially precipitation and temperature are believed to exercise a strong influence on carbon storage in the terrestrial biosphere as they both affect production rates significantly (Schaphoff et al., 2006).

This chapter will discuss carbon storage in

1) Terrestrial soils and wetlands
2) Forests,
3) Aquatic ecosystems, including a thorough discussion on;
4) Reservoir sedimentation rates (based on findings in 9.3).

9.1 Carbon storage in soils and wetlands

Soil organic carbon (SOC) in forests includes litter, humus, small woody debris and duff. It generally varies in quantity between 8.5 and 13.9 $kgC \cdot m^2$ in both boreal, temperate and tropical forests (Tremblay et al., 2005). This number, however, increases when one considers the carbon stored as peat in the forest floor of especially some northern forests, where the cold temperatures and water-saturated conditions are limiting microbial decomposition rates and hence providing favourable conditions for soil accumulation. There seems to be a relationship between the litter layer thickness and the age of the forests and time since last forest fire. This relationship is however still not completely understood (Klopatek, 2002). A common problem with SOC estimates is that they often solely consider the soils first meter (Tremblay et al., 2005).

Picture 16: On the left, typical upland soil, on the right, typical wetland soil

Source: (Wisconsin Department of Natural Resources, 2012)

It has not been investigated further what the effect of hydropower land-use changes will be with regard to the SOC. While most probably will be stored at the bottom of the reservoir, some is also likely to be transported either downstream or into the dam reservoir (Cole et al., 2007; Cole and Caraco, 2001; McCully, 2006; Tremblay et al., 2005). Here parts will be stored at its bottom, while parts will decompose and be transformed into methane gas, of which most finally will be oxidized on its way to the surface, before leaving the reservoir as CO_2. To what extend the flooding of SOC in forests will affect the carbon balance significantly is unknown, but might comprise a significant contribution to the overall picture. This is exemplified in estimations by Tremblay et al. (2005) who find the boreal soil organic carbon pool to be almost similar to that of the entire boreal forest. Also, even though wetlands only cover approximately 2-6% (depending on definition) of the earth's surface (Kayranli et al., 2010), they hold up to 14% of the earth's terrestrial biosphere carbon pool (Euliss Jr. et al., 2006).

9.2 Carbon storage in forests

Forests are understood mainly as areas that contain a high density of trees. The primary focus is the tree stems and only peripheral, the understory (see definition in chapter 2.2.2 p. 25). There have been speculations over the degree to which the understory comprises a significant part of the total vegetation biomass in especially tropical rainforests (see discussion chapter 2.2.5, p.29). The general understanding is that the understory only constitutes a small part of the total biomass (Goodale et al., 2002; Tremblay et al., 2005).

The spatial heterogeneity of forest biomass is pronounced in all biomes. There is however a pattern that suggests that the main factors controlling the distribution of biomass in a specific forest varies between biomes. In *boreal forests*, biomass variability for the most part seems related to *both* natural and anthropogenic disturbances as well as edaphic[82] conditions. In *tropical rainforests,* on the contrary, biomass variability seems more dependent on the distribution of large trees, which again seems to be dependent on natural disturbances and soil nutrient availability (Cummings et al., 2002).

Most of Europe, the United States, Canada, China and Russia have developed comprehensive forest inventories, based on more than a million sample plots, which enables estimates of the growth of the forests and the total wood volume within a 1-5% margin of error (Goodale et al., 2002). The uncertainties related to estimating the carbon stock from forest inventory data from northern forests mainly comes from the conversion of wood volumes into carbon stock (Tremblay et al., 2005). Compared to the northern forests, estimations of carbon storage in the forests of the tropical regions are comprised of a much higher degree of uncertainty (Reddy &

[82] Of, produced by, or influenced by the soil

Price, 1999), mainly as there are no detailed national forest inventories available, and as there are no standard methods for measuring carbon storage in tropical regions (Cummings et al., 2002; Jia & Akiyama, 2005).

In general terms, tropical forests are estimated to have a higher biomass density than boreal and temperate forests, owing to a higher productivity, which is fostered by the warmer temperatures, higher humidity and increased light intensity at tropical latitudes (Huete et al., 2008; Luyssaert et al., 2007a) and possibly also the lengthier growing season in tropical regions (FAO, 2006; "The forest biome," n.d.). In contrast to frequent forest fires and insect outbursts in northern forests, the relatively stable conditions found in tropical rainforests have also contributed to increased carbon accumulation. The increased stability of tropical regions is testified by the many older trees (200-1400 years old) found at tropical latitudes, compared to the boreal region, where old stands found on average are about hundred years old (Pregitzer & Euskirchen, 2004).

Where the *boreal* forests have decreased in extend ever since the beginning of their exploitation they are today most often being replanted for further harvests (Diamond, 2004; Goodale et al., 2002). *Tropical* forests are on the contrary under heavy pressure from being turned into other land uses, not at least due to rapid population growth in the tropical regions over the last decades (Ezeh et al., 2012). For the *temperate* forests, the pattern is the same as their fate historically has lied in the rapid colonization over the last centuries, which has decreased the forest area. Today there are practical no remaining original natural stands in the temperate biome (Pedroni, 1997).

Based on a number of reviews of the global carbon storage, which for the boreal and temperate regions are quite accurate, Tremblay et al. (2005) estimate boreal forests on average to sequester 4-6.4 $kgC \cdot m^2$ and temperate forests 4.8 – 5.7 $kgC \cdot m^2$. For the tropical region, averages are as mentioned more unsecure, but are in the same study estimated to store 15.2-23.3 $kgC \cdot m^2$ for the Amazones, and 13.2–17.4 $kgC \cdot m^2$ for Asian tropical forests. This picture is varied by the US Forest Service that estimates boreal and temperate *hardwood* forests to sequester 4.5-8 $kgC \cdot m^2$, while boreal and temperate *softwood* forests only sequester 2.1-5.5 $kgC \cdot m^2$ (USDA FIA, 2003 in Schaphoff et al., 2006).

9.2.1 Methods for estimating carbon sink in forests

The method is described in the methodology chapter 2.2, p.23.

9.2.2 Variables controlling carbon sequestration in forests

This paragraph will seek to determine which variables are controlling the growth of forests and the potential tree growth of a specific area. This will both function as a mean to discuss and supplement the aforementioned regional span in a specific case, as well as a mean to discuss good site selection in the final chapters. The potential for tree growth is also an important factor, as not only the present carbon pool should be included in estimates of the climate effect of a certain hydropower project, but also the total potential of the ecosystem in the long term. The forest carbon storage potential is indirectly expressed through dam lifetime NEE estimates (see Chapter 13, p. 120).

As the NEE of forests is a driver for carbon sequestration in forests over time, many of the variables presented in chapter 4.5, p.48 can be replicated. To give a fair prediction and a generalized, local and present picture of the quantity of carbon stored in, and the potential of, a certain forested area planned for flooding, some of these variables however pose a slightly different role. The variables are discussed here:

Biome: Tropical forests are in general prone to accumulate more carbon than both boreal and temperate forests. For the latter two; they more or less share similar pool sizes.

Age: Stand age seems to be the most determining factor of total ecosystem carbon storage for all biomes (Jonsson & Wardle, 2010; Pregitzer & Euskirchen, 2004). The age of the forest is affected by stand-replacing ecosystem disturbances, such as harvesting, forest fires, insect outbursts and so on. *In the present study, the factor of age is however somehow outbalanced by the inclusion of NEE of forests over the lifetime of the reservoir on the one side, but will, on the other side function as a valuable means to discuss the present ecosystem carbon storage.*

Forest management: Besides positively affecting steady conditions, forest management can also affect the carbon pool in providing favourable conditions for forest growth (Reddy & Price, 1999). Managed forests hence have the potential to store more carbon than natural forest, both above and below ground (Jonsson & Wardle, 2010), and especially in boreal and temperate regions, where stand-replacing ecosystem disturbances are more frequent (Reddy & Price, 1999).

Temperature: As it was the case for NEE, there does not seem to be a direct relationship between temperature and total carbon storage in forest ecosystems (Goodale et al., 2002), but it seems that temperature affects a shift in the ecosystem structure, where warm conditions foster higher carbon accumulation in the above ground biomass (AGB) of forests and lower subterranean[83] carbon sequestration, compared to forest ecosystems found in cooler conditions which seems to foster relatively high carbon accumulation in the subterranean stocks, and relatively low carbon accumulation in the tree stems (Raich et al., 2006).

Topography (altitude and slope): Also, elevation seems to be a good topographic predictor of AGB storage. When it comes to slope convexity, some research have pointed to a relationship where the more flat areas had a much higher AGB density (McEwan et al., 2011), while others have found no direct relationship between the two (De Castilho et al., 2006).

With regard to altitude, it has in general terms been argued that tree growth is constrained in stressed sites (Craine, 2005). Accordingly, the growth of trees found in forested areas which otherwise share similar characteristics have been found to decline with altitude. For example, the research done by Paulsen et al. (2000) in the Alps suggests that the height of trees falls with 2-17m pr. 100m of elevation. Earlier research has pointed to the fact that the tree line is mostly dependent on temperature, which suggests that the height of the trees is merely a consequence of a change of climate in higher altitudes. The study by Paulsen et. al. (2000) however defeats this assertion, and finds no correlation between changes in climate and the size of the trees. Additionally, other research have also found that trees become more stunted and tend to have more open canopies in the higher areas (Coomes & Allen, 2007; Craine, 2005), which all in all witnesses a pattern where the carbon stocks of forests are less in the higher altitudes. This decline in carbon stocks with altitude is attributed to a number of factors, such as reduced air and soil temperatures, shorter growing seasons, increased exposure to wind and reduced nutrient content of the soils in higher altitudes (Coomes & Allen, 2007).

Soil: The relationship between soil type and AGB, is very dependent on tree species, which makes it more of a local factor, than a variable useful for predicting carbon sequestration of large areas in general (De Castilho et al., 2006). With regard to nutrient availability, its relation with growth is obvious (Coomes & Allen, 2007), however generalization over the relationship between the edaphic conditions of the forest ecosystem and total carbon stocks is just as interesting, as the increased competition over nutrients in the soils do limit the growth rate, but apparently only affects the total carbon stock vaguely over the long term (Coomes & Allen, 2007). Interestingly, trees respond plastically to resource availability, meaning that they have a tendency of allocating more carbon to the above ground biomass, when soil resources are relatively abundant, and more carbon to the roots, when nutrients are limited (Coomes & Allen, 2007).

Tree species: Much research have observed substantially higher growth rates and carbon stocks in hardwood forests compared to softwood forests (Brown & Schroeder, 1999; Brown et al., 1999; McEwan et al., 2011; Reyes et al., 1992), which have lead to resent concerns in the US and elsewhere, as large hardwood forests are expected to be cut down and converted into softwood forests in the coming decades (Sohngen & Brown, 2006). The US Forest Service finds that hardwood forests sequesters from 45 to $80tC \cdot ha^{-1}$ (4.5 to 8.0 $kg \cdot m^2$) on average, depending on site quality, whereas pine stands sequesters 21 to $55tC \cdot ha^{-1}$(2.1 to 5.5 $kg \cdot m^2$) on average (USDA FIA, 2003 in Schaphoff et al., 2006), which urges a need to include tree species in the variables here.

Others factors: Both stem density (the number of stems pr. unit of land), and species diversity seems to be good biotic predictors for carbon density at some sites, but this relationship needs further attention before it is possible to generalize over this as a variable in predicting AGB of forests (McEwan et al., 2011).

[83] Existing, occurring, or done under the earth's surface.

9.2.3 Discussion

Conducting on site research as presented in the methodology chapter might not always be possible, be it as a result of impassable forest conditions, security issues related to collecting the samples, lack of permissions or other reasons (could also be lack of resources). Therefore mapping forest stands through satellite imagery (preferably backed up by some kind of groundtruthing) and combining them with average carbon storage estimates for the regions - preferably with consideration to variables as those presented here, might be the only possibility.

Instead of distinguishing between boreal and temperate forest, the distinction in these biomes should rather be made between softwood and hardwood forests. For the tropics, the values presented demonstrate that it makes little sense to distinguish between tropical South America, and tropical Asia. For these regions, stands that are dominated by either softwood or hardwood species will pull the average values of the biome in either direction. It has unfortunately not been possible to find estimates on average carbon balance of tropical Africa. Values are expected to be in the range of those of the two other tropical biomes:

Table 23: Average C storage in various forest biomes

	$kgC \cdot m^{-2}$
Tremblay et al., (2005)	
Boreal forest	4-6.4
Temperate forest	4.8-5.7
Tropical Forest	15.2-23.3
- South America	
- Tropical Asia	13.2-17.4
No data	
Tropical Africa	13.2-23.3
– expected average	
US Forest Inventory Service (2003)	
Boreal and Temperate	
- Softwood forest	2.1-5.5
- Hardwood forest	4.5-8

The flooding of terrestrial biomass will probably not take all carbon stored in the forests out of storage over the lifetime of the reservoir. In cases where the fate of the existing forests has not been decided at the time of the LULUCF estimates, a problem with the inclusion of forest carbon in the RA arises. However, several factors still justify the inclusion of forest carbon pools.

First of all; forests are often cleared prior to reservoir filling, often in order to mitigate water quality issues regularly experienced in reservoirs with high concentrations of dissolved organic matter (DOM) (Hanson et al., 2003; Tremblay et al., 2005) or to prevent large sedimentation rates which would otherwise shorten the lifetime of the reservoir (Morris & Fan, 1997) or cause flooding (Stefanidis & Stefanidis, 2012).

Another factor is that many reservoirs are often emptied for sediments several times during the first years of operation, and in principle during their entire lifespan (Bashar et al., 2010; Morris & Fan, 1997; Stefanidis & Stefanidis, 2012) for similar reasons as those just mentioned.

Finally, a prominent factor which in combination with the aforementioned contributes to the justification in including the carbon stored forests, is that a large proportion of the DOM stored in the reservoir, will be released again when the dam is commissioned (Morris & Fan, 1997; Parekh, 2004), or disappear from NEE estimates as the DOM is flushed out of the reservoir through turbines and spillways.

Carbon storage and burial rates in reservoirs will receive much more attention in the following chapters, but it has unfortunately not been possible to find any thorough studies which treat the fate of the flooded biomass in hydroelectric reservoirs.

In order to establish a conservative estimate, the case chapters will consider a 75% return rate of the flooded forest biomass.

9.3 Carbon storage in lentic ecosystems

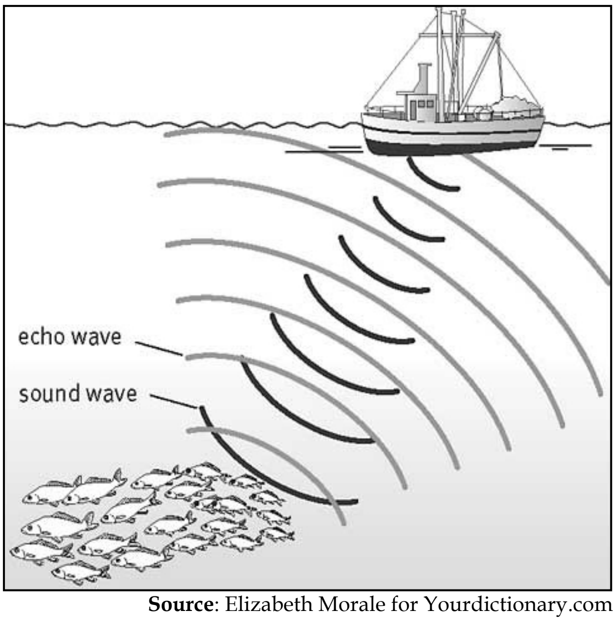
Lakes were initially ignored in global carbon budgets due to their relatively small geographical size. In recent years, inland aquatic ecosystems have however attracted increased attention due to new research which have shown extremely high carbon burial rates, as discussed by Cole et al. (2007) in the preliminary chapters (p.70f). Cole et al. (2007) and others (eg. Dean and Gorham, 1998; Tranvik et al., 2009; Kastowski et al., 2011; Sobek et al., 2012) have shown that these systems do not only emit vast amounts of greenhouse gases, but they are, mainly as a result of a large allochtonous input; also a large sink of atmospheric CO_2.

The sequestration of carbon in the sediment of lakes and reservoirs represents both short and long term impounding of atmospheric CO_2. Different from the carbon stored in trees, the carbon that is stored in the sediments of these water bodies is expected to remain buried after reservoir filling. What is interesting is, however, the areal sink of carbon in the water body, as it will allow for a final understanding of these systems role in carbon budgets.

9.3.1 Methods for estimating carbon sink in aquatic ecosystems

The most accurate method for measuring the sink of carbon in lakes and reservoirs is by comparing and analysing series of consecutively repeated bathymetric[84] examinations executed in different years, because it does not require scaling up from small areal samples or deposition records that can be bias by sediment focusing or non-representative sampling (Downing et al., 2008; Morris & Fan, 1997; Tranvik et al., 2009). These surveys are usually conducted through ice or from boats using sounding rods and sonar, which can be aligned with elevation benchmarks (Picture 17, below).

Picture 17: Sonar is an electrical impulse that is converted into sound waves and is transmitted under water. The sound waves are reflected off objects in their paths, creating echoes that are returned to the vessel and picked up by sonar equipment. The objects could be fish, or it could be the bed of lakes and reservoirs.



Source: Elizabeth Morale for Yourdictionary.com

[84] Bathymetry is the study of underwater depth of lake or ocean floors, or the underwater equivalent to topography.

Sediment mass accumulation (unit dry mass pr. area), can then be calculated from total sediment volume accumulated (as described above) and sediment dry bulk density (DBD). DBD is determined from sediment samples extracted at many sites across water bodies for example by Shelby tubes or using a box corers, that are distributed to represent principal areal of sediment deposition. These samples are finally oven-dried to determine their constant mass[85] and to calculate DBD from standard methods and definitions (Morris & Fan, 1997). The DBD can subsequently be verified by estimating particle size distribution, which is closely related to the DBD (Downing et al., 2008). Finally, the SOC concentration pr. unit dry mass can be calculated from the loss of ignition (LOI) method, from which the total organic carbon (TOC) can be determined through acidification, oxidation and detection and quantification (for reference, please see US EPA (2005)). Approximate TOC concentrations can also be estimated using similar methods as in the simplified method for estimating C content in trees described above, and as it was done by Downing et al. (2008), who assumed average TOC concentration of LOI of 46.95%. This ratio (which was estimated from previous studies of the same area as the paper just mentioned), can be slightly altered if the aquatic environment has received a more substantial amount of soil from, for example, agricultural lands, which will cause somewhat more of LOI to be attributed to TOC. Although values have been found as high as 68.2 of LOI in some agricultural soils, and as low as 33% in some forest soils, the TOC concentration of LOI is usually found in the range of 44.5% to 47.6% (Konen et al., 2002).

9.3.2 Variables controlling carbon sequestration in the aquatic environments

Over the years many theories of which variables were controlling carbon burial in the soils of lakes have been proposed. These include primary production, organic carbon degradation rates, sedimentation rates and bottom water oxygen rates (Hartnett et al., 1998). However, none of these has entirely stood the test when it came to empirical studies (Bühler, 2007; Tranvik et al., 2009).

The variables controlling the role of the lake are best predicted from land-uses in the catchment area, the trophic status and the size of the lakes or reservoirs:

9.3.2.a The role of watersheds and trophic status

The material that accumulates in the sediments of lakes and reservoirs can be airborne deposits from outside the watershed, air- and water-borne deposits imported from inside the watershed (allochtonous inputs), or created by biological or chemical processes that have occurred within the lake or reservoir itself (autochthonous inputs) (Downing et al., 2008). This suggests that the watershed constitutes an important variable in predicting the magnitude of the storage component in lakes and reservoirs. Accordingly, Downing et al. (2008) investigated the role of the watershed on carbon burial of 40 small reservoirs in Iowa, USA, (0.008 to 42 km^2) in which 90% of the total land area were under some kind of intense agricultural use. All of the impoundments were furthermore used for irrigation. In the study, they found that large watersheds had smaller export of SOC pr. unit area, than small watersheds, probably as the large diversity of terrain encountered in large watersheds (wetlands, intermediating water bodies etc.) are delaying the SOC before it is delivered downstream.

What the study also found was that small reservoirs were accumulating much greater volumes of organic carbon (OC) pr. unit time and area compared to large reservoirs (Downing et al., 2008). This happens supposedly due to burial of shore erosional materials, due to the usual more trophic conditions of small reservoirs, which favour conservation of organic sediment material, and due to higher sediment yields in the small watersheds of small reservoirs. The study found that OC burial declines exponentially, when the areal size of the reservoir increased - approximately following this power function:

Equation 10: Sediment OC burial rate

$$B_C = 1060A^{-0.298}$$

[85] Constant mass is estimated as the mass remaining when heating until the mass of the substance remains constant/no longer change

Where B_C is the sediment OC burial rate in $g \cdot m^{-2} \cdot y^{-1}$ and A is the reservoir area, in km^2.

The smallest reservoir (0.008 km^2) in the study was found to bury as much as 17 $kgC \cdot m^{-2} \cdot y^{-1}$, while the second largest reservoir[86] (≈20km^2) was found to bury only 0.15 $kgC \cdot m^{-2} \cdot y^{-1}$. The study is, however, based on very small eutrophic reservoirs within productive agricultural hinterlands in temperate USA, which have received large inputs of agricultural fertilizers that naturally, will have enhanced their autochthonous production. The magnitude of the sediment OC burial rate would furthermore have been influenced, as B_C have been found to be positively related to watersheds rich in terrestrial SOC, which is a typical characteristic of productive agricultural lands (Ritchie, 1989; Ritchie et al., 2004).

Dean and Gorham (1998) also investigated B_C in small and large lakes for the U.S. Government Geological Survey and found that the average B_C of small lakes was only 0.072 $kgC \cdot m^{-2} \cdot y^{-1}$ while large lakes (>5000 km^2) on average only buried 0.005 $kgC \cdot m^{-2} \cdot y^{-1}$. Additionally, the report also estimated the average B_C of reservoirs to only 0.4 $kgC \cdot m^{-2} \cdot y^{-1}$, which lies in the range of small to medium reservoirs in productive agricultural watersheds presented earlier.

Other research have distinguished between small and large mesoeutrophic lakes and small and large oligotrophic lakes and found B_C to 0.094 and 0.018 for the mesoeutrophic lakes, and 0.027 and 0.006 $kgC \cdot m^{-2} \cdot y^{-1}$ for the oligotrophic lakes respectively[87]. The report also distinguishes between reservoirs from Asia, Europe, the United States and Africa, and finds B_C to 0.980, 0.465, 0.350 and 0.260 $kgC \cdot m^{-2} \cdot y^{-1}$ respectively, suggesting a much larger burial in Asian reservoirs than elsewhere. These figures are also in agreement with values presented by Dean and Gorham (1998) previously, and further consolidates the picture that

1) B_C increases with trophic status, that
2) B_C pr. unit area decreases as the surface area of the water body increases, and that
3) B_C is much larger in reservoirs than lakes.

Table 24: SOC burial rates in aquatic ecosystems (in $kgC \cdot m^{-2} \cdot yr^{-1}$)

Environment	*Mean BC*	*n*	*Range*	*Source*
Lakes				
Small lakes	0.072			Dean and Gorham (1998)
Large lakes (>5000km^2)	0.005			Dean and Gorham (1998)
Small mesoeutrophic lake (<100km^2)	0.094	14	0.011 - 0.198	Mulholland and Elwood (1982)
Large mesoeutrophic lake (>500km^2)	0.018	4	0.010 - 0.030	Mulholland and Elwood (1982)
Small oligotrophic lake (<100km^2)	0.027	18	0.003 - 0.128	Mulholland and Elwood (1982)
Large oligotrophic lake (>500km^2)	0.006	5	0.002 - 0.009	Mulholland and Elwood (1982)
Reservoirs				
Small eutrophic reservoirs (0.008-42 km^2) in ag. Watershed	1.000	40	0.150 - 17	Downing et. al. (2008)
Reservoirs	0.400			Dean and Gorham (1998)
Reservoirs (Asia)	0.980	16	0.02 - 3.3	Mulholland and Elwood (1982)
Reservoirs (Europe)	0.465	10	0.014 - 1.7	Mulholland and Elwood (1982)
Reservoirs (US)	0.350	24	0.052 - 2	Mulholland and Elwood (1982)
Reservoirs (Africa)	0.260	1		Mulholland and Elwood (1982)

9.3.3 Discussion

Some of the early research, which has been presented, has been criticized for inconsistent methods. In general, historic sediment deposition estimates have furthermore been found to yield lower estimates than modern estimates with uniform technologies (Downing et al., 2008). The estimates above presented in Downing et al. (2008) by Mulholland and Elwood

[86] There were no measurements on B_C in the largest reservoir.
[87] Estimated from Mulholland and Elwood (1982) in Downing et al. (2008)

(1982) have however, where it was possible, been corrected according to methods used in first mentioned research paper, by the authors.

Converted into CO_{2eq} (according to the method presented in chapter 2.2.6 p.29), the B_C in reservoirs can be expressed in flux units as follows in Table 25, below:

Table 25: Contribution of B_C in aquatic ecosystems to total NEE

Environment	*Average BC [kgC/m2/year]*	*Average BC in CO2eq [mgCO2eq/m2/day]*
Lakes		
Small lakes	0.072	723
Large lakes	0.005	50
Small mesoeutrophic lake (<100km2)	0.094	944
Large mesoeutrophic lake (>500km2)	0.018	181
Small oligotrophic lake (<100km2)	0.027	271
Large oligotrophic lake (>500km2)	0.006	60
Reservoirs		
Small eutrophic reservoirs (0.008-42 km2) in ag. watershed	1.000	10040
Reservoirs	0.400	4016
Reservoirs (Asia)	0.980	9839
Reservoirs (Europe)	0.465	4668
Reservoirs (US)	0.350	3514
Reservoirs (Africa)	0.260	2610

Based on average B_C's presented in **Table 24**, p. 95

These numbers both show a distinct negative relationship between lake/reservoir size and B_C, as well as a positive relationship between lake/reservoir trophic status and B_C.

9.4 Reservoir sedimentation and reservoir life

Both reservoir sedimentation, and its relationship to reservoir life, needs further clarification in order to quantitatively determine the expected B_C, in a specific hydroelectric reservoir.

Generally, reservoir sedimentation differs substantially between reservoirs, and is fundamentally based on variables such as sediment input and trap efficiency[88] (both of which are also dependent on a number of variables). To this comes a dependence on the effectiveness of measurements commenced to avoid reservoir sedimentation - all of which makes reservoir sedimentation extremely hard to predict, let alone analyse. Stefanidis and Stefanidis (2012) conducted a study over the first years of four hydropower reservoirs the Kiki's Prefecture of Central Macedonia, Greece. The reservoirs were at the time 2-5 years old, and the expectation was to be able to analyse reservoir sedimentation in the time after impoundment. However, in all cases, the analysis of the magnitude of the sedimentation was compromised as all of the reservoirs, had to be emptied for sediments two to three times during their first two to five years, despite modern measures to avoid heavy sedimentation had been included both in reservoir and dam design.

This underlines the undeniable fact, that, in the long term, and regardless of which mitigation measures are taken; sediments are still likely to pile up in hydroelectric reservoirs over time (Morris & Fan, 1997; Stefanidis & Stefanidis, 2012), and that in the worst case extensive measures must be taken to remove accumulated matter in the reservoir in order to maintain its generating capacity – sometimes even in the first few years after impoundment(Bashar et al., 2010; Chanson & James, 1998; Morris & Fan, 1997; Stefanidis & Stefanidis, 2012), as it was also demonstrated in the example above. Measures such as sluicing and venting, which seek to mobilize reservoir sediments and reverse loss of water storage capacity, have all been relatively ineffective in the long term (Morris & Fan, 1997; Stefanidis & Stefanidis, 2012). Accord-

[88] Ability of a reservoir to trap and retain sediment, often expressed as a percentage of sediment yield (incoming sediment) which is retained in the reservoir.

ing to Morris and Fan (1997) and others, reservoirs are usually filled with sediments within 50 to 150 years (Bashar et al., 2010; Morris & Fan, 1997; Wang & Hu, 2009).

When considering OC burial rates in LULUCF estimates, some factors play a profound role:

First of all, and most importantly, the OC in river-borne sediments which is trapped in the reservoir in the absence of the dam, have been carried downstream where large parts would still have been deposited along the way or would have been transported to the ocean where they would either have been trapped in marine sediments (UNESCO and IHA, 2009) or fertilized oceanic plankton, which are important consumers of atmospheric carbon dioxide(International Rivers, 2007).

Secondly, and regardless of the timeframe, a time will come where the reservoir will need to be decommissioned. The impetus being anything from a desire for ecosystem restoration to safety, as reservoir sedimentation can cause severe flooding, accidents if the dam wall collapses, or alike. Even though a certain portion of the OC that was buried in its sediments may be stabilized in the ecosystem after decommissioning, a large portion will also be released in the years after (Parekh, 2004).

Therefore, considering:

1) The probable fate of the sediments in the absence of the dam,
2) That minimal sedimentation rates for hydropower reservoirs are pursued by dam builders through design and mitigation measures in order to maximize the lifetime, the generating capacity and hence the (cost-) effectiveness of dams, as well as the fact that;
3) Direct subtraction of sediment deposits with excavators and cranes are routines in-most reservoir management;

Sedimentation rates must be considered minimal when comparing average values for all types and sizes of reservoirs. *In the case chapters a fair estimate is given by including two scenarios; one with a relatively large storage, and one with minimum storage. The consideration for choosing these is elaborated upon in the relevant chapter.*

Chapter 10: Sum-up of the background chapters

Obviously, the kind of simplification used here and throughout this study are subject to a number of possible over and underestimates, but these are no different from other studies which have tried to assemble data for similar reasons (for example Cao et al., 1996; Bastviken et al., 2004, 2011; Tremblay et al., 2005; dos Santos et al., 2006; Luyssaert et al., 2007). Estimates are for the most part considered conservative, *and non-representative average values as those presented throughout these chapters are merely meant to be supplemented with knowledge obtained through field measurements as well as to be understood in relation to the variables defined subsequent to each chapter*[89]. These variables will in the final chapters constitute the foundation for the discussion on good (climate 'friendly') site selection.

While some measurement on a small scale possibly could be obtained with a higher certainty, if resources and time were available, NEE is generally extremely difficult to measure, among other reasons, due to extremely high spatio-temporal variations in all ecosystems presented here (wetlands and aquatic ecosystems in particular) and due to the many variables which each can affect final estimates signifcantly. In these situations, researchers are still somewhat limited to this kind of simplifications in predicting the NEE balances.

The best means to understand the fluxes over a certain ecosystems which are to be inundated is probably if EC towers already exist in the RA and are connected to the FLUXnet network (no EC towers exists to date in SEA or Africa) or even subsequent establishment of EC towers if time (more than a year of measurements) and resources are available in a way, which allows one to do those measurements. The latter of cause evokes other considerations with regard to physical and cultural access (TAMU, 2010) in addition to research permission and consent with local communities as well as regional and national governmental institutions - a permit, which in some regions can be hard to get, especially if the subject of investigation is delicate (TAMU, 2010) (as hydropower planning often can be). Finally, there could also be situations in a given country, where estimates are hard to make (i.e. due to unnavigable terrain), or unsafe (i.e. in countries with political instability, or where the government is reluctant to allow non-governmental assessments).

Especially some areas need much more attention in future studies. These are mentioned and elaborated upon throughout the paper but will briefly be summarized here. The most prominent is probably the fate of the soil OC in reservoirs as well as the fate of the carbon stored in the flooded forests and carbon burial rates in reservoirs. Even though NEE measurements are bound with uncertainties, some areas enjoy a rather comprehensive amount of data and the NEE over these areas are hence relatively well understood. However, these areas also constitute a vast overrepresentation of data, while others including SEA, but especially Africa, enjoy only little representation – if any at all. This is especially critical considering that 68% of the worlds' dams are situated in tropical Asia (Tremblay et al., 2005), that most hydropower development today happens in tropical regions of South America, Africa and Asia (Brewer, 2011), and that the tropical regions are the regions in which bad dams are most likely to be found (chapter 7.5, p. 75f).

The results presented in this paper are nonetheless estimated to give a fair picture of the significance and range of both the terrestrial and the aquatic ecosystems in LULUCF budgets. The compilation of data is furthermore to my knowledge, to date, among the most comprehensive gatherings of data of the NEE of CO_2 over forests[90], wetlands, reservoirs, lakes and rivers[91] and on the NEE of CH_4 over wetlands, reservoirs and lakes[92].

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[89] Also, see reservations mentioned in chapter 3.2 (p. 36), and chapter 6.2 (p. 65), where the data used, and its supposed usage is discussed in more detail.

[90] Possibly except the opaque Luyssaert et al. (2007) report

[91] When earlier mentioned criteria; that data collection must have been done over more than one year, is applied.

[92] When earlier mentioned criteria; that data collection must have been done over more than one year, is applied.

CASE STUDY: SAMBOR DAM

Chapter 11: SAMBOR DAM CAMBODIA

> *"Sambor means "plenty". It is a name that is an invitation to participate in a generous and convivial way of life. It suggests that there is a background of abundance, which can supply the needs of many. It is a name that evokes a vision of people living well, living well together, and living well with the land." (Cornford & La, 2010)*

The vision reflected above suitably mirrors the condition of the Sambor region and the Sambor people living today, according to a report recently published by Oxfam Australia (2010). The report paints a subtle picture of the indigenous people who live along the river, how they live, the challenges they face, and their hopes for the future. By and large, the report gives the impression of the Sambor people, characterized as poor by donors and the international community, as generally satisfied with their way and standard of life, with little wish for it to change (Cornford & La, 2010). However, the wish to avoid change must also rightfully be understood in the light of a tragic history with decades of political instability. Both in the wake of the Vietnam War that came to extend into most of East Cambodia, and the decades hereafter saturated with the tragic of civil wars under the Pol Pot regime.

Picture 18: Sambor villager planting rice

Source: (Cornford and La, 2010)

11.1 Brief overview of the Sambor region

Sambor is the largest province of Kratie in Eastern Cambodia and is home to around 50.000 people. It is situated between the Stung Treng province in the north, the Mondulukiri province to the east and the Kampong Thom province to the south. When the region is split into two, we have the Mekong River, which travels through it from north to south. The Mekong River is the source of life to the entire district and most of the regions inhabitants live along its bank and on the large islands that characterizes this particular stretch of the Mekong. The largest of these islands is Koh Phdao, which stretches 43 kilometres and supports 4 different villages. Most of the farming land in Sambor is following the river corridor. Of the people living in the region, more than 80% are involved in small scale farming, where they produce food for their own consumption and to a lesser degree, to sell on the local markets. Rice growing, raising live-stock, fishing and collecting from the forests represents the four pillars in the Sambor economy, which to this day seems rather independent from the outside world (Cornford & La, 2010).

More than 30% of the people living in Sambor belong to ethnic minority tribes, which do not see themselves as Khmer. The largest of these tribes are the Phnoung, the Kuy, the Mil and the Thourne. Only a few of the younger members in these tribes, and very few of the tribes in their entity, have adopted the Khmer language, religion and culture (Cornford & La, 2010).

In general, the quality of the Sambor people have been improving in the years since the Pol Pot, but in recent years the experience of plenty have for many elaborated into another nightmare as outside interests are starting to pay attention to the area's plentiful resources. The advent of the global economy has

> On the one side meant many immediate benefits, such as improved roads and telecommunications which have made it easier for the government and aid organizations to build schools and health clinics, as well as attract qualified health professionals and teachers, and;
>
> On the other side, the indigenous are now being denied the right to the resources of which they have lived of and been dependent on for centuries. The regions fish are "*being sought for the growing regional fish market, its lands are being sought out by agri-business companies, and the great river itself is being sought as a source of hydropower electricity for regional power trading*" (Cornford and La, 2010).

11.2 The GMS hydropower scene

Damming plans on the Mekong River dates back as far as the 1950s, but was stalled as a result of years with war and political instability. However, the original plans and way of thinking still play a profound influence on energy plans in the region today (Imhof et al., 2006).

As the region opened up in the 1990's, the Asian Development Bank (ADB) established the GMS program. Under the influence of the ADB, one among other key elements was to encourage regional cooperation in the energy sector by establishing a regional power-market primarily fuelled by hydropower. This should happen though the Mekong Power Grid-plan, fostering a complex network of high-voltage transmission lines which would open up mountainous regions in Lao PDR, the Yunnan province of China, and Myanmar. The energy would be sold to the growing economies of Thailand and Vietnam (Yu, 2003). In spite of enormous effort and investment by the ADB to push regional power trade forward and promote private sector involvement, progress has been slow and it is doubtful if the grid will ever be implemented as planned (Middelton, 2009).

Many promising alternative, sustainable and socially responsive energy solutions to meet the regions energy needs already exist and range from comprehensive and advanced energy reduction measures as well as competitive "green" energy solutions, such as wind and solar energy, biomass and more. However, these have never been part of the regional Mekong Power Grid plan (Middelton, 2009). The absence of alternative energy solutions is highlighted by the ADB's involvement in the regions energy planning who both as financier and government advisor to the host countries never included or urged assessments of neither the regions energy needs, nor the best option for meeting these needs. International best-practice standards, such as Integrated Resource Planning (IRP) standards, which would take into account social, environmental and economic factors, have never been utilized either. Especially the IRN has raised huge criticism of this and calls for the ADB to take the opportunity to encourage a comprehensive planning model that would include these factors (Imhof et al., 2006).

At the same time, as attempts to create a regional power grid plan were coming to a halt, governments of SEA were still pursuing their own plans of hydropower development, most of which were being developed without consultation with local communities, NGO's and other relevant involved parts of the civil society. The plans were often pushed forward without opportunity for public debate or assessments of the cumulative impacts on hydrology and ecology of the MRB (Imhof et al., 2006).

Today, hydropower development is still being developed in the absence of any regional planning or decision-making frameworks (Imhof et al., 2006; Middelton, 2009). Chinas rapid economic growth over the last decade has sparked an increased need for energy, and the same is the case further south, in especially, but not exclusively, Thailand and Vietnam. Over the last decades, the energy demand in the GMS has grown annually with 10 to 15% (Lee and Scurrah, 2009). Hence, the total energy demand of the GMS is predicted to grow from 131 TWh in 1997 to 600 TWh in 2020 (Yu, 2003). This growing demand for energy highlights the enormous unexploited hydropower potential the region offers (see table below).

Table 26: Total exploitable hydro potentials and installed capacity in the GMS (MW) by 2001

	Cambodia	*Laos*	*Myanmar*	*Thailand*	*Vietnam*	*Yunnan*	*Total*
Potential	8000	20	25	10	15	90	168
Installed	13	623	247	2565	2756	5000	11.204

Source: (Yu, 2006)

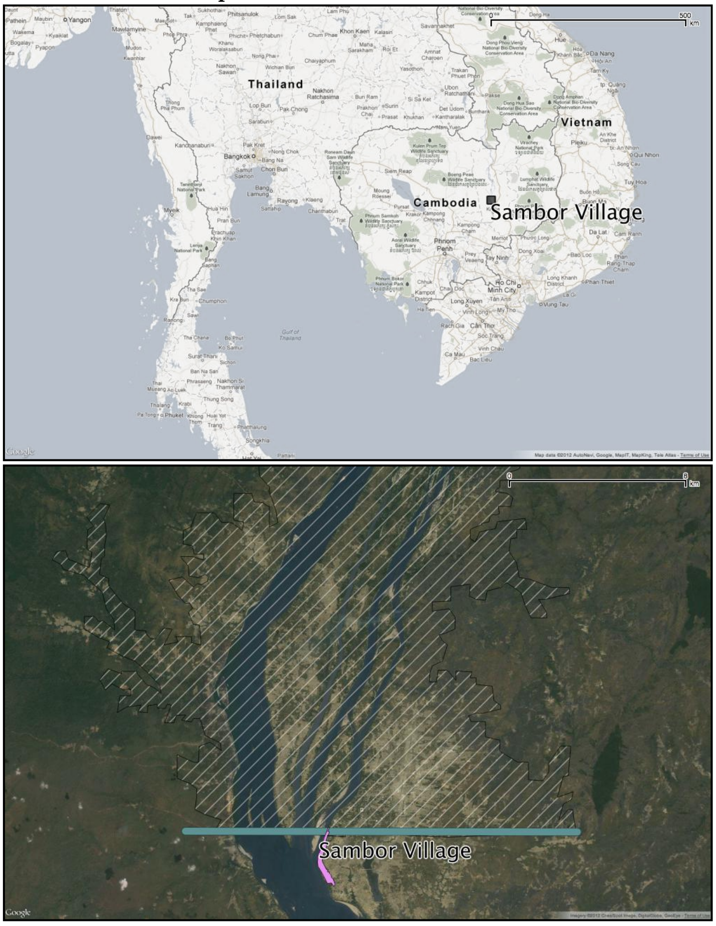
Earlier, the primary international actors were western corporations and multilateral banks (such as the World Bank and the ADB), but nowadays, new players are joining the GMS hydropower scene. Today, hydropower development are being overruled by energy and construction companies from Vietnam, Thailand, Japan, Malaysia and especially China, which are both financing and financially supported by private regional banks and promises of government guarantees through EXIM banks (Middelton, 2009). Many of these new stakeholders have yet to adopt social- and environmental standards in their operations (Imhof et al., 2006), which could help to secure long-term sustainable project outcomes. The fact is however that both regional banks and EXIM banks, contrary to dams supported by development banks, are not subject to public scrutiny either and besides being unaccountable to civil society, they have not been willing to adopt either the WCD guidelines (WCD, 2000) or the Common Approaches on Environment and Officially Supported Export Credits established by the OECD countries (OECD, 2003). The same is the case of the Equator Principles (EPs) (IFC, 2006). (Imhof et al., 2006).

To a large extend the same critique that have been directed at EXIM banks, could be directed at Dam constructors, as they are too unaccountable to civil society. However, especially Chinese companies are beginning to recognize the advantages of a "green profile" – the same is the case of the Chinese government that has enforced laws urging Chinese companies working abroad to adopt certain environmental standards. The GMS is especially interesting to the Chinese government. This is partly because it sees increased regional cooperation as a mean to support regional peace and stability - and partly because it sees it as a means to facilitate cross-border trade. Furthermore, hydropower development provides a comprehensive number of Chinese workers with employment. At the same time, GMS governments welcome Chinese technology transfer and economic investment, which not only also brings with it comprehensive infrastructure development (Brewer, 2011).

11.3 Site description

The Sambor Dam will be situated 160 km north east of Phnom Penh, and 120 km south of the Lao boarder on the Mekong River, close to the village of Sambor, a few kilometres north of Kratie, Kratie Province of Cambodia. The watershed of the dam lies approximately between longitudinal lines 15° to 16° north, and longitude line 105 to 107° east.

Map 4: Location of the Sambor Dam



The terrain are mostly low flat plains and the area is located in Lower Mekong Dry Forest Eco-region partly in an area known as the Eastern Plains Landscape (EPL), which is the largest intact dry forest in Cambodia. The main soil type are the red or yellowish Plinthosols (Michéli et al., 2006), which acquire the colour from the high concentrations of iron (III) and aluminium oxides and hydroxides. Plinthosols are like other oxisols (in the USDA soil taxonomy) somewhat unfertile due to their low organic matter content, and the almost complete absence of soluble minerals leached by the regions monsoonal climate (Buol et al., 2003).

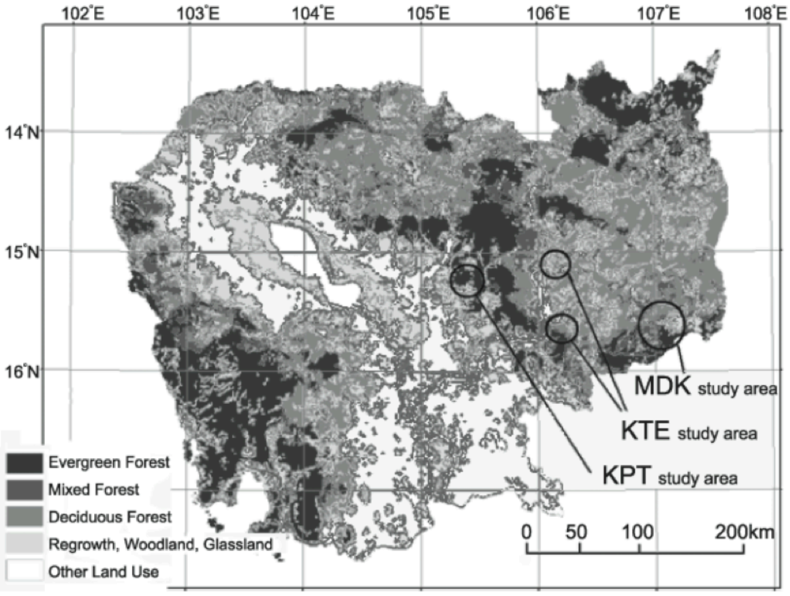
Picture 19: A food vendor on his way through one of the many new plantations south of Stung Treng

Picture: Lasse Jesper Pedersen

The dominant forest type is deciduous dipterocarp forest (Tani et al., 2007), while some of the higher quality soils on higher elevations support mixed deciduous forests and semi-evergreen forests (WWF, 2012).

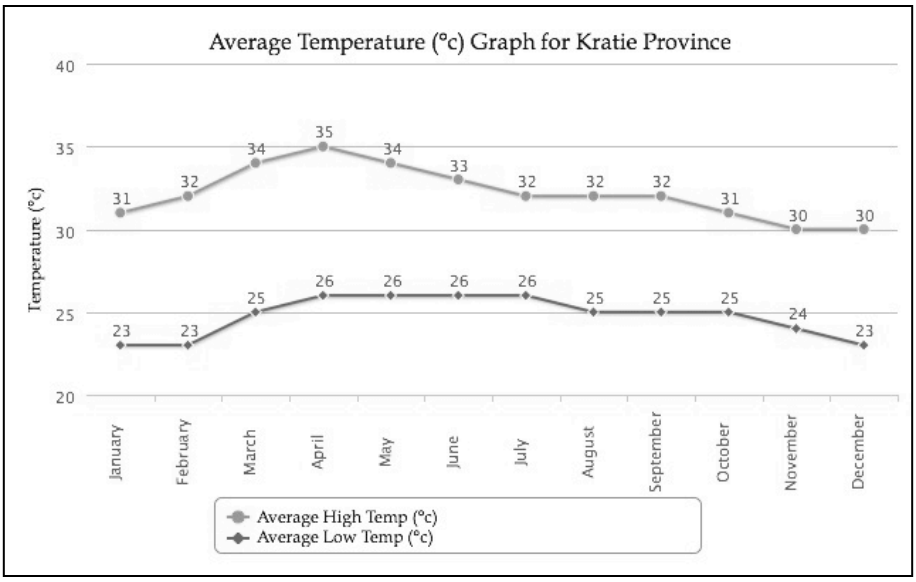
The deciduous dipterocarp forests are hardwood forests that typically have an open canopy and a grassy understory. The Eco-regions are dominated with members of the forest's name-sake family Dipterocarpaceae's. While all other Dipterocarp-trees are evergreen, the six species in the dry forest are the only ones that lose their leaves during the dryer months of November to April (WWF, 2012). This is expected to be an adaptation to the region's strong climate and extended wet and dry seasons. When the trees are shedding the leaves, it decreases the trees' surface area thereby reducing the amount of water that the trees loses due to transpiration (Swarthout and Hogan, 2012; Tani et al., 2007). Research done by Tani et al. (2007) found the dominant species; Dipterocarpustuberculatus, Shoreaobtusa, and Terminaliatomentosa, to dominate approximate 90% of the deciduous dipterocarp forests around Kratie.

Map 5: Forest cover map, Cambodia

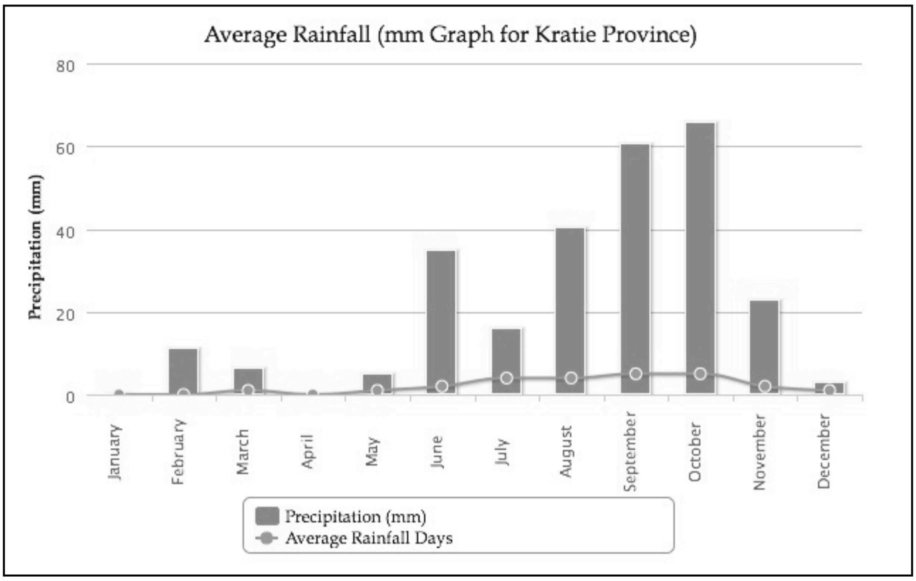


The picture above stems from Tani et al., (2007) who investigated the principal forest types of three Cambodian regions. KTE stands for Kratie, and the two sample areas are approximately 10 km south of Sambor, and just north of Stung Treng. The findings therefore adequately represent the RA.

The unimodal monsoonal climate of the Mekong Basin gives rise to a dynamic flooding regime with seasonal variations in water level of up to 10 m (MacAlister and Mahaxay, 2009). The monsoon cycle is driven by cyclic air pressure changes over SEA; when the pressure drops during the summer months (June to October) moist air is drawn landward from the ocean bringing the summer monsoon rains in Cambodia. During the winter months (November to May), the air pressure rises again, which drives the cool dry air back across SEA, leaving the Sambor-Stung Treng region largely rainless during the dry season (Library of Congress Country Studies, 2012). The annual rainfall in the Kratie Province is 1800mm (mean 150mm) and the average annual temperature is 27° with little seasonal variations (Tani et al., 2007).



Data: (Library of Congress Country Studies, 2012)



Data: (Library of Congress Country Studies, 2012)

11.4 An overview of the Sambor region hydropower plans

The first time the site was investigated for hydropower means was in the 1950's and 1960's where the Australian Snowy Mountains Hydroelectric Authority was brought in to conduct a thorough survey of the area. The team's work was however suspended later due to deteriorating security conditions. In 1994, the Sambor region was again identified as a desirable site in a report prepared for the Mekong River Committee (later the Mekong River Commission) proposing a 3,300 MW dam blocking the entire mainstream of the Mekong River (Osborne, 2009). Both political and financial considerations coupled with environmental and social concerns halted the project then (Nette, 2009). Recently, the plans however seem to have come back in action.

11.4.1 Plans back on the table

Despite massive criticism and concern vis-à-vis the project from both national and international civil society NGO's, the Cambodian Government signed a Memorandum of Understanding (MoU) with the Chinese Southern Power Grid Company in 2006 for a 2,600 MW dam which will span the entire mainstream. No final government decision to build the dam has apparently been taken so far (Osborne, 2009), even though there is little doubt that plans are still on the table; locals are reporting to have seen Chinese surveyors making investigations in the area (Cornford and La, 2010) just as rumours are circulating from various sources in Phnom Penh claiming that "*the Cambodian Government has already made an in-principle decision to press ahead with the larger configuration*" (Nette, 2009). Further to this, the deputy director Tung Sereyvuth of Energy Development for the Ministry of Industry, Mines and Energy (MIME) said at a presentation on a conference held in Laos in 2008 that "*the government is looking at a 2,600 MW dam, which it hopes to have on line by 2019*" (Nette, 2009). Finally, the Secretary of State for MIME, Ith Praing, has said in an interview that the Environmental Impact Assessment is underway, and that "*We hope that it [the dam] will be workable. The dam will be a historic achievement as the first big dam in Cambodia*'(Nette, 2009). Even though the government has yet to confirm the belief, there is little doubt that the plans are moving forward with significant speed.

During the field study in the summer of 2012, interviewees in Phnom Penh and the Sambor – Stung Treng area had the impression as outlined above; though the current statement from the Cambodian government is however, that they do not want to discuss neither the Sambor Dam nor the Strung Teng or Don Sahong Dam. Both Chhoun La (Oxfam)[93] and Gordon Congdon (WWF)[94] mainly attributed this to the fierce on-going negotiations between the Cambodian government and the Lao government over concerns on the impact on Cambodian fisheries and agriculture if Lao goes ahead with their plans to dam the Mekong River upstream of Cambodia. While both also agreed that as soon as the first dam is built on the Mekong in Laos or elsewhere, the rest of the projects will soon follow, Mr. La was quite optimistic of the government's commitment to the wellbeing of the Cambodian people over electricity export revenues, whereas Mr. Congdon did not share his optimism.

11.5 Decoding the content of the current plan and choosing what to believe

If the dam will be built, it will be the largest dam in Cambodia. Besides blocking the SrePok, Sesan and Se Kong Rivers, it will most likely come to extend across the entire mainstream of the Mekong River with all the social- and environmental consequences this will come to mean (see e.g. Osborne, 2004, 2009; Kummu and Varis, 2006; Middelton and Chanthy, 2008; International Rivers, 2009; Lee and Scurrah, 2009; Save the Mekong Coalition, 2012). Of the 12 seriously criticized proposed dams on the mainstream of the Mekong River in the Mekong River Basin (MRB) it will be one of the first - and just as notably; it will become the most shallow, with the largest FA pr. MW. Figures vary enormously on the number of people that need resettlement, the amount of land that will be inundated, even the size of the dam and the alternative options (see Table 27, below).

[93]Chhuon La is the Cambodian Advocacy Coordinator for Oxfam Australia based in Phnom Penh, responsible for community development implementation in Cambodia since 1993.
[94] Gordon Congdon is Freshwater Conservation Manager for WWF-Cambodia based in Kratie Field Office

Table 27: Various reports on the characteristics of the Sambor Dam

Primary option	*Oxfam*[2] *2010*	*MRC (ICEM)*[1] *2009*	*IRN*[4] *2008*	*TERRA*[3] *2008*
Size [MW]	2,600	2,600	3,300	3300
	-	3,300	465	465
Costs [Million USD]	-	4,947 + trans. lines: 312	-	-
	-	-	-	-
Annual Energy Generation [GWh]	-	11,740	14,870	-
	-	14,870	2,800	-
Height [M]	56	56	54	-
	-	35	-	-
Length [KM]	18	18	10	-
	-	30.7	-	-
Inundation [KM^2]	620	620	880	880
	-	2,000	6	6
Resettlement	19-20,000	19,034	(5,120)*	(5120)*
	-	5,120	-	-

Primary option, secondary option
[1] MRC SEA for hydropower on the Mekong Mainstream, conducted by ICEM, October 2009 (ICEM, 2009)
[2] Oxfam, Preserving Plenty, January 2010, (Cornford and La, 2010)
[3] TERRA, Fact sheet, Sambor Dam, Kratie Province, Cambodia, September 2007 (TERRA, 2007)
[4] IRN, Cambodia's Hydropower Development and China's Involvement, January 2008 ((International Rivers, 2012b; Middelton and Chanthy, 2008)
* Based on a 1994 MRC report (MRC, 1994), which is generally accepted, and talked about as outdated today (International Rivers, 2012b; Nette, 2009)

Generally, the Oxfam and MRC reports seem most reliable, as both the IRN and the TERRA report seem to build most of their figures on an old 1994 MRC report (MRC, 1994), where the 3,300 MW dam was the primary option investigated. However, some of the figures by the ICEM report done for the MRC (ICEM, 2009) on the alternative dam (secondary option), seem to be out of sync. It might be that the 3,300 MW dam is back on the table, however the inundated area seems unproportionally large which adds to the incongruous numbers of people who will need resettlement according to their own figures, as this is significantly lower compared to the primary option. Adding to this, peculiarity is that the location is only 20km further down the stream, where the population density is much higher than other areas along the proposed reservoir.

In the following, the primary option will mainly receive attention, as well as the Oxfam- and the ICEM/MRC report will constitute the underlying basis for the reports foundation and general understanding of the details of the proposed project. These figures are also congruent with a number of other sources, e.g. Andrew Nette (2009), and the information retrieved from Mr. Congdon and Mr. La, who also believed in the possibility of a 460 MW option. The size of the reservoir is however still a much debated topic. The sources presented here predict the reservoir to be between 620 and 880 km^2, which also correlates with the mapping of flooded area as it is presented in Cornford and La(2010) and the expected reservoirs location and area, calculated by the Stimson Center for Oxfam (Oxfam Australia, 2010), which was also used for the LULUCF estimates in the following. This estimate is done assuming the dam wall is 56 meters.

11.6 Overview of the proposed project

The following represents what is currently known of the project, or how the project however is understood in the light of government opaqueness. What is presented below is the result of data obtained through interviews with Oxfam (May 2012; Phnom Penh), WWF (June 2012; Kratie) and CRDT (June 2012; Sambor), as well as the following literature: MRC (1994), Osborne (2004), TERRA (2007), Middelton and Chanthy (2008), ICEM, (2009), Nette (2009), Cornford and La (2010) and Oxfam Australia (2010).

The expected name of the project is Sambor Dam. It is known that the memorandum of understanding (MoU) has been signed with the Chinese state owned hydropower construction company, Sinohydro, who has also conducted a pre-feasibility study of the project, which apparently is not publicly available. The partners of the project are (seemingly) the Cambodian Ministry of Industry, Mines and Energy as well as the China Southern Power Grid Company. To this, it seems like both the French Government and the World Bank are considering to engage in the project.

Table 28 (below) represents an overview of the statistical data of the Sambor Dam. The features presented are a compilation of data from the most recent sources, which also in the official understanding seems to be the current data of what the dam will look like. One of these attributes however seems quite unlikely.

While it is widely accepted that the 40 turbines, each of 60 MW will have a generating capacity of 2600MW and that the average yearly (8760 hours) energy production is 11740 GWH ($1.174 \cdot 10^7$ MW) - it is also noted that the maximum hours of operation per day is 12.47, 'if peak load'. The inconsistency herein is that the annual average energy productions then seems to be calculated on the expectation that the dam will run at peak load year round for its entire lifetime, as:

Equation 11: Hours of operation pr. day

$$\frac{1.174 \cdot 10^7\ MWh \cdot yr^{-1}}{2600\ MW} = 4515\ hours \cdot yr^{-1} = 12.36\ hours \cdot\ d^{-1}$$

Morris and Fan(1997) estimate that the worlds hydropower reservoirs on average lose 1% of their storage capacity each year, and, even more markedly, that Asian reservoirs (primarily in China, though) on average are losing their storage capacity with as much as 2.3% each year.

> *Since there is a direct link between storage capacity and annual energy generating capacity (Morris and Fan, 1997) it renders the above estimate highly unlikely. In the respective paper, a conservative annual negative growth rate of 1% is therefore expected.*

Table 28: Sambor dam statistics (based on the most current and reliable data)

Location	Latitude,	12°46'59.4"N
	Longitude,	105°57'0.62"E
Dam Features	Height,	56 m
	Length,	18,002 m
	Type of Dam construction,	Concrete gravity dam and earth rock fill dam
	Rated Head	16.5 (max 22.9 – min 9.5 m)
	Plant discharge	40 x 441.7 = 17,668 cu.m/sec
	Number of units	40
	Installed capacity	40 x 65 MW = 2,600 MW
	Energy generated Annually (average)	11,740 GWH
	Mode of operation?	*Continuous or peak load?*
	- If peak load, hours of operation per day,	*12.37 hours*
	- If peak load, hours of operation per year	*4515 hours*
	Environmental flow discharge	Continuous
	Spillway design	Open flow, gated spillway
	Design discharge for bottom outlet:	
	- Sediment flushing outlets	*37 release sluices*
	- Dimensions and design discharge	*15 m x 20 m elevation, 159 cu.m/sec = 5,883 cu.m/sec*
Purpose	Proposed marked for electricity	
	- National	*30%*
	- Export to Vietnam	*70%*
	Multipurpose uses	Power, flood control and navigation
Reservoir	Full supply level (FSL)	40 masl
	Low supply level (LSL)	39 masl
	Draw down	1 m
	Areal inundiated at FSL	620 km2
	Active volume	465 million cu.m
	Dead storage volume	3794 million cu.m
	Storage coefficient	0.108%
	Expected daily fluctuations	Small daily regulation, generating all the time
	Approximate length of the reservoir	
Construction	Duration of construction	87 months
	Transmissionlines required	3x260km, 500 kv to HCMC, Vietnam
	Expected size of construction workforce	
	- Average	*2700*
	- Max	*3000*
	Dimension of navigation blocks	
	- Weight	*100 tonnes*
	- Design	*481 m long, 8 m wide*
	- Operational height	*40 - 16 masl*
	Fish passes	
	- Design	*3397.8 m*
	- Mitigation	*Dolphin breeding farm included*
Costs	Dam	4974 million USD
	Transmission lines	312.9 million USD
	Resettlement (80.3 3 million USD for 10.000 ppl)	152.62 million USD
	Environmental	21.24 million USD
	Cost pr. kW	1,685 USD/kw
	Cost pr. kWh	0.373 - 0.398 USD/kWh
	Online tariff	7.23 - 7.97 cents/kWh
	Internal Rate of Return (IRR)	13.0%
	Loan agreement	25 years

Source: MRC (1994), TERRA (2007), Middleton and Chanthy (2008), Nette (2009), ICEM (2009), Conlord and La (2010), International Rivers (2012) as well as interviews with Gordon Congdon (WWF, 2012) and Chhoun La (Oxfam, 2012)

11.7 The climate impact of resettlement

When in Kratie, the CRDT pledged that when travelling along the Mekong River, plans to dam the Mekong would not be mentioned to the local people living; as the indigenous people were not yet aware of it. In one of the villages that would get flooded subsequent to the filling of the reservoir (Koh Khnhaer; between sample point 5 and 7, Map 7 below), the social impact of this became particularly pronounced as a father of two small girls (3 and 4 years old) proudly showed off a building ground on which a new school was just starting to be built. An occurrence, which he predicted, would give his girls (and the community as a whole) the capacity to finally break out of their poverty.

When the reservoir is filled, the MRC and OXFAM (ICEM, 2009; Oxfam Australia, 2010) estimates that 19- to 20.000 thousand people will need resettlement – nearly all of whom are small scale farmers and fishermen. Of these, a large proportion of the indigenous population is bound to a number of different tribes, which do not speak Khmer and live according to ancient traditions, customs and cultures. Not only will the traditional ways of living in the RA cause the resettlement to be difficult, but the fact that many tribes have their own distinct cultures and languages suggests that resettlement to larger cities or larger communities (where they will be mixed either other tribes or the Cambodian people), will not be possible.

Besides the obvious social impacts of resettlements, the flooding of land along the Mekong River is therefore also likely to require large land-use changes elsewhere - in order to make room for new settlements, new croplands and possible infrastructure. Neither Mr. Congdon nor Mr. Chhoun has seen any resettlement plans so far, but they both expect that the people living along the river and on the islands will be resettled to the surrounding forests of the new reservoir. Besides deforestation, this will also put extra pressure on the new neighbouring forests, for firewood extraction and alike.

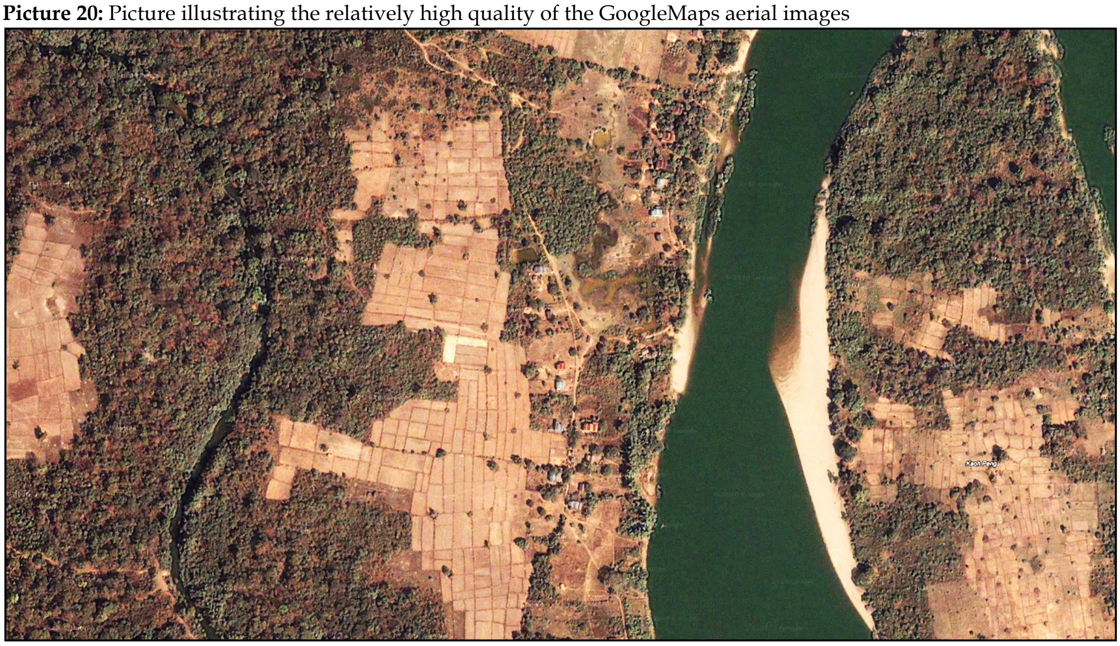
Finally, if the people that were traditionally relying on fisheries in the Mekong River are forced to undertake irrigated agriculture instead, this can result in both additional deforestation and a significant increase of methane emissions (cf. chapter 5.2.4, p. 57).

Chapter 12: Data collection

Prior to the project commencement, the reservoir area (RA) and the area that would be flooded (FA) were mapped using QGIS2.0DEV, according to an expectation of an 867km^2 RA or a total flooded area (FA) of 620km^2. Utilizing the OpenLayers (0.93) plugin, GoogleMaps was used to project and map land-uses of the current area according to the land-use categories defined in the methodology. Some areas have been rendered as *undefinable areas* (UAs). These were areas that would need pre-mapping post groundtruthing and included among others areas that were difficult to distinguish from one another; for example grasslands from fallow lands and forest from swamps. For some of the UAs, groundtruthing was not possible; be it time-wise, inhospitable terrain, security issues, resources or be it another reason. These UAs have all been included in the results as 'other'.

The aerial photographs available through GoogleMaps are primarily from the 2008 dry-season. The aerial images from the western riverbank are however of much higher resolution than the rest of the RA. Consequently, the groundtruthing has been concentrated on the area east of the river as well as the large inhabited island that will see the most areal flooding (Koh Phdao). Groundtruthing was conducted according to the largest UAs and Ad-hoc when travelling on the islands and on the riverbanks. 94% (n=67) of all recorded observations (n=71) were accurate according to the preliminary mapping.

Picture 20: Picture illustrating the relatively high quality of the GoogleMaps aerial images

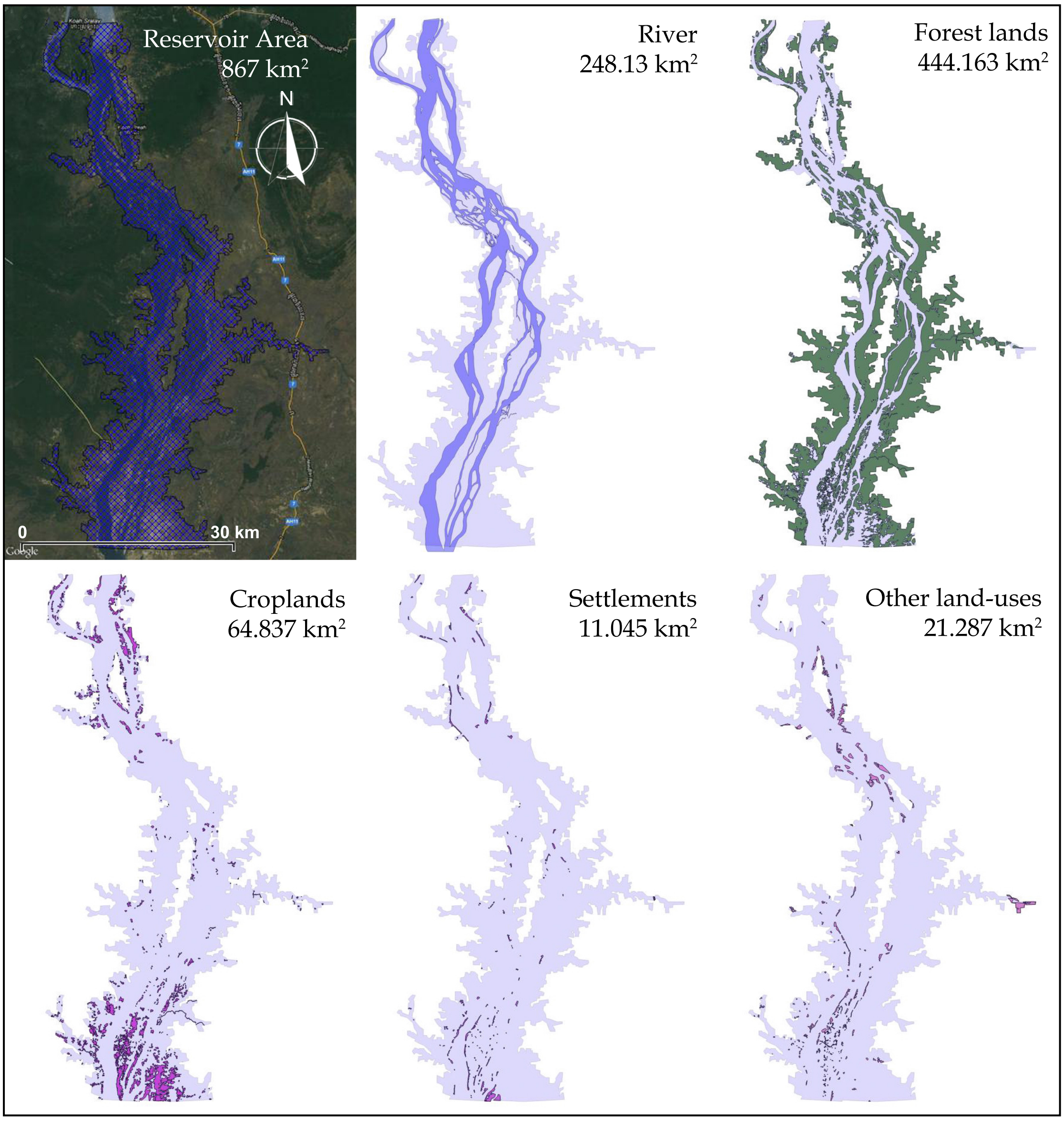


12.1 Areal mapping

The areal results from the preliminary mapping and the subsequent groundtruthing are presented in this subsection. The next chapters will calculate the carbon storage changes and the NEE changes based on these areal measurements.

The maps presented below represents the proportion of the specific areas that are going to be flooded. The illustrations clearly demonstrate how the main proportion of the people living in the FA is concentrated in the SE (in, or close to, the Sambor Village) where the most extensive flooding will occur.

Map 6: Significant flooded areas with flooded area sizes, according to mapping and groundtruthing



Forests:

It is estimated that 444.163 km^2 of *deciduous dipterocarp forest* will be flooded. This area represents 51.22% of the total RA. The preliminary mapping however suggested a relatively larger area of 486.70 m^2 or 56.13% of the RA, but the groundtruthing witnessed massive deforestation in the NE part of the RA between Koh Khnear and Stung Treng. None of the deciduous dipterocarp forests had significant buttresses which would complicate biometric measurements (cf. chapter 2.2.4, p.27).

In addition, 0.183 km^2, of *mixed deciduous forests* and *semi-evergreen forests* is estimated to be flooded. This represents less than 0.03 % of the RA and corresponds to the assertion presented earlier; that all of these forest stands primarily are found at the higher grounds in the NW part of the RA, and in the area W of Koh Khnear.

Croplands:

64.837 km^2 of croplands is estimated to be flooded. This area represents 7.48 % of the RA. Of the agricultural fields, roughly 80% is estimated to be rice fields, which supports one, or rarely two growing seasons. The cultivation methods in the RA are primitive, and the use of pesticides and fertilizers are practically not occurring.

Wetlands:

For *swamps*, one small swamp was identified close to Stung Treng, and another smaller swamp on the western banks of the Koh Phdao island. In total, the swamp areas are estimated to cover less than 0.3% of the RA, or an area of 2.901km^2. Neither the preliminary mapping nor the groundtruthing identified any *peatlands* or *marshes*.

Lakes:	No lakes are expected to be flooded.
Rivers:	The total riverine area that will be engulfed by the reservoirs comprises 248.13 km^2 or 28.62% of the RA. Included in this estimate are some sandy areas, which are exposed at low water levels. There are no tributaries to the Mekong River between Sambor and Stung Treng.
Settlements:	Most of the areas that were inhabited were rather large, and had distinct quadratic shapes, often supported a few big trees, a small area with basic crops, access to the waterfront and an area dedicated for the locals to work, repair their boats, houses or alike. Often, the inhabited lands also accommodated a few pigs or a flock of hens. Included in the settlement areas are also the path systems in-between houses in areas where these stand close together i.e. in small villages. The mapping found that 11.045 km^2 or 1.27% of the RA was covered by settlements.
Grasslands:	Grasslands are understood here as areas covered by land that supports little or no forest vegetation. In total, these areas are estimated to cover 74.49 km^2 or 4.3% of the RA. Included in this estimate are also the large deforested areas south of Stung Treng (37.1 km^2).
UA's and other land-uses:	21.287 km^2 or 3.43% of the RA supported other land-uses than those considered here. And of these, 59% denote UAs that could not be classified and which it was not possible to identify through groundtruthing. The remaining 12.559 km^2 primarily consists of infrastructure such as paths[95], as well as rubber and cassava plantations. Only the villagers in the Sambor village (which will only be partly flooded) and Stung Treng (which are not likely to be flooded) enjoy electricity from the electricity grid, whereas the villages along the river only enjoy limited access to electricity from household diesel generators.

12.1.1 Simplifications in mapping

Generally, only *forested areas*, which are in accordance with the FAO forest definition (defined in chapter 2.2.2, p. 25), are included. This excludes trees in inhabited areas, singular trees, or small clusters of trees on fields, as well as sparse forest vegetation in the transition between forests and non-forested areas despite these trees are often many and large - probably as they are preserved to provide shadow in the warm season, and shelter from wind and rain during the rainy season. The trees have furthermore been left standing in open areas with little competition for nutrients and sunlight, which have likely helped them grow particularly large.

To the probable underestimate of the excluded forested areas, comes a probable underestimate of small scale farming areas (primarily found in the inhabited areas) and croplands that were not supporting produce at the time the aerial images were taken, which rendered them hard to distinguish from grasslands.

Areas such as paths have also been included where they were visible (e.g. through the tree tops). This is slightly expected to contribute to the general picture of a conservative estimate (as most paths in the RA must not be misinterpreted as roads, where trees have been cut down in order to make way for passage). In almost all instances, paths outside of the villages were merely coiling sandy trails (<2m wide), which were barely able to support a single small motorbike or at best, in the areas closest to the habituated areas, a small cart. Having excluded these areas is therefore likely to have decreased the total forested area, as they are not necessary antagonisms to the forested land.

> *In general, all simplifications to the mapping method follow the concept of developing a conservative estimate.*

12.1.2 Difficulties in mapping

The primary difficulty in mapping was the low quality aerial photographs of some areas. It is peculiar why the most inhabited areas of Sambor and the southern part of Koh Phdao are the

[95] The only paved road in the RA was the National Highway 7, of which less than 500m is tangent to the RA East-SE of Koh Khnear.

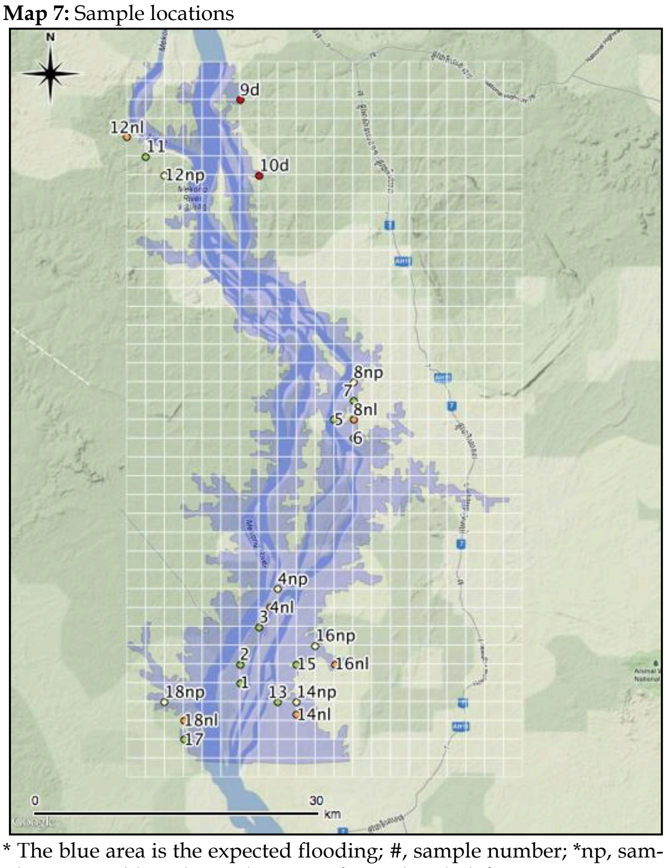
places with the lowest quality areal photos, while the aerial images of the sparsely populated western bank is of very high quality (see Picture 20, p.113). Due to the quality of the aerial imagery it was not adequately possible to distinguish between some young plantations and agricultural lands, and possibly between some of the few relatively older plantations and forest stands. For grown up plantations, some might have been included as forests.

The inhabited areas were in general also especially difficult to distinguish from the surrounding lands, not at least as most consisted of very primitive lodges surrounded by tall trees. Where it was possible, the inhabited areas have been mapped, but the difficulty in distinguishing them from other areas, have undoubtedly led to a rather large percentage of the inhabited areas included in the 'others' category - or possibly even in the forest category.

12.2 Sampling

In total, 40 samples were chosen preliminary to project initiation in accordance with earlier described methods. The circumstances described below were however limiting the amount of samples possible to take each day in the field (1 to, rarely, 3 samples), just as the deforestation in the NE of RA also ruled out a number of the samples. Consequently, only 18 samples were taken throughout the RA (according to the map presented below (Map 7), which also shows the grid used to define the sample locations). Of the conducted samples, only 66.7% (n=12) were taken exactly on the defined coordinate, as it was not possible to penetrate the terrain to the precise location of the remaining. In these cases, samples were taken as close as possible.

Map 7: Sample locations



* The blue area is the expected flooding; #, sample number; *np, sample not possible; *nl, new location of sample; *d, deforestation

Each sample area was 400 m^2, making the total sample area 6800 m^2. All trees with a DBH over 10cm were sampled (n=368). Average tree density was found to 55.1 $trees \cdot ha^{-1}$, range 24.3-98.2 $trees \cdot ha^{-1}$; see Table 29, below.

Table 29: Overview of sample

#	Date	Location	Position	Undisturbed?	Dominant species	n (400m^2)	Trees pr. ha
1	5/6/12	East of Koh Phdao village	Planned	no	deciduous dipterocarp	39	98.2
2	6/6/12	East of Koh Phdao village	Planned	no	deciduous dipterocarp	20	49.6
3	7/6/12	North of Koh Phdao villa	Planned	no	deciduous dipterocarp	35	88.2
4	7/6/12	North of Koh Phdao villa	New	yes	deciduous dipterocarp	24	60.0
5	10/6/12	South of Koh Khnear villa	Planned	no	deciduous dipterocarp	21	52.5
6	11/6/12	South of Koh Khnear Vill	Planned	no	deciduous dipterocarp	10	25.1
7	11/6/12	North of Koh Khnear	Planned	no	deciduous dipterocarp	11	28.4
8	11/6/12	North of Koh Khnear	New	no	deciduous dipterocarp	19	47.5
9	13/6/12	Close to Stung Treng	Planned	-	-	-	-
10	14/6/12	South of Stung Treng	Planned	-	-	-	-
11	16/6/12	South of Kang Cham	Planned	yes	mixed semi-evergreen	32	80.0
12	16/6/12	South of Kang Cham	New	yes	mixed semi-evergreen	27	67.5
13	18/6/12	Close to Sambor	Planned	no	deciduous dipterocarp	18	45.0
14	18/6/12	Close to Sambor	New	no	deciduous dipterocarp	13	31.8
15	19/6/12	North of Sambor	Planned	no	deciduous dipterocarp	26	65.0
16	19/6/12	North of Sambor	New	yes	deciduous dipterocarp	26	65.0
17	20/6/12	South West, no village	Planned	yes	deciduous dipterocarp	24	58.8
18	20/6/12	South West, no village	New	yes	deciduous dipterocarp	23	57.5
		Total/Average				368	57.5

All around the most habituated areas; that is N of Koh Phdao village up to approximately where the third or fourth sample was taken, N of Sambor to between sample 15 and 16, and around Koh Khnear (sample 5-8), there were practically no undisturbed forests. All forests in these areas were subject to light foresting for firewood, building materials and alike. This is also mirrored in the results presented in the final chapters, which shows that these are the samples with the smallest carbon densities. Correspondingly, in these cases when samples were taken further away from the habituated areas, the carbon density was larger (see Table 30, p. 122 below). The widespread resource extraction from the forest was also evident in that tree stumps from large trees were found in all of the sampled cases.

12.2.1 Difficulties in sampling

The actual sampling proved an especially difficult task, primarily due to the inhospitality of the terrain, the humid climate and the heavy rainfalls during mid-day as well as the high water levels, which had devoured many of the roads. There were also no guesthouses between Kratie and Stung Treng, which could provide lodging and food; wherefore much time was used to establish contact with the indigenous people who did not speak Khmer. The transport to the planned sampling locations was also especially strenuous, and often required several hours of transport by motorbike and boat for each spot. Through the island, Koh Phdoa, CRDT was so kind to escort and helped to establish contact with local people for food and lodging, but from here on sampling and getting around became very resource intensive. Due to the limited time (2 months in total for the interviews, groundtruthing and sampling), limited resources, security concerns and an almost impassable terrain in some of the areas along the RA, the amount of forests stands sampled is hence somewhat limited compared to what was first intended (40/18).

Only a very small percentage of the forest is included as mixed deciduous and semi-evergreen forests. To this, it must however be noted that, it was not possible to conduct groundtruthing between sample point 12 and 18 (see Map 7, p. 116) more than what could be done from boat. Furthermore, Mr. Congdon from the WWF was of the impression that at a large proportion of the areas were supporting mixed deciduous forests and semi-evergreen forests. The aerial photographs suggest that this might well be true (the trees have a darker shade of green than the rest of the area), but that the deciduous dipterocarp forest still dominates the low areas closest to the riverbank, where the majority of the flooding will occur. This is in accordance with the experience from the groundtruthing.

Considering the proportion of the forests not verified through groundtruthing to be deciduous dipterocarp forests, contributes to the conservative estimate as the carbon density of the mixed deciduous dipterocarp forests, compared to the semi-evergreen forests, were estimated to be significantly lower (see table Table 30, *p. 122 below).*

12.3 Current trends

The present chapter will discuss current trends in the RA as was experienced during the field trip. The focus is primarily on trends which will affect storage and NEE over the lifetime of the proposed reservoir.

While some sources (as well as some local people) were refusing to have any knowledge of the very obvious fact that large scale deforestation were taking place all along the NE coast of the Mekong River, others reported that extensive deforestation had been going on since early 2000, and escalated since 2008-2009 (for reference, please also see: The Cambodia Daily, 2012). During these years, Chinese corporations had bought vast quantities of land from the Cambodian government in order to establish enormous cassava and rubber plantations.

Apparently the land had been sold off over the head of the indigenous people living in, and of the forest's resources (also see Cornford & La, 2010), which at the time of visit was a painful topic, after a young girl was killed subsequent to having presented a journalist to some of the areas under the heaviest pressure from Chinese land "concessors" (BBC, 2012; The Independent, 2012; Time Magazine, 2012). The unease coupled with this incident, along with the general opaqueness of government decision and planning processes, made it almost impossible to understand if more land was being sold along the Mekong River from Sambor to Stung Treng which would cause a further diminution of the forest covered land. When visiting the sites, large areas of forests were however currently being burned and cut down, which would indicate that much deforestation was still going on.

Picture 21: Deforestation in the mixed deciduous forests NW of the RA

Photo: Lasse Jesper Pedersen

On the contrary recent deforestation events have attracted much attention to the deforestation problematic of the region, which in turn have caused many current politicians to blame former governments for having sold the land rights to Chinese land concessors (BBC, 2012; The Independent, 2012). Additional to this, the WWF and other NGOs have in recent years also started to advocate the importance of the Cambodian dry forest as the largest intact dry forest in Indochina, through the *Dry Forest Eco region Action Programme* (WWF, 2012). This could have (or could have had?) the potential to cause deforestation rates of the entire region to decrease in the years to come.

Along the river, another pattern also seems to emerge, as markedly less deforestation was happening on the riverbanks in the deforested zones. This might possibly mirror an expectation (or maybe even knowledge) of the plans to flood these areas for the dam reservoir in the future – this theory obviously lacks verification, but does seem likely considering that Chinese SOEs are behind both the establishments of many cassava and rubber plantations, as well as the proposed dam in Sambor.

Additional to the deforestation caused by the Chinese SOEs, the local population is burning down forest areas to convert them into croplands. The natural 10m fluctuations of the Mekong River have traditionally been utilized for irrigation of rice fields, but, in recent years, locals have reported the fluctuations as being less predictable and smaller, which, even on the countryside were attributed and reflected upon as a consequence of hydropower development upstream of Cambodia. As a result, the yields of the rice fields which were being fed by the river earlier is now becoming smaller, just as the number of growing seasons in many places along the river have been reduced from two to one. The consequence of this has been that the rice farmers have had to cut down more forests to establish more fields, in order to support themselves and their families with rice. The fewer growing seasons are hence directly responded to by cutting down more forests, which then causes both a reduction of the carbon pool and the possible sink of the forests.

Chapter 13: NEE and storage before RA inundation

In order to estimate the net change in atmospheric GHGs caused by the LULUCF of the hydroelectric reservoir over its lifetime, one must estimate both *current* carbon stocks[96] and the annual NEE over all ecosystems in the RA. Also, IIL must be included in the estimate.

13.1 Inclusion of indirectly implicated lands

Additional to land-use changes in the RA, croplands and inhabited sites are expected to be re-established post inundation. Most croplands and inhabited sites are furthermore anticipated to be re-established in the immediate proximity of the reservoir area, post inundation. That is;

1) Partly as this was the expectation of both Mr. Congdon and Mr. Chhoun,
2) Partly as the majority of the population and the majority of the croplands are found along the riverbanks today, and;
3) Partly as most of the people living in the RA are indigenous tribes, speaking their own language and living according to their own customs, norms and culture, which renders them difficult to integrate in the Cambodian society outside the RA[97].

(For reference please see chapter 11.7, p.112),

The immediate outskirts of the RA were mapped subsequent to the field trip. Here it was found that these primarily consist of forests (cf. Map 8 below). Therefore a conservative estimate would be that (at least) 50% of the current settlements and croplands would replace forest stands post inundation. Also, a large part of the land which is included as others is expected to be path-systems or other land-uses emanated from the presence of humans, hence a conservative 10% of the land included as "others" are too expected to replace forest stands post inundation.

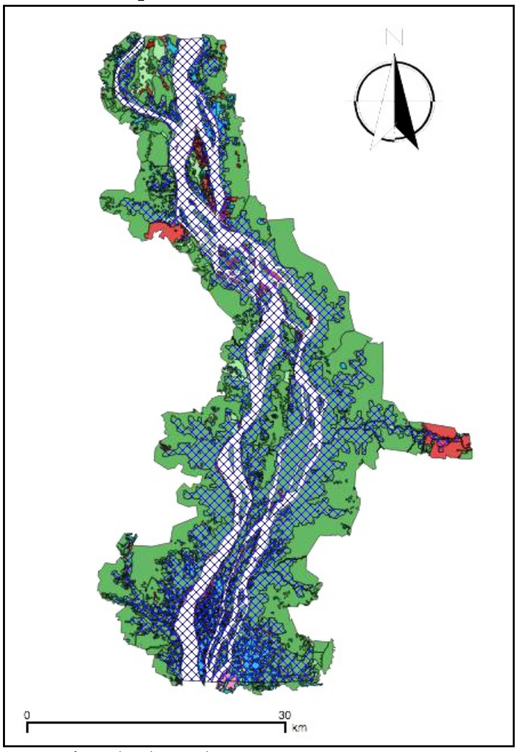
As croplands and settled areas currently comprise 64.837km^2 and 11.045km^2 respectively, or a compiled total of 75.822km^2, and other land-uses currently comprise 12.56km^2;

> *At least 37.911 + 1.26 km^2 of deciduous dipterocarp forests are consequently expected to be lost <u>outside</u> the RA subsequent to reservoir filling.*

Additionally, forestlands lost *inside* the RA, 2.9 km^2 swamp forest close to Stung Treng and West of Koh Khner is also expected to collapse (see chapter 5.4, p.62). Because of the very small areal extend, and difficulties in mapping, of these swamps, it was decided not to do sampling of these areas, and the carbon *storage* in the swamp trees are hereafter therefore included with the forestland estimates.

[96] Expressed here as the storage in the forest biomass
[97] The area consists of 5 tribes; besides possible difficulties in integrating them with outside cambodian society it might even be difficult to integrate them with one another, as cultures and norms differ significantly.

Map 8: The RA and its outskirts



Green = forestlands, Hachure = RA

13.2 Carbon stored in the forests of the Flooded area at present

The height and diameter of the trees was measured with a *Biltmore Stick* and a measuring tape (according to the methods described earlier) to estimate the carbon density of the 400m^2 large sample areas. The average carbon density, ignoring understory and trees with a DBH>10 cm was found to be 8.43 ± 4.75 $kgC \cdot m^{-2}$ (n=16), this number is however reduced to 6.67±1.60 $kgC \cdot m^{-2}$ (n=14 with a much higher significance (SD=1.6), when only the diptero-carp forest is considered; despite that the average tree density when doing so still ranges from 25.1-98.2 $trees \cdot ha^{-1}$.

Findings by McEwan et al. (2011) presented earlier (chapter 4.5, p. 48) indicate a possible positive relationship between stem density (number of trees pr. area land) and carbon stocks, which, however, was not distinct in the samples measured (see Table 30, below)

Table 30: Overview of samples with carbon pr. m^2

#	Date	Dominant species	n (400m^2)	Unisturbed?	Trees pr. ha	kgC pr. m2
1	5/6/12	deciduous dipterocarp	39	no	98.2	5.25
2	6/6/12	deciduous dipterocarp	20	no	49.6	7.29
3	7/6/12	deciduous dipterocarp	35	no	88.2	7.20
4	7/6/12	deciduous dipterocarp	24	yes	60.0	8.09
5	10/6/12	deciduous dipterocarp	21	no	52.5	7.60
6	11/6/12	deciduous dipterocarp	10	no	25.1	8.41
7	11/6/12	deciduous dipterocarp	11	no	28.4	5.52
8	11/6/12	deciduous dipterocarp	19	no	47.5	6.64
9	13/6/12	-	-	-		
10	14/6/12	-	-	-		
11	16/6/12	mixed semi-evergreen	32	yes	80.0	22.17
12	16/6/12	mixed semi-evergreen	27	yes	67.5	16.23
13	18/6/12	deciduous dipterocarp	18	no	45.0	5.05
14	18/6/12	deciduous dipterocarp	13	no	31.8	3.18
15	19/6/12	deciduous dipterocarp	26	no	65.0	5.50
16	19/6/12	deciduous dipterocarp	26	yes	65.0	6.57
17	20/6/12	deciduous dipterocarp	24	yes	58.8	8.27
18	20/6/12	deciduous dipterocarp	23	yes	57.5	8.79
		Average All	*22*		*55*	*8.43*
		Standard deviation (all)	*7*		*18*	*4.75*
		Average deciduous dipterocarp forest	*22*		*55*	*6.67*
		Standard deviation (deciduous depterocarp	*8*		*21*	*1.60*

The understory of the area was mainly grass, and is not estimated to contribute to the total carbon storage. The same is the case for dead trees and other woody debris, which for a very large part were picked up by locals for firewood or other household uses. A contribution of at least 13.3% must, however, be made in order to include trees with a DBH<10cm (cf. chapter 2.2.5, p.29).

This suggests an *average* carbon storage between 7.54[98] and 9.53[99] $kgC \cdot m^{-2}$ (depending on whether or not the mixed semi-evergreen forests is included), or a *total* carbon storage of the forests in the FA (incl. swamp trees) between 3.369 and 4.261$\cdot 10^9 tC$, equivalent to 12.365 or 15.637$\cdot 10^9 tCO_2$[100]. However, since the mixed deciduous dipterocarp forests, and the semi-evergreen forests comprise less than 1% of the total forested area:

> *The total carbon stored in the forest in the RA[101] is estimated to be 447.064 $km^2 \cdot 7.54\ kgC \cdot m^{-2}$, or 13.89$\cdot 10^9 tCO_2$.*

To this, the forests lost due to resettlement and re-establishment of croplands outside the RA must be added (cf. chapter 13.1).

> *The total carbon stored in the forests indirectly implicated by the building of the dam outside the RA is hence estimated to be 37.911+1.26 $km^2 \cdot 7.54\ kgC \cdot m^{-2}$, or 1.08$\cdot 10^9 tCO_2$.*

13.2.1 Evaluating this estimate

The sample results showed little difference between stands with regard to carbon density and tree species (see Table 29, p. 117). Close to all forest samples, as well forest identified through groundtruthing, belonged solitary to the deciduous dipterocarp species, which is in agreement with the impression from most of the preliminary mapping. Also the SD between the deciduous dipterocarp species where reasonably low. This indicates that the estimates pre-

98 6.67+13.3%
99 8.43 + 13.3%
100 Conversion from C to CO_2 cf. chapter 2.2.6, p. 28
101 Including 2.9 $km^2$of swamp landwhich are expected to collapse upon reservoir filling (cf. chapter 13.1, p. 121).

sented in the final chapters, despite the few samples, the uncertainties and difficulties in mapping, are believed to be good indicators of the carbon sequestrated in the forests of the RA.

The estimate on the average carbon storage in kg pr. m^2 presented above is significantly lower than average values for SEA (13.2-17.4 $kgC \cdot m^{-2}$), and more similar to average values presented for boreal and temperate forests (2.1-8 $kgC \cdot m^{-2}$). Many factors could have caused this heterogeneity, but a significant factor is undoubtedly that little of the forest in the sampled areas were undisturbed, and that the ones that appeared so, might as well have been under some pressure from locals extracting resources from it. Correspondingly, there are practically no larger areas that do not support at least little habitation (Map 6, p.114). In addition to the removal of woody biomass, the reiterated extraction of resources might also have caused the stands closest to the larger habituated areas to appear relatively young. The average stand age of these areas as "young" could not be confirmed during the field trip, but it does seem plausible as locals were regularly using large trees to build necessities such as houses and boats. The evidence of this was the numerous large tree stumps that stood behind.

Finally the unfertile plinthosols of the region are also likely to have caused a decreased carbon uptake and hence a relatively lower carbon stock of the young stands. Also, the unfertile soils might have caused the trees to allocate more carbon to the roots than the AGB, just as low species diversity is also thought to cause lower carbon stocks. Finally, the reverberations after Cambodia's very recent and very bloody history under the Pol Pot regime less than 30 years ago, where a quarter of the entire population were murdered, and all cities were ordered abandoned, must have put the forests under immense pressure, from which they are now just slowly recovering.

Factors that would have pulled in the opposite direction are that all tree species were medium to heavy hardwoods, and that warmer conditions generally fosters increased carbon accumulation in the AGB and lower accumulation in the tree roots (possibly somewhat counterbalanced by the low nutrient availability, which had the opposite effect). The low slope convexity and the low altitudes would have been indicating good conditions for high carbon stocks.

Strictly observed from a climate perspective; cutting down large forested areas has its obvious advantages with regard to the climate impact consequent to the reservoir filling. The deforestation in the FA will mean that less organic material will make its way to the reservoir. The forest is however not being cut down, because they are needed to fulfil any demand which would otherwise require that forests would be cut down elsewhere. Rather the deforestation happens in order to make way for croplands and plantations, the consequence of which is just as severe, considering that some of the carbon bound in the flooded forests would otherwise have been sequestered at the bottom of the reservoir.

13.3 Net ecosystem exchange at present

The total NEE of the RA ecosystem at present is mainly a combination of the flux balance over forests, wetlands and aquatic ecosystems as they look today. Here the current NEE of each system is estimated relative to the areal estimates in chapter 12.1 (p. 113) and areal presumptions from chapter 13.1 (p. 120). These estimates are converted into CO_2 equivalents in accordance with the GWP of each gas (chapter 1.3, p. 7). The results are presented below. The degree to which each land-use are analysed before inclusion are relative to the tier-level identification in this papers methodology (chapter 2.1.2.a, p. 21; and Table 4, p. 22).

The NEE over tropical forests in SEA is in average calculated to be *3620±1989* $mgCO_2 \cdot m^{-2} \cdot d^{-1}$, but, *w*ith regards to the forest carbon stocks estimated here, it was evident that the region supports lower carbon stocks per areal unit of forest, compared to other tropical Asian forests (chapter 13.2, p.121). This is probably caused by variables such as human disturbances, the unfertile soil, low species diversity and more[102]. Here it is unknown in which way the low carbon stocks will affect the NEE of the forests, as it was also estimated that most of the stands were very young. In chapter 9.2.2 (p. 90) it was discussed how the role of forest age affected the carbon stocks negatively; while on the contrary chapter 4.5 (p. 48) argued that younger stands, as well as stands in areas with little competition aggregated substantially higher rates of carbon storage per unit time than did the old growth forests.

In addition to this, no other variables suggests that the NEE over forests should be significantly lower in this area over the long term, but to incorporate the possible lower NEE, the forest sink of CO_2, and the forest release of CH_4 and N_2O are reduced by one quarter in the estimates below.

Table 31: NEE over the RA at present

	Area	CO_2		CH_4		N_2O		CO_{2eq} (100yrs[1])	
	$[km^2]$	$[mg \cdot m^{-2} \cdot yr^{-1}]$	$[t \cdot yr^{-1}]$	$[mg \cdot m^{-2} \cdot yr^{-1}]$	$[t \cdot yr^{-1}]$	$[mg \cdot m^{-2} \cdot yr^{-1}]$	$[t \cdot yr^{-1}]$	$[mg \cdot m^{-2} \cdot yr^{-1}]$	$[t \cdot yr^{-1}]$
Forests	444.3	2,896	469,691	-0.24	-39	-0.584	-95	2,774	449,964
Croplands (IIL)[2]	64.8	2,896	34,268	-0.24	-3	-0.584	-7	2,774	32,828
Grasslands	74.5	0	0	0	0	0	0	0	0
W. Peatlands	0.0	-2,343	0	-7.7	0	0	0	-2,536	0
W. Swamps	2.9	-2,343	-2,481	-279	-295	0	0	-9,318	-9,867
W. Marshes[3]	0.0	0	0	-235.8	0	0	0	-5,895	0
Lakes	0.0	-600	0	-122.4	0	0	0	-3,660	0
Reservoirs	0.0	-3,298	0	-75.8	0	0	0	-5,193	0
River	248.1	-1,538	-139,293	-16.4	-1,485	0	0	-1,948	-176,425
Settlements (IIL)[2]	11.0	2,896	5,838	-0.24	0	-0.584	-1	2,774	5,592
Other[4]	21.3	2,896	4,500	-0.24	0	-0.584	-1	2,774	4,311
Total	867.0		362,185		-1,822		-102		296,501

[1]) GWP calculated based on a 100yr timeframe, cf. chapter 1.3, p.7
[2]) At least 37.911 km^2 of forest lands are expected to be replaced due to resettlement and re-establishment of croplands, cf. chapter 13.1, p. 120
[3]) No NEE of CO_2 were identified in the background chapters,
[4]) 10% of other is expected to replace forest lands, cf. chapter 13.1, p. 120

13.3.1 Evaluating this estimate

One might argue that the plantations are likely of greater value than natural forests in the global climate budget, which was also discussed in chapter 4.5 (p. 48). In the case presented here however; the extraction of rubber from the rubber plantations is likely to pose a great deal of stress on the rubber trees, which might cause them to sequester less carbon, or one could argue that the extraction of rubber (rubber particle: C_5H_8) for production somehow causes rubber plantations to play a relatively larger role in carbon budgets. For the cassava trees; their roots and leaves are harvested by pulling up the entire tree stem. Then the replanting is done by burying 10-15 cm of the harvested stem from which a new tree will grow. Upon harvesting, the carbon that is sequestered in the cassava roots are returned to the atmosphere, rendering the planting of cassava trees somewhat of a zero sum carbon exchange. Some larger plantations in areas which were not ground-truthed might have appeared as forest in the preliminary mapping, the consequence of which has not been included in the estimates above.

Finally the original river weighs significantly in these estimates. This underlines the importance of on site NEE measurements to accurately assess its magnitude; measurements which of several reasons[103], where not possible here. Based on what data was obtainable, none of the identified variables suggests that the river should have either significantly high, or significantly low, GHG fluxes.

102 Discussed in chapter 13.2.1, p. 123, above

103 Discussed in the tier-level identification, Chapter 2.1.2.a, p. 20; and Table 4, p. 21

Chapter 14: NEE and storage post RA inundation

The NEE of aquatic ecosystems is a balance between releases and uptakes. In order to estimate the total NEE change of GHGs post inundation, both the net change in releases *over* the ecosystem and the net change in uptakes *in* the reservoir as well as the lifetime of the hydropower dam, must be considered.

14.1 Organic carbon burial in the reservoir sediments

The B_C of Asian reservoirs on average lies between 0.02 and 3.3 $kgC \cdot m^{-2} \cdot yr^{-1}$ (cf. chapter 9.3, p.93). When converted into CO_2 equivalents, this equals 0.06359 to 10.49$\cdot 10^6$ $tCO_{2eq} \cdot yr^{-1}$ for the 867 km^2 reservoir. However, as discussed in the same chapter, the B_C in reservoirs is extremely dependent on the size of the reservoir, for which reason an estimate as the one presented here, might very well mirror the difference between large hydroelectric reservoirs (0.02 $kgC \cdot m^{-2} \cdot yr^{-1}$) and small meso-eutrophic reservoirs (3.3 $kgC \cdot m^{-2} \cdot yr^{-1}$). B_C is therefore probably better understood as a function relative to size, as the one presented by Downing et al. (2008) in the same chapter. The function $B_C = 1060 \cdot A^{-0.298}$ (cf. Equation 10, p. 94) was found to have a high explanatory value for eutrophic reservoirs up to 20 km^2. If this function is extrapolated to the 867 km^2 Sambor reservoir, the OC burial rate is estimated to be 0.448$\cdot 10^6 tCO_{2eq} \cdot yr^{-1}$. The Downing et al. (2008) report did however not included any hydroelectric reservoirs, for which sedimentation rates, for reasons already discussed, are considered relatively low (cf. chapter 9.3, p. 93). Additionally:

1) All reservoirs in the Downing et al. (2008) report were on eutrophic reservoirs, which have the highest B_C (cf. chapter 9.3.2, p. 94);
2) Trophic status is positively related to the use of fertilizers and negatively related to lake size (chapter 9.3.2, p.94); the sole inclusion of eutrophic reservoirs in the report therefore poses an additional probability that the use of the function will pose a serious overestimate,
    a. As fertilizers are not used in the RA (cf. chapter 12.1, p. 113), and;
    b. As the RA is expected to be more than 40 times as big as the largest reservoirs included in his study.

Thus a relatively smaller sedimentation rate will also be considered (scenario 2), namely the 0.02 $kgC \cdot m^{-2} \cdot yr^{-1}$ which represents the low end of the Asian reservoir B_C measured by Mulholland and Elwood (1982). Having committed to maintain a conservative estimate, this is justified in that:

1) These estimates recently have been criticized to be up to 60% to large (Parekh, 2004);
2) That their estimates were not solely on hydroelectric reservoirs, and;
3) The main proportion of the sediments, which are transported in the rivers and into the reservoir, supposedly would have been sequestered downstream or in the ocean neither way.

Based on this presumption, the OC burial rate for the Sambor reservoir is estimated to be 0.0636$\cdot 10^6$ $tCO_{2eq} \cdot yr^{-1}$ *(scenario 2).*

14.1.1 Evaluating this estimate

The operation of hydroelectric dams might alter the river in ways which will cause erosion of the riverbanks, and hence increased sedimentation (Wang & Hu, 2009), but due to the many reasons already discussed (cf. chapter 9.3, p. 93), much of the sediment which will be deposited in the reservoir would have been sequestered downstream neither way. Ellis et al., (2012) for example recently estimated how much OC was transported from the Mekong River into the ocean during 2006 and found that $1.67 \cdot 10^6 t$ OC where captured *en route* (Ellis et al., 2012). The downstream effects of hydropower damming is outside the scope of this report, but these numbers give an idea of the magnitude of OC which would neither way be stored in the biosphere in the absence of the dam.

14.2 NEE of off the reservoir surface

Considering a RA of 867 km² and expecting the average NEE of GHGs over tropical reservoirs as estimated in chapter 7.3 and forward (p. 70f) the annual release of GHGs from the hydroelectric reservoir is expected to be 1000000 $tCO_2 \cdot yr^{-1}$, 23990 $tCH_4 \cdot yr^{-1}$ and 0 $tN_2O \cdot yr^{-1}$ or converted to CO_2 equivalents, a *release* of 1597500 $tCO_{2eq} \cdot yr^{-1}$.

14.2.1 Reservoir age dependency

The mean release values from hydroelectric reservoirs are however, as discussed in chapter 7.7 and 7.8 (p.79f) characterized by a significant dependence on time. As most of the reservoirs included in the study for tropical regions are quite young, a mean value is likely to pose a significant overestimation. The average NEE over tropical reservoirs should rather be understood relative to their age, following a logarithmic function calculated on the background of the values for tropical reservoirs presented in appendix 1; hence:

Equation 12: Function for estimating the total release of CO_2 from tropical reservoirs relative to their age

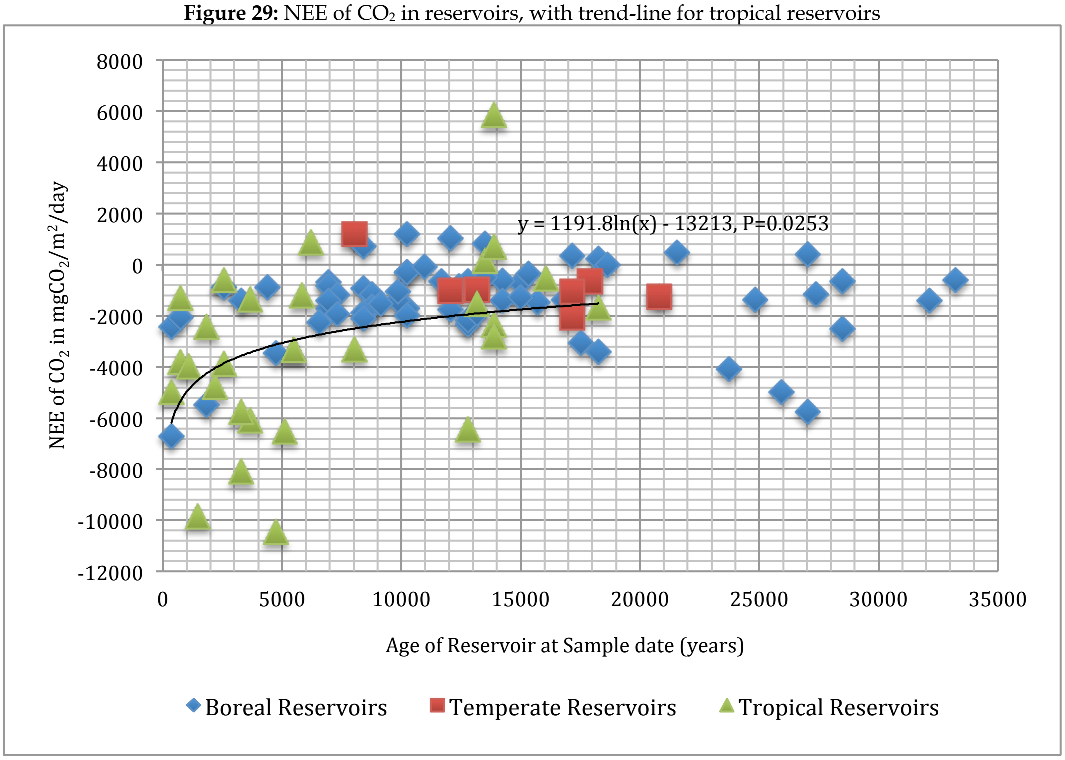
$$y_{CO_2} = 1191.8 \cdot \ln(x) - 13213, P_{y_{CO_2}} = 0.0253$$

Equation 13: Function for estimating the total release of CH_4 from tropical reservoirs relative to their age

$$y_{CH_4} = 8.8779 \cdot \ln(x) - 152.28, P_{y_{CH_4}} = 0.1596$$

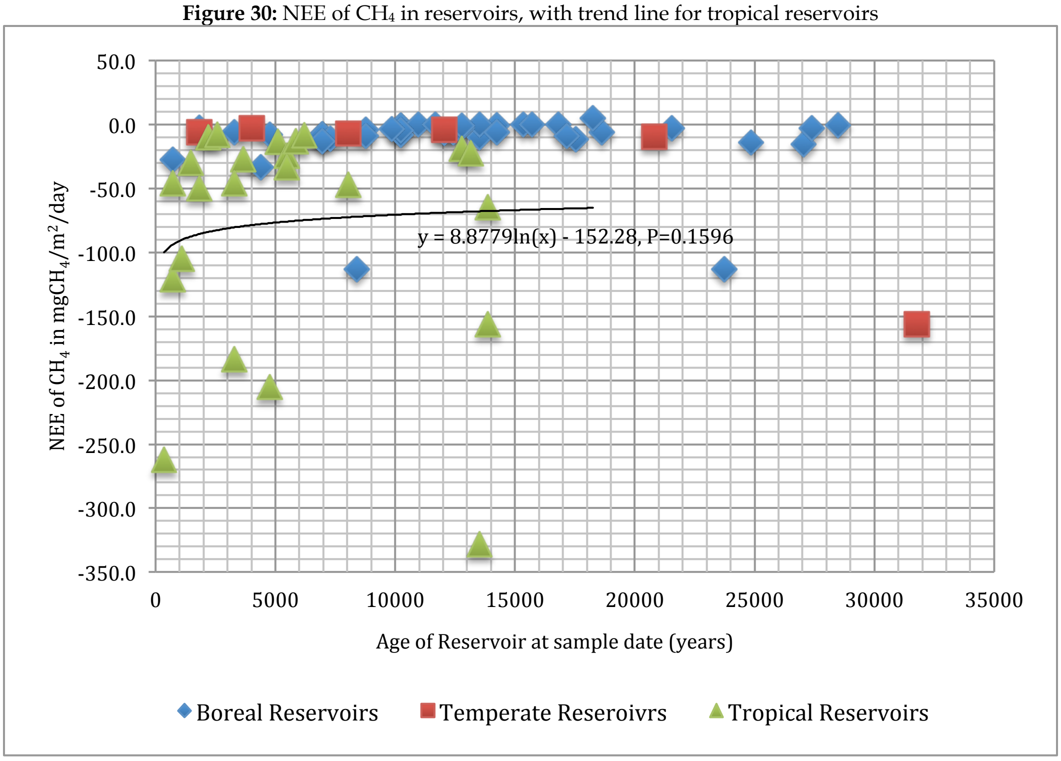
Where x is the age of the reservoir in *days* and y is the release in $mg \cdot m^2 \cdot d^{-1}$ of CO_2 and CH_4 respectively. This is of cause an extrapolation based on average values and presumption that the trend will continue after 50 years, which is the age of the oldest tropical reservoir included in the study. While the function resembling the NEE of CO_2 has a fairly high significance (P=0.0253), the significance of the function resembling NEE of CH_4 is more vague (P=0.1596) which suggests that especially for methane, many other factors age affect NEE.

Figure 29: NEE of CO_2 in reservoirs, with trend-line for tropical reservoirs



Source: Compilation of data from Appendix 1

Figure 30: NEE of CH_4 in reservoirs, with trend line for tropical reservoirs



Source: Compilation of data from Appendix 1

14.2.2 Reservoir depth dependency

A determining proxy for ebullition flux of methane is furthermore; water depth. The more shallow the water; the higher the likeliness of a large ebullition flux component as:

1) The *hydrostatic pressure* that the bubbles have to overcome to leave the sediment is lower in shallow waters;
2) The *temperature* (on which methanogenesis rate depends) is higher in shallow compared to deeper waters, and;
3) The relatively *shorter water column* allows less methane to be oxidized in the water column on the way to the surface.

(For reference, please see chapter 7.8, p. 81).

Average water depth judging from the size of the reservoir (867km²) and the dead storage volume ($3794 \cdot 10^6 m^3$), suggest an average water level of 3.4-4.4m depending on drawdown. In the table below the average water depth of the Sambor Dam is compared with a few tropical reservoirs, from which the needed data was available to calculate average depth. Regrettably, only *two* of the tropical reservoirs were older than 16 years; therefore the remaining fluxes are likely to be high because of the initial high releases.

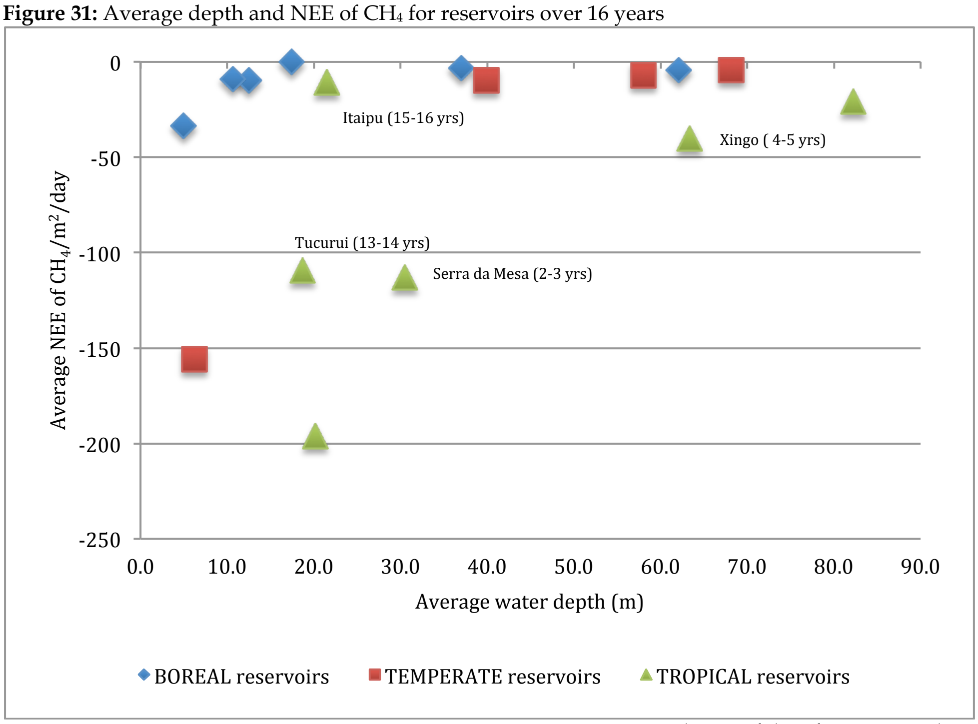
Consequently, data has also been extracted from a number of boreal and temperate reservoirs. The results (extracted from appendix 1) presented in Table 32 (below) suggest that when looking at the biomes separately, there is as expected a distinct relationship between lake depth and NEE of CH_4. It is also significant that none of the (old) deep reservoirs (>20-30 m) releases significant amounts of methane or carbon dioxide.

Table 32: Average water depth and the NEE of CO_2 and CH_4 in reservoirs

Name	*Surface Area*	*Volume*	*Average depth*	*NEE of CO2*	*NEE of CH4*	*>16 years?*
	[km2]	*[million m3]*	*[m]*	*[mgCO2/m2/day]*	*[mgCH4/m2/day]*	
Sambor Dam	*867*	*3794*	*4.4*			
TROPICAL						
Tucurui	2430	45500	18.7	-8474.50	-109.40	no
Três Marias	1040	21000	20.2	-1113.50	-196.25	yes
Itaipu	1350	29000	21.5	-170.50	-10.70	no
Serra da Mesa	1784	54400	30.5	-113.00	-113.00	no
Xingó	60	3800	63.3	-6138.50	-40.10	no
Barra Bonita	312	25660	82.2	-3940.00	-20.70	yes
BOREAL						
Lokka	418		5.0	-1518	-33.6	yes
Wallula	157	1670	10.6	349	-9	yes
Caniaposcau	4318	53800	12.5	-669	-9.8	yes
Bersimis	798	13900	17.4	-1485	-0.1	yes
F.D. Roosevelt	324	11983	37.0	462	-3.2	yes
Dworshak	69	4287	62.1	1195	-4.4	yes
TEMPERATE						
Lake Wohlen	4	25	6.3		-156	yes
Shasta	120	4790	39.9	-1247	-9.5	yes
New Melones	51	2960	58.0	1186	-7.1	yes
Oroville	64	4363	68.2	-1026	-4.2	yes

What is also evident is that the two shallowest reservoirs in the temperate and boreal zones (Lokka and Lake Wohlen), which are only 5 and 6.3 meters respectively, are both extremely large emitters of methane. This corresponds with findings by Bastviken et al. (2004) who found that 25-80% of the total ebullition flux happens at water depths <4 meters (and 90% <8 meters). While the Sambor Dam will be shallower than any of the reservoirs presented in this paper, this suggests that methane emission from the Sambor Dam reservoir might be extremely high.

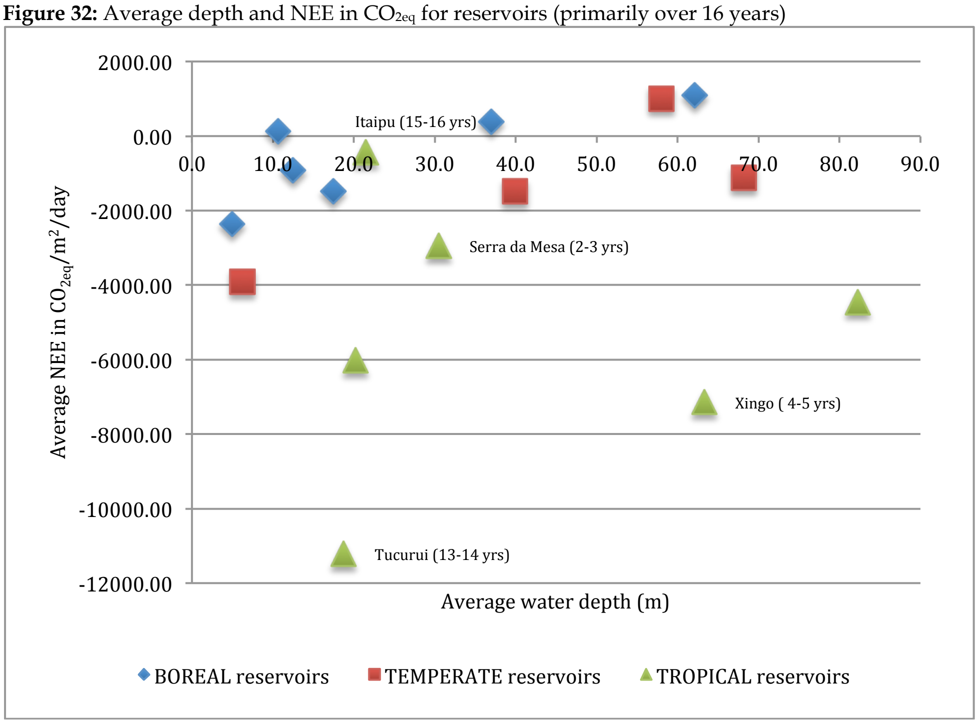
Figure 31: Average depth and NEE of CH_4 for reservoirs over 16 years



Source: Compilation of data from Appendix 1

With regard to CO_2 and water depth, no similar pattern emerges. It does however seem that there might be a vague relationship between average depths and the NEE of CO_2 and CH_4 in CO_2 equivalents, which opens a door for a possible interesting correlation, which as far as I know, has not been looked into before.

Figure 32: Average depth and NEE in CO_{2eq} for reservoirs (primarily over 16 years)



Source: Compilation of data from Appendix 1

All results, which have been presented here, suggest that the NEE of CH_4 and possibly NEE values converted into CO_2 equivalents, should be somewhat higher for the Sambor dam, compared to average values. Placing the Sambor Dam in the top quarter of CH_4 emitters (from -75.8 to -165.7 $mgCH_4 \cdot m^{-2} \cdot yr^{-1}$, compared to average values presented in chapter 7.4, p. 74) suggest that the NEE of CH_4 over the preferred time frame should be multiplied with a factor 2.19 or 117%. *To maintain a conservative estimate only half, namely 58.5% will though be added to the final results hereafter.*

14.2.3 Presenting a function to estimate GHG releases from Sambor Dam

Compiling the function found in chapter 14.2.1 above with the expected higher NEE of CH_4 found in the previous chapter (14.2.2), we can now calculate the NEE of CO_2 and CH_4 over a certain timeframe, e.g. 100-years.

Equation 14: Estimated release of CO_2 over 100 years

$$\int_{36525}^{0}(1191.8 \cdot ln(x) - 13213)dx\ mgCO_2m^2d^{-1} \cdot 867 \cdot 10^6m^2 = 59.66MtCO_2$$

Equation 15: Estimated release of CH_4 over 100 years

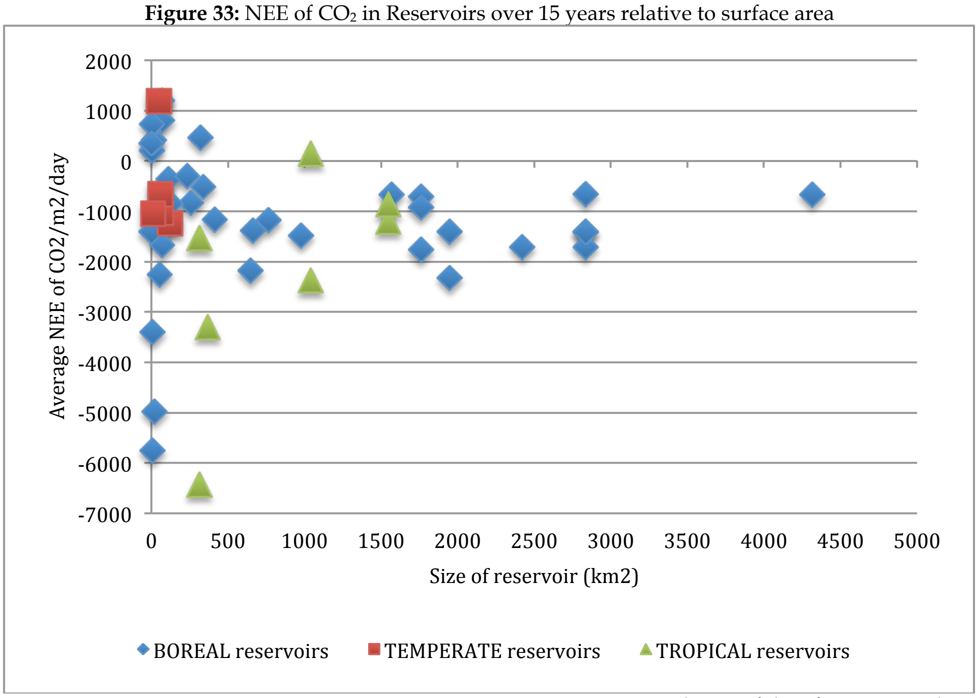
$$\int_{36525}^{0}(8.8779 \cdot ln(x) - 152.28)dx\ mgCO_2m^2d^{-1} \cdot 867 \cdot 10^6m^2 + 58.5\% = 3.408MtCH_4\ or\ 85.19\ MtCO_2eq.$$

14.2.4 Evaluating the estimate

As has been discussed throughout this paper, there are both good and bad dams with regards to their climate impact. Large fluctuations happen in between all biomes, but are particularly distinct for tropical regions.

When comparing the total RA with NEE of CO_2 for hydropower dams older than 15 years (n=62), there is a marked pattern which suggests that large fluctuations are much more likely for reservoirs which have smaller surface areas, whereas CO_2 emissions from reservoirs with large surface areas are much more uniform (see Figure 33, below). This suggests that the NEE of CO_2 from the 867km² Sambor Dam reservoir is likely to fall within the average values.

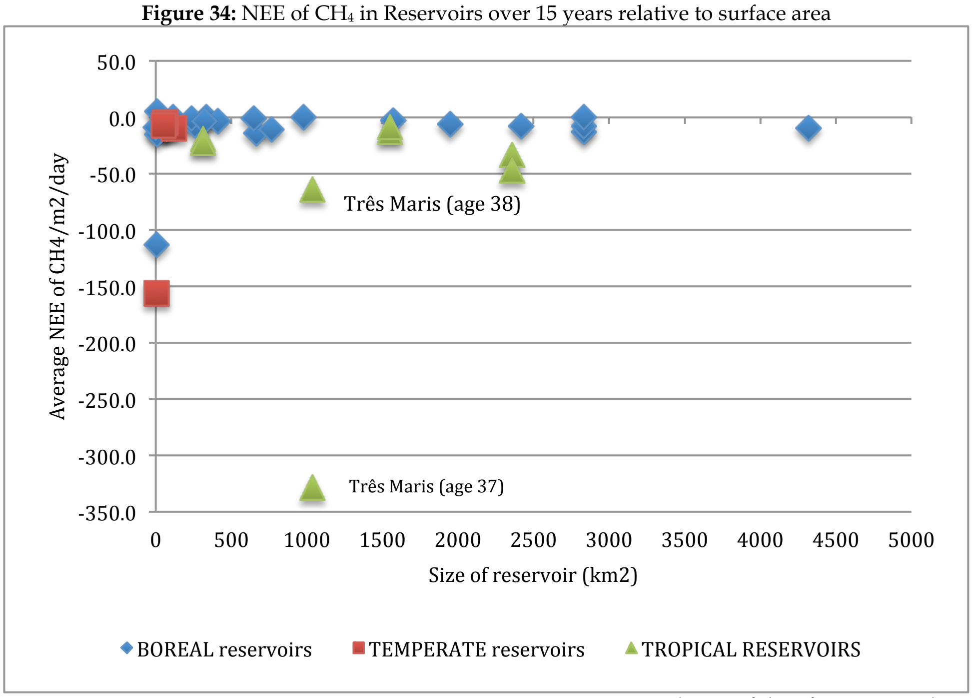
Figure 33: NEE of CO_2 in Reservoirs over 15 years relative to surface area



Source: Compilation of data from Appendix 1

For the NEE of CH_4 for reservoirs over 16 years (n=58), there was a similar pattern, where tropical reservoirs however stood out from boreal and temperate reservoirs in that fluctuations were markedly larger (see Figure 34, below). Additionally, the NEE fluctuations were found to be less uniform for the tropics than for the other biomes, which namely the Três Marias reservoir (included at both the age of 37 and 38) is responsible for. The results presented suggest that for tropical reservoirs *over* the age of 16 years, NEE of CH_4 most often also falls within a relatively small range.

Figure 34: NEE of CH_4 in Reservoirs over 15 years relative to surface area



Source: Compilation of data from Appendix 1

Chapter 15: The approximate carbon budget for the Sambor Dam reservoir

This chapter will compile the results and calculate the net change in the NEE of GHGs and carbon storage, which will be related to the LULUCF for the hydropower reservoir, north of Sambor. The results are presented in the table below.

Table 33: NEE and carbon storage change estimated for the proposed dam

	CO_2 [$MtCO_2$]	CH_4 [$MtCH_4$]	N_2O [MtN_2O]	CO_{2eq} [$MtCO_{2eq}$]
BEFORE:				
NEE				
- Forests (RA)	53.68	-0.0049	-0.0118	51.22
- Forests (ILL)	4.58	-0.0004	-0.0010	4.37
- W. Swamps	-0.25	-0.0236	0.0000	-0.84
- River	-13.93	-0.1485	0.0000	-17.64
Total NEE before	*44.09*	*-0.18*	*-0.01*	37.11
STORAGE in CO_{2eq}				
- Forests (RA incl. swamps)	-	-	-	*13.98*
- Forests (ILL)	-	-	-	2.10
AFTER:				
NEE				
- Reservoir (surface)	*-59.66*	*-3.4080*	*0.0000*	*-144.86*
Reservoir (OC burial) in CO_{2eq}				
- Senario 1, 0.448Mt/yr				*44.88*
- Senario 2, 0.06Mt/yr				*-6.36*
Total NEE after, senario 1				-99.98
Total NEE after, senario 2				-151.22
Total change, senario 1				-153.17
Total change, senario 2				-204.41

15.1.1 Comparison with other energy sources

I order to understand the findings above in a good/bad perspective; this chapter will briefly compare the expected CO_2/energy ratio with thermal alternatives. In this comparison it must be mentioned that the releases coupled with land-use changes are far from comprising all emissions from the reservoir, which would also include downstream emissions, downstream sedimentation, degassing etc. etc. (already discussed), also estimates as those presented below neglects that energy producing technology is likely to evolves in a way which will increase energy efficiency over the lifetime of the dam (NPC, 2007). Thermal energy sources are however thought to be approximating their maximum energy efficiency potential, while the energy efficiency of the much younger renewable energy sources are indeed expected to increase rapidly in the years to come (NPC, 2007; Pehnt, 2006).

The average annual generating capacity of the Sambor Dam is stated to be 11740 $GWh \cdot yr^{-1}$. In chapter 11.6 (p. 109) it is however argued that this is a vast over estimate. Both as

1) This would presuppose that the dam would run at peak load year round, and;
2) Because hydropower reservoirs on average loose their storage capacity (and hence their energy generating capacity) at an annual range of 1 to 2.3%.

(For reference please see chapter 11.6, p. 109.)

To conservatively compensate for this overestimation, an annual negative growth rate of 1% is applied; the total energy produced over 100 years (TE_{100}) is hence estimated to:

Equation 16: Applying 1% discount rate to total energy production over 100yrs

$$\mathrm{TE}_{100} = \sum_{t=0}^{t=99} \left(\frac{11740}{1+1\%^{t}}\right) = 747358\ GWh \cdot 100yr^{-1}$$

The CO_2 pr. kWh ratio for gases and oil have been found by multiplying the CO_2 emissions factor for specific fuel types (see U.S. EIA, 2011a) with average heat rate values for steam-electric generators (see U.S. EIA, 2011b). The CO_2 pr. kWh ratio for solar (PV) - and wind power are average values compiled from Pehnt (2006) and Sovacool (2008).

Table 34: Comparison with alternative energy sources

	Average tCO_2/GWh	Source
Coal	916 - 962	U.S. EIA, (2011a+b)
Natural gas	508	U.S. EIA, (2011a+b)
Oil	712 - 771	U.S. EIA, (2011a+b)
Wind (offshore/onshore)	9-10	Pehnt (2006); Sovacool (2008).
Solar (thermal/PV)	13-32	Pehnt (2006); Sovacool (2008).
Biomass (various fuel types)	14-41	Pehnt (2006); Sovacool (2008).
Nuclear (Various reactor types)	66	Pehnt (2006)
Geothermal (80 MW, hot dry rock)	38	Pehnt (2006)
Sambor Dam (Hydropower, this report)		
- Senario 1	-205	This study
- Senario 2	-274	This study

To rule out insecurities related to losses from operation and management; all estimates have been calculated over at least 1 year (Pehnt, 2006; Sovacool, 2008). However, for natural gas, fugitive emissions, mainly caused by minor leaks throughout the entire distribution network, have not been added. In the total estimates this is however estimated to be not significant. Brazil's fugitive emissions is in comparison only estimated to comprise about an added 4.7% (dos Santos et al., 2006).

> *While hydropower is certainly not a 'green' or 'CO_2-neutral' energy source judging from these results, the CO_2/energy ratio related to the direct effect of LULUCF upstream of Sambor Hydropower reservoir will not approximate even the most "green" non-renewable alternative (natural gas). Compared to the renewable energy sources, though, the case presented here certainly stands out as the worse case.*

15.1.2 Evaluating the final estimate

The amount of speculation needed to loosely predict the climate effect of hydropower projects like the Sambor Dam case here, naturally renders estimates quite vague. However, conservative estimates on forest carbon stocks, the total area of forests and rice fields, the effect of resettlement on forest carbon stocks and NEE and more are all suggesting that the estimate here expresses what can be understood as a minimum climate impact related to the LULUCF associated to the Sambor dam reservoir. In addition to the *direct impacts*, which are here understood as:

1) NEE of, and storage in, the terrestrial lands of the RA
2) NEE of, and storage in, the aquatic systems of the RA
3) NEE of, and storage in, the IILs

Subtracted from the

4) Estimated NEE of, and storage in, the proposed reservoir,

Indirect impacts must also be added. This include among others:

5) Emissions at dam turbines and spillways
6) Changes in downstream river emissions
7) Changes in downstream sedimentation of OC
8) Changes in sediment available to fertilize oceanic plankton (which are an important consumer of CO_2 form the atmosphere).

15.1.3 Final results

Is has at no point been the purpose to estimate the exact climate impact of the Sambor dam, but rather to use the proposed Sambor Dam as a case in which the findings throughout the report can be quantified and understood. While the background chapters functions as a tool to understand the variables which affect NEE and Storage in terrestrial and aquatic ecosystem, the case has demonstrated how;

1) Groundtruthing,
2) Sampling, and;
3) Local knowledge

- are essential means in understanding these variables in relation to a specific case and how they need to be included in 'climate-friendly' site-selection for hydropower reservoirs. While *groundtruthing and sampling* will reveal local factors which are difficult, if not impossible to understand in the preliminary mapping, local knowledge is essential in understanding i.e. the possibilities of resettlement, re-establishment of croplands and alike.

The case chapter furthermore identified the below land-uses as the largest contributors to the total estimate - according to significance:

1) The NEE of the planned reservoir
2) The NEE of the lost forests (RA+ILL)
3) The NEE of the lost river
4) The Storage in the forests (RA+ILL)
5) The Storage in the reservoir

While this knowledge is concurrent with the present case, most other cases are believed to fit fairly well in this picture. Primarily as the reservoir area always will pose the largest areal change (and therefore likely also poses the largest NEE effect), but also as reservoirs which floods large areas are most often build in areas with little inhabitation such as forested areas (Ledec and Quintero, 2003). Moreover, the storage in the reservoir might eventually pose a significant role, but in the planning phases, dam builders and designers for obvious reasons pursue minimum storage (sedimentation). For the reservoir to be economically viable this is an obvious precondition for building the reservoir in the first place, and is hence not believed to be in the top tree of the most significant factors. This is clearly a generalization and a thorough mapping (based on current knowledge) of the most significant factors are believed to be necessary in almost all cases before the appropriate tier levels are appointed to the specific land-use change.

GOOD SITE SELECTION

Chapter 16: Discussion of good site selection

This chapter will, based on the findings up until here, discuss good site selection for hydroelectric reservoirs. This will provide a methodology for easily comparing proposed hydropower project sites in terms of their adverse climate impacts and can be understood as a complementary to the broader process-oriented advice other recent reports on dams, as well as reports on good site selection for mitigating social and environmental impacts (see for example WCD (2000); Ledec and Quintero (2003); World Bank (2009) and IHA (2011)).

The discussion below will first reveal the inhospitable context in which good site selection needs to find its legitimacy. The findings here are accordingly meant to bring more shades to the current debate, hopefully foster more attention to adequate pre-assessments so as to help mitigate not only climate impacts, but also environment and social impacts.

16.1 Good site selection in a contemporary context

Large hydropower projects (>10MW) are probably among the most controversial types of development projects in the world. At the same time the debate is often highly polarized.

While it has long been recognized that:

1) Hydropower projects can have large social and environmental impacts, and that;
2) Many social- and environmental impacts fairly well *can* be mitigated through good site selection.

It is also fairly well recognized - that they seldom are (Ledec and Quintero, 2003).

When hydropower is still being pushed forward (also by developmental organizations), it happens partly due to the undeniable fact, that electricity is a key ingredient in improving the lives of millions in the developing world where rapid urbanization and population growth will increase electricity demands significantly in the decades to come (UN Deptartment of Public Information, 2005). These circumstances are however not unambiguously pointing at hydropower as the only solution, hence the obese devotion to hydropower over alternative (renewable) energy means from, among others, the World Bank (see introduction, Chapter 0, p.2), must also partly be understood in accordance to the beliefs outlined here:

1) Hydropower is economically the least-cost source of electric power available to feed large urban centers;
2) Other alternative renewable energy options also imply significant social and environmental impacts, and;
3) Hydropower is a 'green source of energy' (hence it qualifies as a mean for annex 1 countries to meet their energy obligation.

(For reference please see Ledec and Quintero (2003) or World Energy Council, (2009)).

Several of these statements are nonetheless highly controversial. Critics to the beliefs summarized above, among others, claim that these statements, largely neglects *long-term* social, environmental and economic implications from hydropower, and that the main reasons rather are:

4) That hydropower is being pushed forward by Chinese SEOs
    a. Eager to export hydropower technology and workforce abroad, and
    b. Eager to import electricity to *their* growing markets.
5) That no alternative energy solutions have been investigated to meet the regions energy need, and;
6) That the benefits of hydropower including the economic proceeds are often overestimated, while;

7) The environmental and social consequences are often underestimated.

(For reference please see Imhof et al. (2006); International Rivers (2012, 2009); Osborne (2007, 2004); Save the Mekong Coalition (2012); Yu (2003)).

Accordingly critics also state that the cumulative benefits of hydropower are rarely, if at all, felt locally or even nationally.

While the defenders of hydropower obviously have their good reasons, so do the critics. See for example Imhof et al. (2006) or Brewer (2011) who both discusses how environmental assessments are often inadequate to international standards developed by, among others, the World Commission on Dam (WCD), the International Hydropower Association (IHA), the International Commission On Large Dams (ICOLD) and others.

The current paper finally wants to recognize that hydropower might not always be the best solution to meet a regions energy need. Prior to good site selection must naturally come a thorough pre-assessment of the best means to do so, in which all promising alternatives are considered.

16.2 Previous work and this report

As far as it is know, the only subsequent attempt to develop good site selection criteria for hydroelectric reservoirs with regard to GHGs is currently being conducted as a joint venture between the IHA and UNESCO (see UNESCO and IHA, 2009). The study, which has already been 4 years underway, will at finalization be based on hundreds of thousands, if not millions of dollars of research and workshops, with the participation of researchers from some of the most prominent organizations in the field. Hence this paper do not try to smother itself in the belief that I in less than one year can cover, let alone comprehend, the amount of knowledge needed to probably assess all aspects of good site selection for hydroelectric reservoirs. Nonetheless, this is its humble contribution.

The only publicly available material from the IHA/UNESCO on reservoir site selection with regard to GHG identifies the areas of interest as outlined below, but has still not posted any suggestions to their influence on GHG from large dams. *This is what this report seeks to do.* Moreover the findings throughout these papers have identified 10 additional areas of interest.

The areas of interest as identified are:

1) Reservoir area
2) Reservoir depth
3) Residence time (here included as turnover rate[104])
4) Reservoir fetch
5) Engineering issues such as intake level and location of gates
6) Flooded soil and vegetation (total carbon stock)
7) Climate
8) Hypolimnion (oxic/anoxic), and;
9) The size of the drawdown zone[105].

To these I would like to add:

10) Flooded area
11) Altering environmental flows
12) Resettlement (including re-establishment of croplands)
13) Resettlement and re-establishment of land-uses
14) Indirect disturbances

[104] For the whole system, the turnover rate (at equilibrium) is flux/standing stock and the residence time is standing stock/flux.
[105] The drawdown zone is the area at the edge of a body of water that is frequently exposed to the air due to changes in water level. Changes in water level can be caused by evaporation or by water usage in the case of reservoirs (Pitts, 2012).

15) Reservoir age
16) Sedimentation and sedimentation rates
17) Sustaining prestine ecosystems
18) Watershed
19) Altitude and slope convexity

The sequence from above is not reflected in the table on the next page, partly as it makes sense to discuss some variables in sequence to one another, and partly as some variables are complimentary. Finally 'engineering issues' does not directly relate to site selection, and is furthermore primarily believed to affect downstream emissions, for the effect of the 'flooded soil' this has not been investigated in this paper, primarily as knowledge in this area is extremely sparse. These variables have therefore been excluded.

Some variables furthermore point in different direction. Use of fertilizer in the reservoir watershed will for example increase the carbon storage in waterbodies, while also increasing the cumulative GHGs over waterbodies. These have therefore been left out

16.3 Climate criteria for good site-selection

The following will discuss variables relative to site selection in a good/bad perspective.

While CO_2 and CH_4 emissions respond differently to some variables, the GWP of methane is 25 times higher than that of CO_2 (over 100 years). Situations that are beneficial to CO_2 fluxes on the expense of CH_4 fluxes are therefore considered attractive in a good/bad perspective. Correspondingly a variable such as increased water depth is considered appealing as it in effect causes more methane to be oxidized in the water column and transformed into CO_2. Also several factors point to a relationship where increased OC burial in the reservoir, does not necessarily mean a significant OC removal in the long term, especially when the reduced deposition downstream is considered. The factors have been discussed in detail in chapter 9.3 (p. 93). What this suggests is that factors that increase the NEE over the ecosystem might be more significant, compared to factors that increase OC burial *in* the ecosystem. Such variables are therefore weighted in favour to the NEE over the ecosystem, but it is recognized that this is a large insecurity. An example is reservoir trophic status.

In the table on the next page, a plus sign will denote a positive relationship between the variable and the climate impact (good), as opposed to a minus sign, which will denote a negative relationship between the variable and the climate impact (bad). Finally an o denotes neutral variables or variables which are depending on more than one factor, and which cannot be explained as an either/or.

Variable	+/-	Reason	(Primary) references
Flooded area	-	*Reservoirs that flood large areas is likely to have a larger climate impact than reservoirs with a limited FA*: If site selection is the single most important climate (environmental and social) measure, the single most important factor to consider in designating hydropower dam sites, is probably the total surface of the FA, as it (roughly) is the determining proxy for the magnitude and severity of almost all factors below. Transforming a river or a lake to a reservoir does not cause significant changes to that system's carbon balance. The FA is obviously linked to the RA, but since land-uses such as rivers, lakes and wetlands are likely to have a greater or similar climate impact than reservoirs, a large RA is of less importance or even insignificant if the FA is relatively small.	*Chapters 7, 8 and 9*
Reservoir area	-	*Large reservoirs potentially has a larger climate impact than small reservoirs:* The surface of the RA yields the largest positive impact on both the total CO_2 and the total CH_4 emissions (total flux pr. lake) – despite the fact that small reservoirs have a larger areal flux of CH_4 (flux pr. unit area). Total surface area also has a somewhat positive relationship to reservoir fetch, discussed hereafter, which contributes further to its negative relationship to climate.	*Chapter 7 and 8*
Reservoir fetch	-	*Placing the dam in an area, which is more exposed to wind increases the climate impact of the dam:* Reservoir fetch is the constant area of water over which the wind blows in largely the same direction (Şentürk, 1994). The reservoir fetch hence has to do with the reservoirs piston velocity, which has a positive relationship to the removal of both CO_2 and CH_4 from surface waters. Reservoirs with a large reservoir fetch are for similar reasons also subject to waves and turbulence in the surface waters, which are too factors increasing the air-water exchange of CO_2 and CH_4.	*Chapter 7*
Reservoir depth	+	*Deeper reservoirs usually has a lower climate impact than shallow reservoirs (GHG/Energy ratio)*: While depth seems to have little impact on CO_2 emissions, there is a clear tendency, which endorses shallow reservoirs to emit more methane – probably partly as less methane will be oxidized on its way through the water column, partly because methanogenesis rates are very sensitive to the colder temperatures in the more deep waters and finally because plants, of which some facilitate significant vegetation flux, do not grow at deep waters. 90% of all methane ebullition flux, which are estimated to comprise 40-60% of the total methane flux, i.e. happens at water depths less than 8 meters. This suggests a critical height of the water table, which planners should strive to overcome for the majority of the reservoir. Shallow reservoirs consequently have a smaller *area-efficiency*, both for *area pr. unit of energy*, but also for *CO_{2eq} pr. unit of energy* and are therefore unpreferable in reservoir carbon budgets.	*Chapter 7 and 14*

Variable	+/-	Reason	(Primary) references
Turnover rate/ Hypolimnion	+	*Reservoirs with high turnover rates, is likely to have a lower climate impact than reservoirs with low turnover rates:* A high turnover rate in reservoirs effectively reduces their anoxic volume fraction (the hypolimnion layer), the effect of which will cause an increase in the amount of methane that will be oxidized in the water column, after leaving the sediments, and hence a decrease in the cumulative climate impact. Stratification in reservoirs are much more pronounced in the tropics than in the boreal and temperate regions, as stratification is a direct response to a lack of season as well as a unique relationship between water density and temperature, where warm water has the lowest density, and maximum water density happens at 3.9° Celsius. In warm weathers stratification occurs as the first few feet of the water is warmed up, and mixed into the surface layer (the epilimnion) by wind and wave action. These variables, however, do seldom have the strength to reach below the first few meters, and a barrier occurs between the warm top layer and cold/dense water (the hypolimnion) at the bottom of the water body. In areas where seasonal variations are low, stratification is therefore often pronounced, whereas aquatic ecosystems in regions, which experiences pronounced seasonal changes usually are better mixed, as falling temperatures during fall and winter eventually will cool down the top water layer, which will increase the density of the water, causing it eventually to sink and mix with the lower water layers, effectively and finally neutralizing the effect of stratification. There is hence a positive relationship between seasonal changes (boreal and temperate regions), turnover rates and climate.	*Chapter 2 and 7*
Warm climate	-	*The warmer the climate the larger the climate impact:* Much hydroelectric energy is being exported to other countries, sometimes over thousands of kilometers. In SEA, for example, both Cambodia and Lao PDR exports hydroelectric energy to Vietnam, Thailand and China. This opens further up for a possibility to discuss which country (site) to choose when discussing hydropower site-selection. Seen from a climate perspective (and ignoring possible developmental advantages (hereunder economic emolument), boreal sites should be preferred over temperate sites, and temperate sites over tropical sites if the possibility exists, because warmer climates seems to increase releases of GHGs over the aquatic ecosystems, as well as the sink in (flooded) forest ecosystems - both leading to an effect where the climate impact as well as the risk of the dam having exceptional high GHG emission rates are higher in the warmer regions.	*Chapters 4, 5, 6, 7, 8 and 9*

Variable	+/-	Reason	(Primary) references
Flooded vegetation	-	*In carbon budgets the flooding of forest are undoubtedly best avoided on the expense of all other land-use types. Within forests, the flooding of some forest types is exceedingly more preferable to others:* 80% of the terrestrial biomass is stored in forest vegetation and soils; flooding of forests is hence especially significant in reservoir carbon budgets. This impact increases further if the dominant forest species are hardwoods, as hardwood forests store up to 3.8 times more carbon than softwoods forests, and/or humid- and semiarid deciduous forests as they also seem to store more carbon over time than semi-arid evergreen forests. For forests, also stand age has an immediate impact on the current carbon storage in forests, but long-term carbon estimates renders this factor somewhat insignificant, as young forests on the contrary are likely to store more carbon pr. unit of area over time. Keeping in mind that less flooding is almost always preferable; a possible, and simplistic, climate ranking, according to which land-uses immediately appears most problematic in reservoir carbon budgets, would look as follows: 1) Hardwood forests; 2) Softwood forests; 3) Croplands and Settlements, and; 4) Grasslands. Whereas; 5) Wetlands; 6) Rivers, and; 7) Lakes - are close to neutral, neutral of negative in reservoir carbon budgets.	*Chapters 4, 5, 6, 7, 8 and 9*
Forested watershed	-	*Forests in the watershed heightens the reservoirs climate impact*: While the size of the watershed yields little influence on the reservoirs climate impact, experience from forest lakes suggests that these have higher heterotrophic traits compared to open lakes which is attributed to a higher light attenuation, increased DOC content (and consequent increased R) and increased incidences and strengths of CO_2 super-saturation. The establishment of reservoirs in forest areas hence yields a double effect where the temporal sink in the forests, an the carbon stored in forest biomass is lost, while the remaining forests in the watershed will contribute additionally to an increase of the GHG release over the reservoir, and hence the negative effect of placing reservoirs in forest areas.	*Chapter 4*

Variable	+/-	Reason	(Primary) references
Environmental flows	+	*Sustaining environmental flows are preferable in climate budgets*: In areas where natural river fluctuations are altered, traditional farmers may have depended on the river fluxes for irrigation. Changing the environmental flows, might hence force traditional farmers (either as the yields pr. growing season are falling, or as the number of growing seasons are decreased) to include more land through changing land-uses such as cutting down forests. Also, if changing river fluctuations alters the ecology of the river in a way which affects the fish life in the river, it might also necessitate that populations which are sustaining their livelihoods through fishing practices today, must shift to farming in a similar way. Finally swamps, which are extremely vulnerable to changing water flows, is likely to collapse if water flows are altered. However, the climate effect of returning the carbon in the swamp trees can be somewhat counterbalanced by the decrease in GHG releases over the swamp area. It is therefore recommended that environmental flows must be pursued through both management and design or that dams are built in areas where they will affect river flows the least - especially if the construction will necessitate a, climate-wise, negative areal expanding of agricultural practices.	*Chapters 3, 5, 11 and 12*
Indirectly implicated lands	-	*Also the indirectly implicated lands needs to be considered in carbon budgets:* When reservoirs flood large areas of settlements and croplands they affect land-uses that needs to be re-established elsewhere to support what ever need they where supporting before inundation. In some situations, like in the case presented here, social, political, practical or other factors influence on the options for resettlement sites and the re-establishment of settlements will hence, in combination with lost croplands, happen on the expense of other land-uses. In some situations re-establishment of croplands might necessitate new cultivation methods, which will then further have to be accounted for in reservoir carbon budgets.	*Chapters 2, 11, 13 and 15*
Reservoir trophic status	o	*The trophic status of the reservoir points in different directions here*: On the one side it increases OC burial in the reservoir, on the other side it also increases the total NEE of CO_2 over the reservoir. Immediately this suggests that the climate impact of the reservoir is less dependent on the trophic status of the reservoir, than the other variables mentioned here. However, several factors suggests that OC burial rates in reservoirs are less significant when the whole system is considered (due to reasons already discussed), suggesting that eutrophic and especially hypereutrophic reservoirs does contribute to a higher atmospheric GHG concentration in the long term.	*Chapter 7 and 9*
Sedimentation and reservoir age	-	*Old reservoirs with low sedimentation rates should be preferred in good climate site selection:* Reservoir age directly effects the release of CO_{2eq} pr. unit of energy ratio over the lifetime of the reservoir, and sedimentation and reservoir age are directly associated. While high sedimentation rates likely traps more OC in the reservoir, it also decreases both the energy efficiency of the reservoir and its potential age. Again a number of factors discussed throughout this paper suggest that reservoir sedimentation should not receive too much weight in carbon storage budgets. Reservoir sedimentation is therefore, despite increasing OC burial, considered a negative in a good/bad perspective.	*Chapters 7, 9, 14*
Salinity	o	Salinity has been found to decrease the partial pressure of CO_2 in aquatic ecosystems. This indicates that saline waters might store more carbon than fresh waters, and that reservoirs build close to the ocean, where saline water might have traveled up the river previously, might somehow change the NEE balance. This however needs further consideration in future studies to be understood adequately, not at least as increased or decreased water salinity will ultimately also alter the agricultural options in the watershed.	*Chapter 8*

Variable	+/-	Reason	(Primary) references
Altitude and slope convexity	+	*High altitudes and a high slope convexity are both positive factors in climate budgets:* Trees at higher altitudes and on steep slopes stores less carbon, due to a number of factors. In effect this encourages a preference for building reservoirs at higher altitudes, and in areas with a high slope convexity. Additionally the steep slopes also spurs deeper reservoirs relative to reservoir volume and thereby a smaller FA. Finally slopes and mountainous areas are less hospitable for human settlement. Therefore building in such areas are also likely to harmonize with the wish to limit the need for resettlements.	*Chapter 4 and 7*
Sustaining pristine (and sensitive) ecosystems	+	Because disturbances affect the carbon stocks of, and carbon sink in, forests negatively, and because human impacts on aquatic ecosystems risks to affect fisheries negatively (which will necessitate more establishment of more croplands) and sensitive ecosystems such as wetlands negatively (which can cause them to collapse and possibly transform from being a sink to a source of GHGs), pristine (and especially sensitive) ecosystems are better left untouched. Also the effect of clearing forests for transmission lines or access roads, has in some development countries led to increased deforestation as it provides access to hitherto untouched forests (Osborne, 2004).	*Chapters 3, 5, 11 and 12*

Chapter 17: Conclusion

First all available literature on NEE and storage from and in the selected land-uses was identified and selected with respect to the sole requirement: that research must have been conducted over more than one year. The findings in these reports then made the foundation to discuss which variables contributed the most to changes in greenhouse gas budgets for hydroelectric energy production (a), and in combination with a 2 month fieldtrip to Cambodia, these findings also facilitated a calculation of the approximate cumulative greenhouse impact of the proposed Sambor Hydropower Dam Reservoir (b), and finally how the climate impact of dams could be mitigated through good site selection (c). The variables which seemed to affect the GWP of hydropower dams the most appeared to be the total FA (including IILs) and the depth of the reservoir. Additionally there seems to be a tendency where land-use changes are more significant in the tropical region than elsewhere, and hence that hydropower development in the warmer climates bears with it a much higher degree of risk, with regard to their climate impact - if appropriate considerations are not carefully planned for.

In general, the paper harbours no illusions that it has succeeded in explaining or identifying *all* variables that influence on reservoir GHG balances. Also a few of the variables are quite contradictory in that they i.e. affect both storage in and the NEE over the reservoir in similar ways. There is thus undoubtedly a high degree of uncertainty in the results here, but the conservative application of the findings do nonetheless obscure earlier days views of hydropower as a green source of energy significantly. To accommodate the many uncertainties especially the:

a) NEE of GHG over rivers, and;
b) Storage in aquatic ecosystems,

- requires much more attention in future studies.

While the variables identified can provide a valuable mean to identify appropriate hydropower dam sites with respect to their climate impact, there are however a few other considerations to make.

> *First of all,* the variables identified here will now need to be understood in relation to good site selection with regard to site specific social- and environmental impacts. These have been investigated by several authors i.e. Ledec and Quintero (2003) and WCD (2000).
>
> *Secondly*, dam construction companies have no good record for taking into consideration social- and environmental impacts (i.e. Brewer (2011) and Imhof et al. (2006)), and it is therefore dubious if they, in the future, will put more emphasis on climate impacts, with no economic incentive to do so. There are however movements in China[106] and among funding EXIM banks, which suggests that also these funders are beginning to take increasing responsibility, and therefore that they hopefully will sign some of the many agreements on limiting social- and environmental impacts, which they have previously denied. This includes among others the WCD guidelines, the Equator Principles and the MRC collaboration agreements[107]. Additionally, increased attention to reservoir GHG emissions are also likely to make the WB, the ADB and developmental organization in general focus more on GHG mitigation in the future, just as it will compel countries seeking to meet the certified emission reduction goal, to take the climate impact of hydropower dams seriously; and this project has certainly, regardless of the many insecurities, showed that hydropower dams are not insignificant in GHG budgets.

[106] Which is the worlds largest exporter of hydropower, responsible for more than 60% of all hydropower dams which are build in the developing world today Brewer (2011).
[107] Discussed briefly in the relevant chapters

Thirdly, it cannot be neglected that countries hosting hydropower dams also experiences many advantages. These have been mentioned already[108], but could include increasing energy independence and energy security, export revenue, infrastructure development and more. For regions where countries gain the opportunity to export energy, it is also likely to mean increased regional stability in unstable developing regions such as Africa and SEA. Building hydropower dams is however not a national affair. For the countries along the Mekong River, i.e., alteration of water flows downstream of dams in China, have already had severe consequences to fisheries, agriculture and more. In the Mekong Delta more than 60 million people depend on the river for subsistence (MRC, 2003), which underlines just how serious this issue is. Building dams does therefore not only increase stability, but also has the ability to foster unease in regions. This is exemplified in the current Lao/Cambodia dispute, where the Cambodian and the Lao government are fighting passionately over Lao plans to commence construction of the Xayaburi dam on the mainstream of the Mekong upstream of Cambodia next month (Fisher, 2012). This is at the same time quite paradoxical, knowing that the Cambodian government are doing the same to the Vietnamese with the Sambor Dam, and many other dams planned on the mainstream of the Mekong River in the years to come.

In the big picture GHG releases disappears on the expense of the immediate challenges the developing world faces, therefore it is increasingly important for those who finances such projects to find the surplus to include such considerations in hydropower planning. Interestingly several of the factors to limit the climate impact of hydropower dams might very well correlate with means to mitigate social- and environmental impacts. This for example includes seeking to minimize the FA, resettlement and sustaining environmental flows in the affected systems. Investigating these situations further might prove a valuable mean in the creation of sustainable hydropower development.

Finally the recent recognition of a possible large methane release at dam turbines and spillways, have actually fostered research in how to capture this methane in order to utilize it elsewhere. Succeeding in doing so will create a whole new, and extremely interesting angle to consider in future GHG budgets of hydropower dams.

[108] Cf. Chapter 16.1, p. 139

Bibliography:

1. Åberg, J., Bergström, A.-K., Algesten, G., Söderback, K., Jansson, M., 2004. A comparison of the carbon balances of a natural lake (L. Örträsket) and a hydroelectric reservoir (L. Skinnmuddselet) in northern Sweden. Water Research 38, 531–538.
2. Åberg, J., Jansson, M., Jonsson, A., 2010. Importance of water temperature and thermal stratification dynamics for temporal variation of surface water CO2 in a boreal lake. J. Geophys. Res. 115, 10 PP.
3. Abril, G., 2005. Carbon dioxide and methane emissions and the carbon budget of a 10-year old tropical reservoir (Petit Saut, French Guiana). Global Biogeochemical Cycles 19.
4. Acharya, S., Pattarkine, V.M., Knud-Hansen, C.F., 2010. Lake and Reservoir Management. Water Environment Research 82, 1767–1836.
5. Alabama Forestry Commission, 2012. How Much Carbon Have your Trees Stored? [WWW Document]. AFC Homepage. URL http://www.forestry.state.al.us/howmuchcarbonhaveyourtreesstored.aspx?bv=5&s=0 (accessed 8.26.12).
6. Alm, J., Schulman, L., Walden, J., Nykänen, H., Martikainen, P.J., Silvola, J., 1999. Carbon Balance of a Boreal Bog during a Year with an Exceptionally Dry Summer. Ecology 80, 161–174.
7. Anand, S., Dahiya, R.P., Talyan, V., Vrat, P., 2005. Investigations of methane emissions from rice cultivation in Indian context. Environment International 31, 469–482.
8. Anderson, D.E., Farrar, C.D., 2001. Eddy covariance measurement of CO2 flux to the atmosphere from an area of high volcanogenic emissions, Mammoth Mountain, California. Chemical Geology 177, 31–42.
9. Arneth, A., Kelliher, F.M., McSeveny, T.M., Byers, J.N., 1998. Net ecosystem productivity, net primary productivity and ecosystem carbon sequestration in a Pinus radiata plantation subject to soil water deficit. Tree Physiol. 18, 785–793.
10. Association for Industrial Archaeology, 2000. Industrial Archaeology Review, 2nd ed. Oxford University Press, United Kingdom.
11. Australian Greenhouse Office, 2006. Growing trees as greenhouse sinks : an overview for landholders / Australian Greenhouse Office. Australian Greenhouse Office, Canberra :
12. Australian Greenhouse Office, 2012. Australia's National Greenhouse Accounts - Glossary [WWW Document]. URL http://ageis.climatechange.gov.au/Help/PublicTutorialGlossary.aspx (accessed 11.16.12).
13. Banker, B.C., Kludze, H.K., Alford, D.P., DeLaune, R.D., Lindau, C.W., 1995. Methane sources and sinks in paddy rice soils: relationship to emissions. Agriculture, Ecosystems & Environment 53, 243–251.
14. Barford, C.C., Wofsy, S.C., Goulden, M.L., Munger, J.W., Pyle, E.H., Urbanski, S.P., Hutyra, L., Saleska, S.R., Fitzjarrald, D., Moore, K., 2001. Factors Controlling Long- and Short-Term Sequestration of Atmospheric CO2 in a Mid-latitude Forest. Science 294, 1688–1691.
15. Barr, A.G., Griffis, T.J., Black, T.A., Lee, X., al, et, 2002. Comparing the carbon budgets of boreal and temperate deciduous forest stands. Canadian Journal of Forest Research 32, 813–822.
16. Barr, A.G., Morgenstern, K., Black, T.A., McCaughey, J.H., Nesic, Z., 2006. Surface energy balance closure by the eddy-covariance method above three boreal forest stands and implications for the measurement of the CO2 flux. Agricultural and Forest Meteorology 140, 322–337.
17. Bartlett, K.B., Harriss, R.C., 1993. Review and assessment of methane emissions from wetlands. Chemosphere 26, 261–320.
18. Bashar, K., ELTahir, E., Fattah, S., Ali, A., Musnad, M., Siyam, A.M., Crosato, A., 2010. Nile Basin Reservoir Sedimentation Prediction and Mitigation. NBCBN-RE.

19. Bastviken, D., Cole, J., Pace, M., Tranvik, L., 2004. Methane emissions from lakes: Dependence of lake characteristics, two regional assessments, and a global estimate. Global Biogeochem. Cycles 18, 12 PP.
20. Bastviken, D., Cole, J.J., Pace, M.L., Bogert, M.C.V. de, 2008. Fates of methane from different lake habitats: Connecting whole-lake budgets and CH4 emissions. J. Geophys. Res. 113, G02024.
21. Bastviken, D., Downing, J.A., Tranvik, L.J., EnrichPrast, A., Crill, P.M., 2011. Freshwater Methane Emissions Offset the Continental Carbon Sink. Science.
22. BBC, 2012. Teenage girl in Cambodia killed during violent eviction [WWW Document]. World News. URL http://article.wn.com/view/2012/05/16/Teenage_girl_in_Cambodia_killed_during_violent_eviction/ (accessed 10.21.12).
23. Beaulieu, J.J., Shuster, W.D., Rebholz, J.A., 2012. Controls on gas transfer velocities in a large river. J. Geophys. Res. 117, G02007.
24. Belger, L., Forsberg, B., Melack, J., 2011. Carbon dioxide and methane emissions from interfluvial wetlands in the upper Negro River basin, Brazil. Biogeochemistry 105, 171–183.
25. Bergstrom, A.K., Algesten, G., Sobek, S., Tranvik, L., Jansson, M., 2004. Emission of CO2 from hydroelectric reservoirs in northern Sweden. Archiv f&# 252; r Hydrobiologie 159, 25–42.
26. Berliant, L., 2009. World Bank Puts Hydropower Back Into Favor, NGOs Do Not. Inside Climate News.
27. Bonan, G.B., 1991. Seasonal and annual carbon fluxes in a boreal forest landscape. J. Geophys. Res. 96, 17329–17,338.
28. Borges, A.V., Abril, G., Delille, B., Descy, J.-P., Darchambeau, F., 2011. Diffusive methane emissions to the atmosphere from Lake Kivu (Eastern Africa). Journal of Geophysical Research. Biogeosciences 116.
29. BP, 2011. BP Statistical Review of World Energy 2011. British Petroleum.
30. Brewer, N., 2011. The New Great Walls: A Guide to China's Overseas Dam Industry (Working Papers). International Rivers Network.
31. Bridgham, S.D., Updegraff, K., Pastor, J., 2001. A Comparison of Nutrient Availability Indices Along an Ombrotrophic–Minerotrophic Gradient in Minnesota Wetlands. Soil Science Society of America Journal 65, 259.
32. Brown, J., nd. Sampling in Forestry.
33. Brown, S.L., Schroeder, P., Kern, J.S., 1999. Spatial distribution of biomass in forests of the eastern USA. Forest Ecology and Management 123, 81–90.
34. Brown, S.L., Schroeder, P.E., 1999. Spatial Patterns of Aboveground Production and Mortality of Woody Biomass for Eastern U.S. Forest. Ecological Applications 9, 968–980.
35. Bubier, J., Crill, P., Mosedale, A., Frolking, S., Linder, E., 2003. Peatland responses to varying interannual moisture conditions as measured by automatic CO2 chambers. Global Biogeochem. Cycles 17, 1066.
36. Buffam, I., Turner, M.G., Desai, A.R., Hanson, P.C., Rusak, J.A., Lottig, N.R., Stanley, E.H., Carpenter, S.R., 2011. Integrating aquatic and terrestrial components to construct a complete carbon budget for a north temperate lake district. Global Change Biology 17, 1193–1211.
37. Bühler, L., 2007. Burial of Organic Carbon in Lakes.
38. Buol, S.W., Southard, R.J., Graham, R.C., McDaniel, P.A., 2003. Soil Genesis and Classification. John Wiley & Sons.
39. Butler, A., Hofmann, D., Conway, T., Dlugokencky, E., Elkins, J., Masarie, K., Montzka, S., Schnell, R., 2010. The NOAA annual greenhouse gas index (AGGI). NOAA Earth Systems Research Laboratory.
40. Canadell, J., Pataki, D., Gifford, R., Houghton, R., Luo, Y., Raupach, M., Smith, P., Steffen, W., 2007. Saturation of the Terrestrial Carbon Sink, in: Canadell, J.G., Pataki, D.E., Pitelka, L.F. (Eds.), Terrestrial Ecosystems in a Changing World, Global Change — The IGBP Series (closed). Springer Berlin Heidelberg, pp. 59–78.

41. Cao, M., Gregson, K., Marshall, S., Dent, J.B., Heal, O.W., 1996. Global Methane Emissions from Rice Paddies. Chemosphere 33, 879–897.
42. Caraco, N., Cole, J., 2004. When terrestrial organic matter is sent down the river: the importance of allochthonous carbon inputs to the metabolism of lakes and rivers. Food webs at the landscape level 301–316.
43. Carbon cycle, 2012. . Wikipedia, the free encyclopedia.
44. Carbon sink, 2012. . Wikipedia, the free encyclopedia.
45. Carlson, R.E., Simpson, J., 1996. A Coordinator's Guide to Volunteer Lake Monitoring Methods [WWW Document]. The Great North American Secchi Dip-In. Phosphorus.
46. Carrara, A., Kowalski, A.S., Neirynck, J., Janssens, I.A., Yuste, J.C., Ceulemans, R., 2003. Net ecosystem CO2 exchange of mixed forest in Belgium over 5 years. Agricultural and Forest Meteorology 119, 209–227.
47. Carroll, P., Crill, P., 1997. Carbon balance of a temperate poor fen. Global Biogeochemical Cycles 11, 349–356.
48. Casper, P., Maberly, S.C. (Stephen), Hall, G.H., Finlay, B.J. (Bland), 2000. Fluxes of methane and carbon dioxide from a small productive lake to the atmosphere.
49. Cavaleri, M.A., Oberbauer, S.F., Ryan, M.G., 2008. Foliar and ecosystem respiration in an old-growth tropical rain forest. Plant, Cell & Environment 31, 473–483.
50. CDIAC, 2011. Global Fossil-Fuel CO2 Emissions. Carbon Dioxide Information Analysis Center, USA.
51. CERG, 2010. Soil Biogeochemistry and Proxy Development [WWW Document]. Continental Environments Research Group. URL http://www.earth.lsa.umich.edu/~nsheldon/research.html (accessed 10.18.12).
52. Chanson, H., James, D.P., 1998. Teaching case studies in reservoir siltation and catchment erosion. International Journal of Engineering Education 14, 265–275.
53. Chanudet, V., Descloux, S., Harby, A., Sundt, H., Hansen, B.H., Brakstad, O., Serça, D., Guerin, F., 2011. Gross CO2 and CH4 emissions from the Nam Ngum and Nam Leuk sub-tropical reservoirs in Lao PDR. Science of The Total Environment 409, 5382–5391.
54. Chave, J., Swenson, N.G., Jansen, S., Lewis, S.L., Coomes, D., Zanne, A.E., 2009. Towards a worldwide wood economics spectrum. Ecology letters 12, 351–366.
55. Chimner, R.A., Cooper, D.J., 2003. Carbon dynamics of pristine and hydrologically modified fens in the southern Rocky Mountains. Canadian Journal of Botany 81, 477–491.
56. Christensen, T.R., Ekberg, A., Ström, L., Mastepanov, M., Panikov, N., Öquist, M., Svensson, B.H., Nykänen, H., Martikainen, P.J., Oskarsson, H., 2003. Factors controlling large scale variations in methane emissions from wetlands. Geophys. Res. Lett. 30, 1414.
57. Citizendium, 2011. Henry's Law [WWW Document]. URL http://en.citizendium.org/wiki/Henry's_law
58. Clark, D.A., 2004. Tropical Forests and Global Warming: Slowing It down or Speeding It up? Frontiers in Ecology and the Environment 2, 73–80.
59. Clark, D.A., Piper, S.C., Keeling, C.D., Clark, D.B., 2003. Tropical Rain Forest Tree Growth and Atmospheric Carbon Dynamics Linked to Interannual Temperature Variation During 1984–2000. PNAS 100, 5852–5857.
60. Clark, D.B., Clark, D.A., 1996. Abundance, growth and mortality of very large trees in neotropical lowland rain forest. Forest Ecology and Management 80, 235–244.
61. Clark, I.D., Fritz, P., 1997. Environmental Isotopes in Hydrogeology, 1st ed. CRC Press.
62. Cole, J., Prairie, Y., Caraco, N., McDowell, W., Tranvik, L., Striegl, R., Duarte, C., Kortelainen, P., Downing, J., Middelburg, J., others, 2007. Plumbing the global carbon cycle: integrating inland waters into the terrestrial carbon budget. Ecosystems 10, 172–185.
63. Cole, J.J., Caraco, N.F., 2001. Carbon in catchments: connecting terrestrial carbon losses with aquatic metabolism. Freshwater Resources.

64. Colls, J., 2007. Greenhouse Gas Sinks. Edited by D. Reay, C. N. Hewitt, K. Smith and J. Grace. Wallingford, UK: CABI (2007), Pp. 290, ISBN 978-1-84593-189-6. Experimental Agriculture 43, 529.
65. Cook, K.H., 2009. Abrupt climate change: Atmospheric tipping points. IOP Conference Series: Earth and Environmental Science 6, 062003.
66. Coomes, D.A., Allen, R.B., 2007. Effects of size, competition and altitude on tree growth. Journal of Ecology 95, 1084–1097.
67. Cornford, J., La, C., 2010. Preserving Plenty. The Beauty, achievements and struggle of the people of Sambor. Oxfam, Australia, Australia.
68. Couwenberg, J., Dommain, R., Joosten, H., 2010. Greenhouse gas fluxes from tropical peatlands in south-east Asia. Global Change Biology 16, 1715–1732.
69. Craine, J.M., 2005. Reconciling plant strategy theories of Grime and Tilman. Journal of Ecology 93, 1041–1052.
70. Crosswell, J.R., Wetz, M.S., Hales, B., Paerl, H.W., 2012. Air-water CO2 fluxes in the microtidal Neuse River Estuary, North Carolina. J. Geophys. Res. 117, C08017.
71. Cummings, D.L., Boone Kauffman, J., Perry, D.A., Flint Hughes, R., 2002. Aboveground biomass and structure of rainforests in the southwestern Brazilian Amazon. Forest Ecology and Management 163, 293–307.
72. Danevčič, T., Mandic-Mulec, I., Stres, B., Stopar, D., Hacin, J., 2010. Emissions of CO2, CH4 and N2O from Southern European peatlands. Soil Biology and Biochemistry 42, 1437–1446.
73. Daniel N. Miller, William C. Ghiorse, J.B.Y., 1999. Seasonal Patterns and Controls on Methane and Carbon Dioxide Fluxes in Forested Swamp Pools. Geomicrobiology Journal 16, 325–331.
74. Dansk Ornitologisk Forening, n.d. Sjælden amerikansk vadefugl i Lille Vildmose [WWW Document]. Dansk Ornitologisk Forening. URL http://www.dof.dk/index.php?id=nyheder&s=nyheder&m=visning&nyhed_id=759 (accessed 10.3.12).
75. De Castilho, C.V., Magnusson, W.E., De Araújo, R.N.O., Luizão, R.C.C., Luizão, F.J., Lima, A.P., Higuchi, N., 2006. Variation in aboveground tree live biomass in a central Amazonian Forest: Effects of soil and topography. Forest Ecology and Management 234, 85–96.
76. Dean, W.E., Gorham, E., 1998. Magnitude and Significance of Carbon Burial in Lakes, Reservoirs, and Peatlands. USGS Staff -- Published Research.
77. DeLAUNE, R.D., Smith, C.J., Patrick, W.H., 1983. Methane release from Gulf coast wetlands. Tellus B 35B, 8–15.
78. Delmas, R., Galy-Lacaux, C., Richard, S., 2001. Emissions of greenhouse gases from the tropical hydroelectric reservoir of Petit Saut (French Guiana) compared with emissions from thermal alternatives. Global Biogeochemical Cycles 15, 993–1003.
79. Demarty, M., Bastien, J., 2011. GHG emissions from hydroelectric reservoirs in tropical and equatorial regions: Review of 20 years of CH4 emission measurements. Energy Policy 39, 4197–4206.
80. Demarty, M., Bastien, J., Tremblay, A., Hesslein, R.H., Gill, R., 2009. Greenhouse Gas Emissions from Boreal Reservoirs in Manitoba and Québec, Canada, Measured with Automated Systems. Environ. Sci. Technol. 43, 8908–8915.
81. Devol, A.H., Richey, J.E., Clark, W.A., King, S.L., Martinelli, L.A., 1988. Methane Emissions to the Troposphere From the Amazon Floodplain. J. Geophys. Res. 93, 1583–1592.
82. Diamond, J., 2004. Collapse: How Societies Choose to Fail or Succeed, 1st ed. Viking Adult.
83. Dillon, P.J., Rigler, F.H., 1974. The Phosphorus-Chlorophyll Relationship in Lakes. Limnology and Oceanography 19, 767–773.
84. Dise, N.B., 1993. Methane emission from Minnesota peatlands: Spatial and seasonal variability. Global Biogeochemical Cycles 7, 123–142.
85. Dos Santos, M.A., Rosa, L.P., Sikar, B., Sikar, E., Dos Santos, E.O., 2006. Gross greenhouse gas fluxes from hydro-power reservoir compared to thermo-power plants. Energy Policy 34, 481–488.

86. Downing, J.A., Cole, J.J., Middelburg, J.J., Striegl, R.G., Duarte, C.M., Kortelainen, P., Prairie, Y.T., Laube, K.A., 2008. Sediment organic carbon burial in agriculturally eutrophic impoundments over the last century. Global Biogeochem. Cycles 22, GB1018.
87. Ehman, J.L., Schmid, H.P., Grimmond, C.S.B., Randolph, J.C., Hanson, P.J., Wayson, C.A., Cropley, F.D., 2002. An initial intercomparison of micrometeorological and ecological inventory estimates of carbon exchange in a mid-latitude deciduous forest. Global Change Biology 8, 575–589.
88. Einola, E., Rantakari, M., Kankaala, P., Kortelainen, P., Ojala, A., Pajunen, H., Mäkelä, S., Arvola, L., 2011. Carbon pools and fluxes in a chain of five boreal lakes: A dry and wet year comparison. J. Geophys. Res. 116, G03009.
89. Ellis, E.E., Keil, R.G., Ingalls, A.E., Richey, J.E., Alin, S.R., 2012. Seasonal variability in the sources of particulate organic matter of the Mekong River as discerned by elemental and lignin analyses. J. Geophys. Res. 117, G01038.
90. Engle, D., Melack, J.M., 2000. Methane Emissions from an Amazon Floodplain Lake: Enhanced Release during Episodic Mixing and during Falling Water. Biogeochemistry 51, 71–90.
91. Epule, E.T., Peng, C., Mafany, N.M., 2011. Methane Emissions from Paddy Rice Fields: Strategies towards Achieving A Win-Win Sustainability Scenario between Rice Production and Methane Emission Reduction. Journal of Sustainable Development 4, 188–196.
92. ESA21, 2005. Trees and Carbon.
93. Eugster, W., DelSontro, T., Sobek, S., 2011. Eddy covariance flux measurements confirm extreme CH4 emissions from a Swiss hydropower reservoir and resolve their short-term variability. Biogeosciences 8, 2815–2831.
94. Euliss Jr., N.H., Gleason, R.A., Olness, A., McDougal, R.L., Murkin, H.R., Robarts, R.D., Bourbonniere, R.A., Warner, B.G., 2006. North American Prairie Wetlands are Important Nonforested Land-Based Carbon Storage Sites. USGS Northern Prairie Wildlife Research Center.
95. Evans, J.R., 2007. Resolving methane fluxes. New Phytologist 175, 1–4.
96. Ezeh, A.C., Bongaarts, J., Mberu, B., 2012. Global population trends and policy options. Lancet 380, 142–148.
97. Fan, S.-M., Goulden, M.L., Munger, J.W., Daube, B.C., Bakwin, P.S., Wofsy, S.C., Amthor, J.S., Fitzjarrald, D.R., Moore, K.E., Moore, T.R., 1995. Environmental Controls on the Photosynthesis and Respiration of a Boreal Lichen Woodland: A Growing Season of Whole-Ecosystem Exchange Measurements by Eddy Correlation. Oecologia 102, 443–452.
98. FAO, 2006. Global forest resources assessment 2005: progress towards sustainable forest management. Food and Agriculture Organization of the United Nations, Rome, Italy.
99. Farrèr, C., Senn, D., 2007. Hydroelectric Reservoirs-the Carbon Dioxide and Methane Emissions of a "Carbon Free" Energy Source. ETH Eidgenössische Technische Hochschule Zürich.
100. Fearnside, P.M., 2002. Greenhouse Gas Emissions from a Hydroelectric Reservoir (Brazil's Tucuruí Dam) and the Energy Policy Implications. Water Air Soil Pollution 133, 69–96.
101. Fearnside, P.M., 2004. Greenhouse Gas Emissions from Hydroelectric Dams: Controversies Provide a Springboard for Rethinking a Supposedly "Clean" Energy Source. An Editorial Comment. Climatic Change 66, 1–8.
102. Fearnside, P.M., 2005. Do Hydroelectric Dams Mitigate Global Warming? The Case of Brazil's CuruÁ-una Dam. Mitigation and Adaptation Strategies for Global Change 10, 675–691.
103. Fiedler, S., Sommer, M., 2000. Methane emissions, groundwater levels and redox potentials of common wetland soils in a temperate-humid climate. Global Biogeochemical Cycles 14, 1081–1093.
104. Fisher, J., 2012. Laos approves Mekong "mega" dam. BBC.

105. Forster, P., Ramaswamy, V., Artaxo, P., Berntsen, T., Betts, R., Fahey, D.W., Haywood, J., Lean, J., Lowe, D.C., Myhre, G., 2007. Changes in atmospheric constituents and in radiative forcing. Climate change 20.
106. Francis Stuart Chapin (III.), Matson, P.A., Mooney, H.A., 2002. Principles of Terrestrial Ecosystem Ecology. Birkhäuser.
107. Franken, R.O.G., Van Vierssen, W., Lubberding, H.J., 1992. Emissions of some greenhouse gases from aquatic and semi-aquatic ecosystems in the Netherlands and options to control them. Science of The Total Environment 126, 277–293.
108. Frolking, S., Crill, P., 1994. Climate controls on temporal variability of methane flux from a poor fen in southeastern New Hampshire: Measurement and modeling. Global Biogeochemical Cycles 8, 385–397.
109. Furukawa, Y., Inubushi, K., Ali, M., Itang, A., Tsuruta, H., 2005. Effect of changing groundwater levels caused by land-use changes on greenhouse gas fluxes from tropical peat lands. Nutrient Cycling in Agroecosystems 71, 81–91.
110. Gaumont-Guay, D., Black, T.A., Mccaughey, H., BARR, A.G., Krishnan, P., JASSAL, R.S., Nesic, Z., 2009. Soil CO2 efflux in contrasting boreal deciduous and coniferous stands and its contribution to the ecosystem carbon balance. Global Change Biology 15, 1302–1319.
111. Giles, J., 2006. Methane quashes green credentials of hydropower. Nature 444, 524–525.
112. Goodale, C.L., Apps, M.J., Birdsey, R.A., Field, C.B., Heath, L.S., Houghton, R.A., Jenkins, J.C., Kohlmaier, G.H., Kurz, W., Liu, S., Nabuurs, G.-J., Nilsson, S., Shvidenko, A.Z., 2002. Forest Carbon Sinks in the Northern Hemisphere. Ecological Applications 12, 891–899.
113. Goulden, M.L., Wofsy, S.C., Harden, J.W., Trumbore, S.E., Crill, P.M., Gower, S.T., Fries, T., Daube, B.C., Fan, S.-M., Sutton, D.J., Bazzaz, A., Munger, J.W., 1998. Sensitivity of Boreal Forest Carbon Balance to Soil Thaw. Science 279, 214–217.
114. Government of Canada, N.R.C., 2003. Canadian Forest Service Publications : Temporal changes of forest net primary production and net ecosystem production in west central Canada associated with natural and anthropogenic disturbances [WWW Document]. URL http://cfs.nrcan.gc.ca/publications?id=23745 (accessed 7.6.12).
115. Grace, J., Lloyd, J., McIntyre, J., Miranda, A.C., Meir, P., Miranda, H.S., Nobre, C., Moncrieff, J., Massheder, J., Malhi, Y., Wright, I., Gash, J., 1995. Carbon Dioxide Uptake by an Undisturbed Tropical Rain Forest in Southwest Amazonia, 1992 to 1993. Science 270, 778–780.
116. Graham-Rowe, D., 2005. Hydroelectric power's dirty secret revealed [WWW Document]. NewScientist. URL http://www.newscientist.com/article/dn7046-hydroelectric-powers-dirty-secret-revealed.html (accessed 11.30.11).
117. Granier, A., Pilegaard, K., Jensen, N.., 2002. Similar net ecosystem exchange of beech stands located in France and Denmark. Agricultural and Forest Meteorology 114, 75–82.
118. Griffis, T.., Black, T.., Morgenstern, K., Barr, A.., Nesic, Z., Drewitt, G.., Gaumont-Guay, D., McCaughey, J.., 2003. Ecophysiological controls on the carbon balances of three southern boreal forests. Agricultural and Forest Meteorology 117, 53–71.
119. Griffis, T.J., 2000. Inter-annual variability of net ecosystem carbon dioxide exchange at a subarctic fen.
120. Grubb, M., Vrolijk, C., Brack, D., Forsyth, T., 1999. The Kyoto Protocol: a guide and assessment. Royal Institute of International Affairs London.
121. Guérin, F., Abril, G., Richard, S., Burban, B., Reynouard, C., Seyler, P., Delmas, R., 2006. Methane and carbon dioxide emissions from tropical reservoirs: Significance of downstream rivers. Geophys. Res. Lett. 33, L21407.
122. Hadi, A., Inubushi, K., Furukawa, Y., Purnomo, E., Rasmadi, M., Tsuruta, H., 2005. Greenhouse gas emissions from tropical peatlands of Kalimantan,Indonesia. Nutrient Cycling in Agroecosystems 71, 73–80.
123. Hanson, P.C., Bade, D.L., Carpenter, S.R., Kratz, T.K., 2003. Lake metabolism: Relationships with dissolved organic carbon and phosphorus. Limnology and Oceanography 48, 1112–1119.

124. Hartnett, H.E., Keil, R.G., Hedges, J.I., Devol, A.H., 1998. Influence of oxygen exposure time on organic carbon preservation in continental margin sediments. Nature 391, 572–574.
125. Helie J.-F., Hillaire-Marcel C., Rondeau B., 2002. Seasonal changes in the sources and fluxes of dissolved inorganic carbon through the St. Lawrence River-isotopic and chemical constraint. Chemical Geology 186, 117–138.
126. Hirano, T., Jauhiainen, J., Inoue, T., Takahashi, H., 2009. Controls on the Carbon Balance of Tropical Peatlands. Ecosystems 12, 873–887.
127. Hollinger, D.Y., Goltz, S.M., Davidson, E.A., Lee, J.T., Tu, K., Valentine, H.T., 1999. Seasonal patterns and environmental control of carbon dioxide and water vapour exchange in an ecotonal boreal forest. Global Change Biology 5, 891–902.
128. Hollinger, D.Y., Kelliher, F.M., Schulze, E.-D., Vygodskaya, N.N., Varlagin, A., Milukova, I., Byers, J.N., Sogachov, A., Hunt, J.E., McSeveny, T.M., Kobak, K.I., Bauer, G., Arneth, A., 1995. Initial Assessment of Multi-Scale Measures of CO 2 and H 2 O Flux in the Siberian Taiga. Journal of Biogeography 22, 425.
129. Houghton, R.A., 2003. Why are estimates of the terrestrial carbon balance so different? Global Change Biology 9, 500–509.
130. Huete, A.R., Restrepo-Coupe, N., Ratana, P., Didan, K., Saleska, S.R., Ichii, K., Panuthai, S., Gamo, M., 2008. Multiple site tower flux and remote sensing comparisons of tropical forest dynamics in Monsoon Asia. Agricultural and Forest Meteorology 148, 748–760.
131. Hunt, N., Tyrrell, S., 2004. Stratified Sampling [WWW Document]. URL http://www.coventry.ac.uk/ec/~nhunt/meths/strati.html (accessed 10.9.12).
132. Huotari, J., Ojala, A., Peltomaa, E., Nordbo, A., Launiainen, S., Pumpanen, J., Rasilo, T., Hari, P., Vesala, T., 2011. Long-term direct CO2 flux measurements over a boreal lake: Five years of eddy covariance data. Geophysical Research Letters 38.
133. Huxman, T.E., Turnipseed, A.A., Sparks, J.P., Harley, P.C., Monson, R.K., 2003. Temperature as a control over ecosystem CO₂ fluxes in a high-elevation, subalpine forest. Oecologia 134, 537–546.
134. ICEM, 2009. Inception Report, Vol.2: Mainstream Project Profile Summaries. MRC SEA for Hydropower on the Mekong Mainstream. International Center for Environmental Management, Hanoi.
135. ICEM, 2012. ICEM materials, maps and geospatial work [WWW Document]. URL http://www.icem.com.au/02_contents/06_materials/06-maps.htm (accessed 10.11.12).
136. IEA, 2011. World Energy Outlook 2011. International Energy Agency, Paris.
137. IFC, 2006. the "Equator Principles": A financial industry benchmark for determining, assessing and managing social & environmental risk in project financing. International Finance Corporation (IFC).
138. IHA, 2010. Hydro's Contribution, Factsheet. International Hydropower Association, London.
139. IHA, 2011. IHA Congress - Seeking the truth about Hydropower's greenhouse gas footprint [WWW Document]. World Congress. Advancing sustainable hydropower. URL http://ihacongress.org/News/NewsHolder/Seeking-the-truth-about-Hydropower-s-greenhouse-ga (accessed 1.9.12).
140. Imhof, A., Lawrence, S., Middelton, C., 2006. Hydropower Development in the Mekong Basin: Nam Theun 2 and the need for better planning processes. International Rivers, Laos.
141. Indo-Pacific Conservation Alliance., n.d. Greater Lorentz Lowlands - Indo-Pacific Conservation Alliance [WWW Document]. URL http://www.indopacific.org/gll.asp (accessed 10.3.12).
142. International Rice Research Institute, n.d. IRRI Rice Knowledge Bank [WWW Document]. URL http://www.knowledgebank.irri.org/ (accessed 10.2.12).
143. International Rivers, 2007. Greenhouse Gas Emissions from Dams FAQ [WWW Document]. International Rivers: People, Water, Life. URL http://www.internationalrivers.org/node/1398 (accessed 11.21.10).

144. International Rivers, 2009. Mekong Mainstream Dams, Threatening Southeast Asia's Food Security. International Rivers.
145. International Rivers, 2012a. China's Three Gorges Dam: A Model of the Past [WWW Document]. International Rivers. URL http://www.internationalrivers.org/resources/china-s-three-gorges-dam-a-model-of-the-past-2638 (accessed 11.21.12).
146. International Rivers, 2012b. Sambor [WWW Document]. Mekong Mainstream Dams. URL http://www.internationalrivers.org/southeast-asia/mekong-mainstream-dams/sambor (accessed 1.6.12).
147. IPCC, 2003. Good Practice Guidance for Land Use, Land-Use Change and Forestry (IPCC National Greenhouse Gas Inventories Programme). Institute for Global Environmental Strategies (IGES) for the IPCC.
148. IPCC, 2007. Climate Change 2007: Mitigation of Climatechange. Intergovernmental Panel on Climate Change, Geneva.
149. IPCC, 2008. Climate Change and Water 2008 (IPCC Techical Paper VI). Intergovernmental Panel on Climate Change, Geneva.
150. IPCC, 2011. IPCC SREX summary for policymakers.
151. IPCC, T., 2001. Climate Change 2001: Impacts, Adaptation and Vulnerability. IPCC Third Assessment Report. Cambridge University Press.
152. Jackowicz-Korczyński, M., Christensen, T.R., Bäckstrand, K., Crill, P., Friborg, T., Mastepanov, M., Ström, L., 2010. Annual cycle of methane emission from a subarctic peatland. J. Geophys. Res. 115, G02009.
153. Jaksic, V., Kiely, G., Albertson, J., Oren, R., 2006. Net ecosystem exchange of grassland in contrasting wet and dry years. Agricultural and Forest Meteorology 139, 323–334.
154. Jang, I., Lee, S., Hong, J.-H., Kang, H., 2006. Methane oxidation rates in forest soils and their controlling variables: a review and a case study in Korea. Ecological Research 21, 849–854.
155. Jauhiainen, J., Takahashi, H., Heikkinen, J.E.P., Martikainen, P.J., Vasander, H., 2005. Carbon fluxes from a tropical peat swamp forest floor. Global Change Biology 11, 1788–1797.
156. Jia, S., Akiyama, T., 2005. A precise, unified method for estimating carbon storage in cool-temperate deciduous forest ecosystems. Agricultural and Forest Meteorology 134, 70–80.
157. Joiner, D.W., Lafleur, P.M., McCaughey, J.H., Bartlett, P.A., 1999. Interannual variability in carbon dioxide exchanges at a boreal wetland in the BOREAS northern study area. J. Geophys. Res. 104, 27663–27,672.
158. Jonsson, M., Wardle, D.A., 2010. Structural equation modelling reveals plant-community drivers of carbon storage in boreal forest ecosystems. Biol. Lett. 6, 116–119.
159. Jørgensen, S.E., 2009. Ecosystem Ecology. Academic Press.
160. Jouzel, J., Masson-Delmotte, V., Cattani, O., Dreyfus, G., Falourd, S., Hoffmann, G., Minster, B., Nouet, J., Barnola, J.M., Chappellaz, J., Fischer, H., Gallet, J.C., Johnsen, S., Leuenberger, M., Loulergue, L., Luethi, D., Oerter, H., Parrenin, F., Raisbeck, G., Raynaud, D., Schilt, A., Schwander, J., Selmo, E., Souchez, R., Spahni, R., Stauffer, B., Steffensen, J.P., Stenni, B., Stocker, T.F., Tison, J.L., Werner, M., Wolff, E.W., 2007. Orbital and Millennial Antarctic Climate Variability over the Past 800,000 Years. Science 317, 793–796.
161. Ju, W., Chen, J.M., Black, T.A., Barr, A.G., Liu, J., Chen, B., 2006. Modelling multi-year coupled carbon and water fluxes in a boreal aspen forest. Agricultural and Forest Meteorology 140, 136–151.
162. Juutinen, S., Alm, J., Larmola, T., Huttunen, J.T., Morero, M., Saarnio, S., Martikainen, P.J., Silvola, J., 2003. Methane (CH4) release from littoral wetlands of Boreal lakes during an extended flooding period. Global Change Biology 9, 413–424.
163. Juutinen, S., Rantakari, M., Kortelainen, P., Huttunen, J.T., Larmola, T., Alm, J., Silvola, J., Martikainen, P.J., 2009. Methane dynamics in different boreal lake types. Biogeosciences 6, 209–223.

164. Kalff, J., 2001. Limnology, 2nd ed. Prentice Hall.
165. Kastowski, M., Hinderer, M., Vecsei, A., 2011. Long-term carbon burial in European lakes: Analysis and estimate. Global Biogeochem. Cycles 25, GB3019.
166. Kate Day, 2010. Kate Day. Culture - Telegraph Blogs.
167. Kayranli, B., Scholz, M., Mustafa, A., Hedmark, Å., 2010. Carbon Storage and Fluxes within Freshwater Wetlands: a Critical Review. Wetlands 30, 111–124.
168. Keddy, P.A., 2010. Wetland Ecology: Principles and Conservation, 2nd ed. Cambridge University Press.
169. Kellman, L., Kavanaugh, K., 2008. Nitrous oxide dynamics in managed northern forest soil profiles: is production offset by consumption? Biogeochemistry 90, 115–128.
170. Kelly, C.A., Martens, C.S., III, W.U., 1995. Methane Dynamics Across a Tidally Flooded Riverbank Margin. Limnology and Oceanography 40, 1112–1129.
171. Kelly, C.A., Rudd, J.W.M., Louis, V.L.S., Moore, T., 1994. Turning attention to reservoir surfaces, a neglected area in greenhouse studies. Eos Trans. AGU 75, 332–333.
172. Kemenes, A., Forsberg, B.R., Melack, J.M., 2011. CO2 emissions from a tropical hydroelectric reservoir (Balbina, Brazil). Journal of Geophysical Research. Biogeosciences 116.
173. Kevin Zobrist, 2008. Measuring your forest stand.
174. Khalil, M. a. K., Shearer, M.J., Rasmussen, R.A., Duan, C., Ren, L., 2008. Production, oxidation, and emissions of methane from rice fields in China. J. Geophys. Res. 113, G00A04.
175. Kiehl, J.T., Trenberth, K.E., 1997. Earth's Annual Global Mean Energy Budget. Bulletin of the American Meteorological Society 78, 197.
176. Kirschbaum, M.U.F., Keith, H., Leuning, R., Cleugh, H.A., Jacobsen, K.L., Van Gorsel, E., Raison, R.J., 2007. Modelling net ecosystem carbon and water exchange of a temperate Eucalyptus delegatensis forest using multiple constraints. Agricultural and Forest Meteorology 145, 48–68.
177. Kirschbaum, M.U.F., Mueller, R., 2001. Net Ecosystem Exchange: Workshop Proceedings, CRC for Greenhouse Accounting, April 2001. CRC for Greenhouse Accounting.
178. Kitamura, K., Nakai, Y., Suzuki, S., Ohtani, Y., Yamanoi, K., Sakamoto, T., 2012. Interannual variability of net ecosystem production for a broadleaf deciduous forest in Sapporo, northern Japan. Journal of Forest Research 17, 323–332.
179. Klopatek, J.M., 2002. Belowground carbon pools and processes in different age stands of Douglas-fir. Tree Physiol. 22, 197–204.
180. Knohl A., Schulze E.-D., Kolle O., Buchmann N., 2003. Large carbon uptake by an unmanaged 250-year-old deciduous forest in Central Germany. Agricultural and Forest Meteorology 118, 151–167.
181. Koh, H., Ochs, C.A., Yu, K., 2009. Hydrologic gradient and vegetation controls on CH4 and CO2 fluxes in a spring-fed forested wetland. Hydrobiologia 630, 271–286.
182. Kominami, Y., Jomura, M., Dannoura, M., Goto, Y., Tamai, K., Miyama, T., Kanazawa, Y., Kaneko, S., Okumura, M., Misawa, N., Hamada, S., Sasaki, T., Kimura, H., Ohtani, Y., 2008. Biometric and eddy-covariance-based estimates of carbon balance for a warm-temperate mixed forest in Japan. Agricultural and Forest Meteorology 148, 723–737.
183. Konen, M.E., Jacobs, P.M., Burras, C.L., Talaga, B.J., Mason, J.A., 2002. Equations for predicting soil organic carbon using loss-on-ignition for north central U.S. soils. Soil Science Society of America Journal 66, 1878–1881.
184. Körner, C., 1998. A re-assessment of high elevation treeline positions and their explanation. Oecologia 115, 445–459.
185. Kosten, S., Roland, F., Da Motta Marques, D.M.L., Van Nes, E.H., Mazzeo, N., Sternberg, L. da S.L., Scheffer, M., Cole, J.J., 2010. Climate-dependent CO2 emissions from lakes. Global Biogeochemical Cycles 24.
186. Kristensen, C.J., 2007. Interview med enkeltpersoner in Teknikker i samfundsvidenskaberne. Roskilde Universitetsforlag, Frederiksberg.
187. Kruijt, B., Elbers, J.A., Von Randow, C., Araújo, A.C., Oliveira, P.J., Culf, A., Manzi, A.O., Nobre, A.D., Kabat, P., Moors, E.J., 2004. THE ROBUSTNESS OF EDDY

CORRELATION FLUXES FOR AMAZON RAIN FOREST CONDITIONS. Ecological Applications 14, 101–113.
188. Kummu, M., Varis, O., 2006. Sediment-related impacts due to upstream reservoir trapping the Lower Mekong River. Laboratory of Water Resources, Helsinki University of Technology, Helsinki.
189. Lafleur, P.M., 1999. Growing season energy and CO2 exchange at a subarctic boreal woodland. J. Geophys. Res. 104, 9571–9580.
190. Lafleur, P.M., Roulet, N.T., Admiral, S.W., 2001. Annual cycle of CO2 exchange at a bog peatland. J. Geophys. Res. 106, 3071–3081.
191. Lambert, M., Fréchette, J.-L., 2005. Analytical Techniques for Measuring Fluxes of CO2 and CH4; from Hydroelectric Reservoirs and Natural Water Bodies, in: Tremblay, A., Varfalvy, L., Roehm, C., Garneau, M. (Eds.), Greenhouse Gas Emissions — Fluxes and Processes, Environmental Science and Engineering. Springer Berlin Heidelberg, pp. 37–60.
192. Law, B. e., Thornton, P. e., Irvine, J., Anthoni, P. m., Van Tuyl, S., 2001. Carbon storage and fluxes in ponderosa pine forests at different developmental stages. Global Change Biology 7, 755–777.
193. Law B.E., Falge E., Gu L., Baldocchi D.D., Bakwin P., Berbigier P., Davis K., Dolman A.J., Falk M., Fuentes J.D., Goldstein A., Granier A., Grelle A., Hollinger D., Janssens I.A., Jarvis P., Jensen N.O., Katul G., Mahli Y., Matteucci G., Meyers T., Monson R., Munger W., Oechel W., Olson R., Pilegaard K., Paw U K.T., Thorgeirsson H., Valentini R., Verma S., Vesala T., Wilson K., Wofsy S., 2002. Environmental controls over carbon dioxide and water vapor exchange of terrestrial vegetation. Agricultural and Forest Meteorology 113, 97–120.
194. Ledec, G., Quintero, J.D., 2003. Good Dams and Bad Dams: Environmental Criteria for Site Selection of Hydroelectric Projects (Sustainable Development Working Paper No. 16). The World Bank Latin America and Caribbean Region Environmentally and Socially Sustainable Development Department (LCSES).
195. Lee, G., Scurrah, N., 2009. Power and Responsibility: The Mekong River Commission and Lower Mekong mainstream dams. Australian Mekong Resource Centre, University of Sydney and Oxfam Australia, Australia.
196. Lenton, T.M., 2011. Early warning of climate tipping points. Nature Climate Change 1, 201–209.
197. Li, S., Lu, X., 2012. Uncertainties of carbon emission from hydroelectric reservoirs. Natural Hazards 62, 1343–1345.
198. Li, Y.-L., Zhou, G.-Y., Zhang, D.-Q., Wenigmann, K.O., Otieno, D., Tenhunen, J., Zhang, Q.-M., Yan, J.-H., 2012. Quantification of ecosystem carbon exchange characteristics in a dominant subtropical evergreen forest ecosystem. Asia-Pacific Journal of Atmospheric Sciences 48, 1–10.
199. Library of Congress Country Studies, 2012. Geography of Cambodia. Wikipedia, the free encyclopedia.
200. Lima, I.B.T., Ramos, F.M., Bambace, L.A.W., Rosa, R.R., 2008. Methane emissions from large dams as renewable energy resources: a developing nation perspective. Mitigation and Adaptation Strategies for Global Change 13, 193–206.
201. Lindroth, A., Grelle, A., Morén, A.-S., 1998. Long-term measurements of boreal forest carbon balance reveal large temperature sensitivity. Global Change Biology 4, 443–450.
202. Liu, L., Chen, H., Yuan, X., Chen, Z., Wu, Y., 2011a. Unexpected CH4 emission from the Three Gorges Reservoir and its implications. Acta Ecologica Sinica 31, 233–234.
203. Liu, S., Bond-Lamberty, B., Hicke, J.A., Vargas, R., Zhao, S., Chen, J., Edburg, S.L., Hu, Y., Liu, J., McGuire, A.D., Xiao, J., Keane, R., Yuan, W., Tang, J., Luo, Y., Potter, C., Oeding, J., 2011b. Simulating the impacts of disturbances on forest carbon cycling in North America: Processes, data, models, and challenges. J. Geophys. Res. 116, 22 PP.
204. Loescher, H.W., Oberbauer, S.F., Gholz, H.L., Clark, D.B., 2003. Environmental controls on net ecosystem-level carbon exchange and productivity in a Central American tropical wet forest. Global Change Biology 9, 396–412.

205. Lopes, E.C., 2005. Wood and soil-atmosphere carbon dioxide fluxes from a tropical forest ecosystem (Ph.D.).
206. López Bellido, J., Ojala, A., Peltomaa, E., 2011. An urban boreal lake basin as a source of CO2 and CH4. Environmental Pollution 159, 1649–1659.
207. Lund, M., Lindroth, A., Christensen, T.R., StröM, L., 2007. Annual CO 2 balance of a temperate bog. Tellus B 59, 804–811.
208. Luthi, D., Le Floch, M., Bereiter, B., Blunier, T., Barnola, J.-M., Siegenthaler, U., Raynaud, D., Jouzel, J., Fischer, H., Kawamura, K., Stocker, T.F., 2008. High-resolution carbon dioxide concentration record 650,000-800,000[thinsp]years before present. Nature 453, 379–382.
209. Luyssaert, Inglima, I., Jung, M., Richardson, A.D., Reichstein, M., et al., 2007a. CO2 balance of boreal, temperate and tropical forests derived from a global database. Global Change Biology 13, 2509–2537.
210. Luyssaert, S., Inglima, I., Jung, M., Richardson, A.D., Reichstein, M., et al., 2007b. CO2 balance of boreal, temperate, and tropical forests derived from a global database. Global Change Biology 13, 2509–2537.
211. LWA, 1997. Use of saline water in rice based farming systems | Land and Water Australia. Office of Land and Water, Australia, Sydney, N.S.W.
212. MacAlister, C., Mahaxay, M., 2009. Mapping wetlands in the Lower Mekong Basin for wetland resource and conservation management using Landsat ETM images and field survey data. Journal of Environmental Management 90, 2130–2137.
213. Malhi, Y., Grace, J., 2000. Tropical forests and atmospheric carbon dioxide. Trends in Ecology & Evolution 15, 332–337.
214. Marinho, C.C., Palma Silva, C., Albertoni, E.F., Trindade, C.R., Esteves, F.A., 2009. Seasonal dynamics of methane in the water column of two subtropical lakes differing in trophic status. Brazilian Journal of Biology 69, 281–287.
215. Markkanen, T., Rannik, U., Keronen, P., Suni, T., Vesala, T., 2001. Eddy covariance fluxes over a boreal Scots pine forest. Boreal environment research 6, 65–78.
216. Martin, A.R., Thomas, S.C., 2011. A Reassessment of Carbon Content in Tropical Trees. PLoS ONE 6, e23533.
217. Marty, R., 1999. Aids to Professional Forestry Practice: Point Sampling.
218. McCaughey, J.H., Pejam, M.R., Arain, M.A., Cameron, D.A., 2006. Carbon dioxide and energy fluxes from a boreal mixedwood forest ecosystem in Ontario, Canada. Agricultural and Forest Meteorology 140, 79–96.
219. McCully, P., 2006. Fizzy science: loosening the hydro industry's grip on reservoir greenhouse gas emissions research. International Rivers Network.
220. McEwan, R.W., Lin, Y.-C., Sun, I.-F., Hsieh, C.-F., Su, S.-H., Chang, L.-W., Song, G.-Z.M., Wang, H.-H., Hwong, J.-L., Lin, K.-C., Yang, K.-C., Chiang, J.-M., 2011. Topographic and biotic regulation of aboveground carbon storage in subtropical broad-leaved forests of Taiwan. Forest Ecology and Management 262, 1817–1825.
221. Megonigal, J.P., Schlesinger, W.H., 2002. Methane-limited methanotrophy in tidal freshwater swamps. Global Biogeochem. Cycles 16, 1088.
222. Megonigal, P.J., Hines, M.E., Visscher, P.T., 2007. Anaerobic Metabolism: Linkages to Trace Gases and Aerobic Processes, in: Treatise on Geochemistry. Elsevier, pp. 317–424.
223. Melling, L., Hatano, R., Goh, K.J., 2005. Methane fluxes from three ecosystems in tropical peatland of Sarawak, Malaysia. Soil Biology and Biochemistry 37, 1445–1453.
224. Michael Carlowicz, 2012. Seeing Forests for the Trees and the Carbon: Mapping the World's Forests in Three Dimensions : Feature Articles [WWW Document]. NASA. Earth observatory. URL http://earthobservatory.nasa.gov/Features/ForestCarbon/page2.php (accessed 10.11.12).
225. Michéli, E., Schad, P., Spaargaren, O., Dent, D., Nachtergaele, F., 2006. World reference base for soil resources: 2006: a framework for international classification, correlation and communication. FAO.

226. Micro*scope, 2006. Microbes of Lundy Lake [WWW Document]. URL http://starcentral.mbl.edu/microscope/portal.php?pagetitle=getcollection&collectionID=356 (accessed 10.11.12).
227. Middelton, C., 2009. Mekong Regional Initiatives [WWW Document]. International Rivers. URL http://www.internationalrivers.org/campaigns/mekong-regional-initiatives (accessed 11.11.12).
228. Middelton, C., Chanthy, S., 2008. Cambodia's Hydropower Development and China's Involvement. International Rivers and Rivers Coalition in Cambodia.
229. Miller, S.D., Goulden, M.L., Menton, M.C., Rocha, H.R. da, Freitas, H.C. de, E Silva Figueira, A.M., Sousa, C.A.D. de, 2004. Biometric and Micrometeorological Measurements of Tropical Forest Carbon Balance. Ecological Applications 14, S114–S126.
230. Monson, R.K., Turnipseed, A.A., Sparks, J.P., Harley, P.C., Scott-Denton, L.E., Sparks, K., Huxman, T.E., 2002. Carbon sequestration in a high-elevation, subalpine forest. Global Change Biology 8, 459–478.
231. Morris, G.L., Fan, J., 1997. Reservoir Sedimentation Handbook, 1st ed. McGraw-Hill Professional.
232. Moss, B., 2008. The kingdom of the shore: achievement of good ecological potential in reservoirs. Freshwater Reviews 1, 29–42.
233. MRC, 1994. Mekong Mainstream Run-of-river Hydropower. Mekong Secretariat.
234. Mukhophadhya, S.K., Biswas, H., Das, K.L., De, T.K., Jana, T.K., 2001. Diurnal variation of carbon dioxide and methane exchange above Sundarbans mangrove forest, in NW coast of India. Indian journal of marine sciences 30, 70–74.
235. Mulholland, P.J., Elwood, J.W., 1982. The role of lake and reservoir sediments as sinks in the perturbed global carbon cycle. Tellus 34, 490–499.
236. N. Panikov, V.Z., 1991. Methane and carbon dioxide production and uptake in some boreal ecosystems of Russia. In: Carbon Cycling in Boreal Forests and Sub-arctic Ecosystems (Vinson T.S. and Kolchugina T.P., eds.) Washington, DC: Unated States Environmental Protection Agency Report EPA/600R-93/084, Office of Research and Development 125–138.
237. Nagy, M.T., Janssens, I.A., Curiel Yuste, J., Carrara, A., Ceulemans, R., 2006. Footprint-adjusted net ecosystem CO2 exchange and carbon balance components of a temperate forest. Agricultural and Forest Meteorology 139, 344–360.
238. Nahlik, A.M., Mitsch, W.J., 2011. Methane emissions from tropical freshwater wetlands located in different climatic zones of Costa Rica. Global Change Biology 17, 1321–1334.
239. NASA, 2012. NASA Multimedia Page [WWW Document]. URL http://www.nasa.gov/multimedia/index.html (accessed 10.11.12).
240. Nette, A., 2009. Hydropower dam on the Mekong River less competitive to other sources. NoticiasFinancieras.
241. Neubauer, S.C., Cofman Anderson, I., Miller, W.D., 2000. Carbon cycling in a tidal freshwater marsh ecosystem:a carbon gas flux study. Marine Ecology Progress Series 199, 13–30.
242. Neue, H.U. (Internationa. R.R.I., 1993. Methane emission from rice fields: Wetland rice fields may make a major contribution to global warming.
243. NIEA, 2011. About peatlands [WWW Document]. Ireland Department of Environment. URL http://www.doeni.gov.uk/niea/biodiversity/habitats-2/peatlands/about_peatlands.htm (accessed 8.29.12).
244. Nix, S., 2012. Forest Resource Glossary and Definition of Terms - H [WWW Document]. URL http://forestry.about.com/library/glossary/blforglh.htm (accessed 11.22.12).
245. NPC, 2007. NPC Global Oil and Gas Study: #4 Electric Generation Efficiency.
246. Nykanen, H., Alm, J., Lang, K., Silvola, J., Martikainen, P., 1998. Emissions of CH4, N2O and CO2 from a virgin fen and a fen drained for grassland in Finland. J. Biogeogr. 22, 351–357.
247. Nykänen, H., Alm, J., Silvola, J., Tolonen, K., Martikainen, P.J., 1998. Methane fluxes on boreal peatlands of different fertility and the effect of long-term experimental lowering of the water table on flux rates. Global Biogeochemical Cycles 12, 53–69.

248. OECD, 2003. Recommendation on the Common Approaches on Environment and Officially Supported Export Credits. The Organisation for Economic Co-operation and Development.
249. Olson, D.M., Dinerstein, E., Wikramanayake, E.D., Burgess, N.D., Powell, G.V.N., Underwood, E.C., D'amico, J.A., Itoua, I., Strand, H.E., Morrison, J.C., Loucks, C.J., Allnutt, T.F., Ricketts, T.H., Kura, Y., Lamoreux, J.F., Wettengel, W.W., Hedao, P., Kassem, K.R., 2001. Terrestrial Ecoregions of the World: A New Map of Life on Earth. BioScience 51, 933–938.
250. Osborne, M., 2004. Rivers at risk, The Mekong and the water politics of China and Southeast Asia (Lowy Institute Paper 02). Lowy Institute for International Policy.
251. Osborne, M., 2007. The Water Politics of China and Southeast Asia II - Rivers, Dams, Cargo Boats and the Environment, Lowy Institute Perspectives. Lowy Institute for International Policy, Australia.
252. Osborne, M., 2009. the Mekong River under threat. Lowy Institute for International Policy, Australia.
253. Oxfam Australia, 2010. Sambor Dam [WWW Document]. Damming the Mekong. URL https://www.oxfam.org.au/explore/infrastructure-people-and-environment/save-the-mekong/damming-the-mekong/sambor-dam/ (accessed 10.19.12).
254. Pan, Y., Birdsey, R.A., Fang, J., Houghton, R., Kauppi, P.E., Kurz, W.A., Phillips, O.L., Shvidenko, A., Lewis, S.L., Canadell, J.G., Ciais, P., Jackson, R.B., Pacala, S.W., McGuire, A.D., Piao, S., Rautiainen, A., Sitch, S., Hayes, D., 2011. A Large and Persistent Carbon Sink in the World's Forests. Science 333, 988–993.
255. Pannucci, C.J., Wilkins, E.G., 2010. Identifying and Avoiding Bias in Research. Plast Reconstr Surg 126, 619–625.
256. Parekh, P., 2004. A Preliminary Review of the Impact of Dam Reservoirs on Carbon Cycling. International Rivers Network.
257. Paulsen, J., Weber, U.M., Körner, C., 2000. Tree Growth near Treeline: Abrupt or Gradual Reduction with Altitude? Arctic, Antarctic, and Alpine Research 32, 14–20.
258. Pedroni, L., 1997. Forest ecosystems, forest management and the global carbon cycle: Michael J. Apps and David T. Price (Editors), 1996, 452 pp., DM 280.00. Forest Ecology and Management 97, 91–92.
259. Pehnt, M., 2006. Dynamic life cycle assessment (LCA) of renewable energy technologies. Renewable Energy 31, 55–71.
260. Peichl, M., Brodeur, J.J., Khomik, M., Arain, M.A., 2010. Biometric and eddy-covariance based estimates of carbon fluxes in an age-sequence of temperate pine forests. Agricultural and Forest Meteorology 150, 952–965.
261. Peng, S., 1995. Climate Change and Rice. Int. Rice Res. Inst.
262. Penman, J., Gytarsky, M., Hiraishi, T., Krug, T., Kruger, D., Pipatti, R., Buendia, L., Miwa, K., Ngara, T., Tanabe, K., 2003. Good practice guidance for land use, land-use change and forestry. Institute for Global Environmental Strategies.
263. Phogat, V., Yadav, A.K., Malik, R.S., Kumar, S., Cox, J., 2010. Simulation of salt and water movement and estimation of water productivity of rice crop irrigated with saline water. Paddy Water Environ 8, 333–346.
264. Photos: A Forest of Blue - Canada's Boreal Forest - Pew Environment Group [WWW Document], n.d. Pew Environment Group. URL http://www.pewenvironment.org/news-room/other-resources/Photos-A-Forest-of-Blue-Canadas-Boreal-Forest-328892 (accessed 10.3.12).
265. Pitts, K., 2012. Drawdown zone - Definition of Drawdown zone in the Entomologists' glossary - Amateur Entomologists' Society (AES) [WWW Document]. URL http://www.amentsoc.org/insects/glossary/terms/drawdown-zone (accessed 12.15.12).
266. Planetary boundary layer, 2012. . Wikipedia, the free encyclopedia.
267. Pregitzer, K.S., Euskirchen, E.S., 2004. Carbon cycling and storage in world forests: biome patterns related to forest age. Global Change Biology 10, 2052–2077.
268. Purvaja, R., Ramesh, R., Frenzel, P., 2004. Plant-mediated methane emission from an Indian mangrove. Global Change Biology 10, 1825–1834.

269. Raich, J.W., Russell, A.E., Kitayama, K., Parton, W.J., Vitousek, P.M., 2006. Temperature Influences Carbon Accumulation in Moist Tropical Forests. Ecology 87, 76–87.
270. Ramos, F.M., Lima, I.B.T., Rosa, R.R., Mazzi, E.A., Carvalho, J.C., Rasera, M.F.F.L., Ometto, J.P.H.B., Assireu, A.T., Stech, J.L., 2006. Extreme event dynamics in methane ebullition fluxes from tropical reservoirs. Geophys. Res. Lett. 33, L21404.
271. Randerson, J.T., III, F.S.C., Harden, J.W., Neff, J.C., Harmon, M.E., 2002. Net Ecosystem Production: A Comprehensive Measure of Net Carbon Accumulation by Ecosystems. Ecological Applications 12, 937–947.
272. Raymond, P.A., Caraco, N.F., Cole, J.J., 1997. Carbon Dioxide Concentration and Atmospheric Flux in the Hudson River. Estuaries 20, 381.
273. Reddy, S.R.C., Price, C., 1999. Carbon Sequestration and Conservation of Tropical Forests Under Uncertainty. Journal of Agricultural Economics 50, 17–35.
274. Reyes, G., Brown, S., Chapman, J., Lugo, A.E., 1992. Wood Densities of Tropical Tree Species (General Technical Report No. S0-88). United States Department of Agriculture. Forest Service. Southern Forest Experiment Station.
275. Richey, J.E., Melack, J.M., Aufdenkampe, A.K., Ballester, V.M., Hess, L.L., 2002. Outgassing from Amazonian rivers and wetlands as a large tropical source of atmospheric CO2. Nature 416, 617–20.
276. Riebeek, H., 2011. The Carbon Cycle : Feature Articles [WWW Document]. NASA. Earth observatory. URL http://earthobservatory.nasa.gov/Features/CarbonCycle/page1.php (accessed 1.11.12).
277. Rinne, J., Riutta, T., Pihlatie, M., Aurela, M., Haapanala, S., Tuovinen, J.-P., Tuittila, E.-S., Vesala, T., 2007. Annual cycle of methane emission from a boreal fen measured by the eddy covariance technique. Tellus B 59, 449–457.
278. Ritchie, J.C., 1989. Carbon Content of Sediment of Small Reservoirs. JAWRA Journal of the American Water Resources Association 25, 301–308.
279. Ritchie, J.C., McCarty, G.W., Venteris, E.R., Kaspar, T.C., Owens, L.B., Nearing, M., 2004. Assessing soil organic carbon redistribution with fallout 137Cesium. Conserving soil and water for society: Sharing solutions. Proc. of the ISCO.
280. River Photos -- National Geographic [WWW Document], n.d. National Geographic. URL http://environment.nationalgeographic.com/environment/photos/freshwater-rivers/ (accessed 10.11.12).
281. Roberts, T.R., 2011. Downstream ecological implications of China's Lancang Hydropower and Mekong Navigation project. International Rivers.
282. Roland, F., Vidal, L., Pacheco, F., Barros, N., Assireu, A., Ometto, J., Cimbleris, A., Cole, J., 2010. Variability of carbon dioxide flux from tropical (Cerrado) hydroelectric reservoirs. Aquatic Sciences - Research Across Boundaries 72, 283–293.
283. Rosa, L.P., Dos Santos, M.A., Matvienko, B., Dos Santos, E.O., Sikar, E., 2004. Greenhouse gas emissions from hydroelectric reservoirs in tropical regions. Climatic Change 66, 9–21.
284. Rosa, L.P., Dos Santos, M.A., Matvienko, B., Sikar, E., 2002. Hydroelectric reservoirs and global warming. UFRJ-Coppe, Rio.
285. Roulet, N.T., Jano, A., Kelly, C.A., Klinger, L.F., Moore, T.R., Protz, R., Ritter, J.A., Rouse, W.R., 1994. Role of the Hudson Bay lowland as a source of atmospheric methane. J. Geophys. Res. 99, 1439–1454.
286. Saigusa, N., Yamamoto, S., Murayama, S., Kondo, H., Nishimura, N., 2002. Gross primary production and net ecosystem exchange of a cool-temperate deciduous forest estimated by the eddy covariance method. Agricultural and Forest Meteorology 112, 203–215.
287. Salm, J.-O., Maddison, M., Tammik, S., Soosaar, K., Truu, J., Mander, Ü., 2012. Emissions of CO2, CH4 and N2O from undisturbed, drained and mined peatlands in Estonia. Hydrobiologia 692, 41–55.
288. Sand-Jensen, K., Staehr, P.A., 2007. Scaling of Pelagic Metabolism to Size, Trophy and Forest Cover in Small Danish Lakes. Ecosystems 10, 127–141.
289. Save the Mekong Coalition, 2012. Fact Sheet: Mekong Mainstream Dams.

290. Schaphoff, S., Lucht, W., Gerten, D., Sitch, S., Cramer, W., Prentice, I.C., 2006. Terrestrial biosphere carbon storage under alternative climate projections. Climatic Change 74, 97–122.
291. Schimel, D., Alves, D., Enting, I., Heimann, M., Joos, F., Raynaud, D., Wigley, T., Prather, M., Derwent, R., Ehhalt, D., 1996. Radiative forcing of climate change. Climate change 1995: The science of climate change 65–131.
292. Schrier-Uijl, A., Veraart, A., Leffelaar, P., Berendse, F., Veenendaal, E., 2011. Release of CO2 and CH4; from lakes and drainage ditches in temperate wetlands. Biogeochemistry 102, 265–279.
293. Şentürk, F., 1994. Hydraulics of Dams and Reservoirs. Water Resources Publication.
294. Silvola, J., Alm, J., Ahlholm, U., Nykanen, H., Martikainen, P.J., 1996. CO 2 Fluxes from Peat in Boreal Mires under Varying Temperature and Moisture Conditions. The Journal of Ecology 84, 219.
295. Smith, A., 1997. Oxford dictionary of biochemistry and molecular biology. Oxford University Press, Oxford [u.a.].
296. Smith, L.K., Lewis, W.M., Chanton, J.P., Cronin, G., Hamilton, S.K., 2000. Methane Emissions from the Orinoco River Floodplain, Venezuela. Biogeochemistry 51, 113–140.
297. Sobek, S., 2005. Temperature independence of carbon dioxide supersaturation in global lakes. Global Biogeochemical Cycles 19.
298. Sobek, S., DelSontro, T., Wongfun, N., Wehrli, B., 2012. Extreme organic carbon burial fuels intense methane bubbling in a temperate reservoir. Geophys. Res. Lett. 39, L01401.
299. Sohngen, B., Brown, S., 2006. The influence of conversion of forest types on carbon sequestration and other ecosystem services in the South Central United States. Ecological Economics 57, 698–708.
300. Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K., Tignor, M., Miller, H., 2007. IPPC Fourth Assessment Report (AR4). Climate Change 2007: The Physical Science Basis. Contribution of Working Group 1 to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, ISBN 978, 70596–7.
301. Soumis, N., Duchemin, É., Canuel, R., Lucotte, M., 2004. Greenhouse gas emissions from reservoirs of the western United States. Global Biogeochem. Cycles 18, 11 PP.
302. Sovacool, B.K., 2008. Valuing the greenhouse gas emissions from nuclear power: A critical survey. Energy Policy 36, 2950–2963.
303. St Louis, V.L., Kelly, C.A., Duchemin, E., Rudd, J.W.M., Rosenberg, D.M., 2000. Reservoir surfaces as sources of greenhouse gases to the atmosphere: A global estimate. Bioscience 50, 766–775.
304. St. Louis, V.L., Kelly, C.A., Duchemin, É., Rudd, J.W.M., Rosenberg, D.M., 2000. Reservoir surfaces as sources of greenhouse gases to the atmosphere: A global estimate. BioScience 50, 766–775.
305. Stefanidis, P., Stefanidis, S., 2012. Reservoir sedimentation and mitigation measures. Lakes & Reservoirs: Research & Management 17, 113–117.
306. Stephen, P., 2001. The Australian Master TreeGrower Program [WWW Document]. URL http://www.mtg.unimelb.edu.au/publications/farmers_forest.htm (accessed 8.27.12).
307. Striegl, R.G., Michmerhuizen, C.M., 1998. Hydrologic influence on methane and carbon dioxide dynamics at two north-central Minnesota lakes. Limnology and Oceanography 43, 1519–1529.
308. Suzuki S, Ishida T, Nagano T, Waijaroen S, 1999. Influences of Deforestation on Carbon Balance in a Natural Tropical Peat Swamp Forest in Thailand. Environment Control in Biology 37, 115–128.
309. Swarthout, D., Hogan, M.C., 2012. Stomata. The Encyclopedia of Earth.
310. Tadonléké, R.D., Marty, J., Planas, D., 2012. Assessing factors underlying variation of CO2 emissions in boreal lakes vs. reservoirs. FEMS Microbiology Ecology 79, 282–297.
311. TAMU, 2010. Getting Permission.

312. Tan, Z., Zhang, Y., Yu, G., Sha, L., Tang, J., Deng, X., Song, Q., 2010. Carbon Balance of a Primary Tropical Seasonal Rain Forest. Journal of Geophysical Research. Atmospheres 115.
313. Tani, A., Ito, E., Kanzaki, M., Ohta, S., Khorn, S., Pith, P., Tith, B., Pol, S., Lim, S., 2007. Principal Forest Types of Three Regions of Cambodia: Kampong Thom, Kratie, and Mondolkiri, in: Sawada, H., Araki, M., Chappell, N.A., LaFrankie, J.V., Shimizu, A. (Eds.), Forest Environments in the Mekong River Basin. Springer Japan, Tokyo, pp. 201–213.
314. Taufarová, K., Havránková, K., Czerný, R., Janouš, D., 2008. ATMOSPHERIC FACTORS INFLUENCING NET ECOSYSTEM PRODUCTION OF NORWAY SPRUCE FOREST IN BESKYDY MOUNTAINS.
315. Teh, Y.A., Silver, W.L., Sonnentag, O., Detto, M., Kelly, M., Baldocchi, D.D., 2011. Large Greenhouse Gas Emissions from a Temperate Peatland Pasture. Ecosystems 14, 311–325.
316. Telmer, K., Veizer, J., 1999. Carbon fluxes, pCO2 and substrate weathering in a large northern river basin, Canada: carbon isotope perspectives. Chemical Geology 159, 61–86.
317. Teodoru, C.R., Bastien, J., Bonneville, M.-C., Giorgio, P.A. del, Demarty, M., Garneau, M., Hélie, J.-F., Pelletier, L., Prairie, Y.T., Roulet, N.T., Strachan, I.B., Tremblay, A., 2012. The net carbon footprint of a newly created boreal hydroelectric reservoir. Global Biogeochem. Cycles 26, GB2016.
318. TERRA, 2007. Sambor Dam, Kratie province, Cambodia (Fact sheet on the proposed Sambor Dam). TERRA.
319. The Cambodia Daily, 2012a. As soldiers leave Kratie Village, Problems Remain 1, 4–5.
320. The Cambodia Daily, 2012b. Past Bodes Poorly for Future of Land Concession Freeze.
321. The forest biome [WWW Document], n.d. . URL http://www.ucmp.berkeley.edu/exhibits/biomes/forests.php (accessed 7.3.12).
322. The Independent, 2012. Teenage girl in Cambodia killed during violent eviction [WWW Document]. World News. URL http://article.wn.com/view/2012/05/16/Teenage_girl_in_Cambodia_killed_during_violent_eviction/ (accessed 10.21.12).
323. Time Magazine, 2012. Cambodia Suspends Land Concessions [WWW Document]. World News. URL http://article.wn.com/view/2012/05/08/Cambodia_Suspends_Land_Concessions/ (accessed 10.21.12).
324. Tipping point (climatology), 2012. . Wikipedia, the free encyclopedia.
325. Tranvik, L.J., Downing, J.A., Cotner, J.B., Loiselle, S.A., Striegl, R.G., Ballatore, T.J., Dillon, P., Knoll, L.B., Kutser, T., Larsen, S., Laurion, I., Leech, D.M., McAllister, S.L., McKnight, D.M., Melack, J., Overholt, E., Porter, J.A., Prairie, Y.T., Renwick, W.H., Roland, F., Sherman, B.S., Schindler, D.W., Sobek, S., Tremblay, A., Vanni, M.J., Verschoor, A.M., Wachenfeldt, E., Weyhenmeyer, G., 2009. Lakes and reservoirs as regulators of carbon cycling and climate [WWW Document]. Limnology and Oceanography. URL http://depot.knaw.nl/6255/ (accessed 10.15.12).
326. Trees for the future, 2005. How to calculate the amount of CO2 sequestered in a tree per year.
327. Tremblay, A., Varfalvy, L., Roehm, C., Garneau, M. (Eds.), 2005. Greenhouse Gas Emissions - Fluxes and Processes: Hydroelectric Reservoirs and Natural Environments, 1st ed. Springer.
328. Trolle, D., Staehr, P., Davidson, T., Bjerring, R., Lauridsen, T., Søndergaard, M., Jeppesen, E., 2012. Seasonal Dynamics of CO₂ Flux Across the Surface of Shallow Temperate Lakes. Ecosystems 15, 336–347.
329. Trophic state index, 2012. . Wikipedia, the free encyclopedia.
330. U.S. Department of State, 2007. Projected Greenhouse Gas Emissions [WWW Document]. U.S. Department of State. URL http://www.state.gov/e/oes/rls/rpts/car4/90324.htm (accessed 11.17.12).
331. U.S. EIA, 2011. Carbon Dioxide Uncontrolled Emission Factors, Electric Power Annual 2010.

332. Ullah, S., Frasier, R., Pelletier, L., Moore, T.R., 2009. Greenhouse gas fluxes from boreal forest soils during the snow-free period in Quebec, Canada. Canadian Journal of Forest Research 39, 666–680.
333. Ullah, S., Moore, T., 2012. Greenhouse Gas Fluxes from Deciduous and Boreal Forest Soils in Eastern Canada, in: EGU General Assembly Conference Abstracts. Presented at the EGU General Assembly Conference Abstracts, p. 5398.
334. UN Deptartment of Public Information, 2005. The Millennium Development Goals report 2005. New York: United Nations.
335. UNESCO, 2009. The 3rd United Nations World Water Development Report: Water in a Changing World. UNESCO, Paris.
336. UNESCO, IHA, 2009. UNESCO/IHA Greenhouse Gas (GHG) Research Project. UNESCO/IHA measurement specification guidance for evaluating the GHG status of man-made freshwater reservoirs.
337. UNFCCC, 2012a. Glossary of climate change acronyms [WWW Document]. URL http://unfccc.int/essential_background/glossary/items/3666.php#L (accessed 5.26.12).
338. UNFCCC, 2012b. Land Use, Land-Use Change and Forestry (LULUCF) under the Koyote Protocol [WWW Document]. URL http://unfccc.int/methods_and_science/lulucf/items/3060.php (accessed 11.14.12).
339. UNFCCC, 2012c. Reporting of the LULUCF sector under the Convention [WWW Document]. URL http://unfccc.int/methods_and_science/lulucf/items/4127.php (accessed 11.14.12).
340. US EPA, 2005. Method 415.3 - Measurement of total organic carbon, disolved organic carbon and specific UV absorbance at 254 nm in source water and drinking water.
341. USDA FIA, 2003. Forest Inventory and Analysis National Program - Tools and Data [WWW Document]. URL http://www.fia.fs.fed.us/tools-data/default.asp (accessed 8.26.12).
342. Valentini, R., Matteucci, G., Dolman, A.J., Schulze, E.-D., Rebmann, C., Moors, E.J., Granier, A., Gross, P., Jensen, N.O., Pilegaard, K., Lindroth, A., Grelle, A., Bernhofer, C., Grünwald, T., Aubinet, M., Ceulemans, R., Kowalski, A.S., Vesala, T., Rannik, Ü., Berbigier, P., Loustau, D., Guðmundsson, J., Thorgeirsson, H., Ibrom, A., Morgenstern, K., Clement, R., Moncrieff, J., Montagnani, L., Minerbi, S., Jarvis, P.G., 2000. Respiration as the main determinant of carbon balance in European forests. Nature 404, 861–865.
343. Van Bodegom, P.M., Leffelaar, P.A., Stams, A.J.M., Wassmann, R., 2000. Modeling Methane Emissions from Rice Fields: Variability, Uncertainty, and Sensitivity Analysis of Processes Involved. Nutrient Cycling in Agroecosystems 58, 231–248.
344. Victoria, R.L., Krusche, A.V., Alin, S.R., Richey, J.E., Rasera, M. de F.F.L., Ballester, M.V.R., Montebelo, L.A., Salimon, C., 2008. Estimating the surface area of small rivers in the southwestern Amazon and their role in CO2 outgassing. Earth Interactions preprint, 1.
345. Waddington, J.M., Roulet, N.T., 2000. Carbon balance of a boreal patterned peatland. Global Change Biology 6, 87–97.
346. Walter, B.P., Heimann, M., Matthews, E., 2001. Modeling modern methane emissions from natural wetlands 1. Model description and results. J. Geophys. Res. 106, 34189–34,206.
347. Walter, K.M., Smith, L.C., Chapin, F.S., 2007. Methane Bubbling from Northern Lakes: Present and Future Contributions to the Global Methane Budget. Philosophical Transactions: Mathematical, Physical and Engineering Sciences 365, 1657–1676.
348. Wang, F., Wang, B., Liu, C.-Q., Wang, Y., Guan, J., Liu, X., Yu, Y., 2011. Carbon dioxide emission from surface water in cascade reservoirs–river system on the Maotiao River, southwest of China. Atmospheric Environment 45, 3827–3834.
349. Wang, Z., Hu, C., 2009. Strategies for managing reservoir sedimentation. International Journal of Sediment Research 24, 369–384.
350. WCD, 2000. Dams and Development. A framework for decision-making. World Commission on Dams, Earthscan, London.

351. Weinschenck, G., Henrichsmeyer, W., Aldinger, F., 1969. The Theory of Spatial Equilibrium and Optimal Location in Agriculture: A Survey. Review of Marketing and Agricultural Economics 37.
352. Whalen, S.C., 2005. Biogeochemistry of Methane Exchange between Natural Wetlands and the Atmosphere. Environmental Engineering Science 22, 73–94.
353. Whiting, G.J., 1994. CO2 exchange in the Hudson Bay lowlands: Community characteristics and multispectral reflectance properties. J. Geophys. Res. 99, 1519–1528.
354. Whiting, G.J., Chanton, J.P., 2001. Greenhouse carbon balance of wetlands: methane emission versus carbon sequestration. Tellus B 53, 521–528.
355. Wilson, J.O., Crill, P.M., Bartlett, K.B., Sebacher, D.I., Harriss, R.C., Sass, R.L., 1989. Seasonal Variation of Methane Emissions from a Temperate Swamp. Biogeochemistry 8, 55–71.
356. Wilson, K.B., Baldocchi, D.D., 2001. Comparing independent estimates of carbon dioxide exchange over 5 years at a deciduous forest in the southeastern United States. J. Geophys. Res. 106, 34167–34,178.
357. Wisconsin Department of Natural Resources, 2012. Wetlands checklist C0101a [WWW Document]. Wetlands. URL http://dnr.wi.gov/topic/wetlands/checklist/checklist_C0101a.html (accessed 10.11.12).
358. World Bank, 2009. Hydropower. Frequently Asked Questions on World Bank Support to Hydropower.
359. World Energy Council, 2009. Survey of Energy Resources - Interim Update 2009. United Kingdom.
360. WWF, 2012. Dry Forest Ecology [WWW Document]. WWF. URL http://cambodia.panda.org/wwf_in_cambodia/dry_forests/dry_forest_ecology/index.cfm (accessed 10.19.12).
361. Xing, Y., Xie, P., Yang, H., Ni, L., Wang, Y., Rong, K., 2005. Methane and carbon dioxide fluxes from a shallow hypereutrophic subtropical Lake in China. Atmospheric Environment 39, 5532–5540.
362. Yan, X., Akiyama, H., Yagi, K., Akimoto, H., 2009. Global estimations of the inventory and mitigation potential of methane emissions from rice cultivation conducted using the 2006 Intergovernmental Panel on Climate Change Guidelines. Global Biogeochem. Cycles 23, GB2002.
363. Yu, X., 2003. Regional cooperation and energy development in the Greater Mekong Sub-region. Energy Policy 31, 1221–1234.
364. Yuan, F., Arain, M.A., Barr, A.G., Black, T.A., Bourque, C.P.-A., Coursolle, C., Margolis, H.A., McCAUGHEY, J.H., Wofsy, S.C., 2008. Modeling analysis of primary controls on net ecosystem productivity of seven boreal and temperate coniferous forests across a continental transect. Global Change Biology 14, 1765–1784.
365. Zeng, F., Masiello, C.A., 2010. Sources of CO2 evasion from two subtropical rivers in North America. Biogeochemistry 100, 211–225.
366. Zha, T., Xing, Z., Wang, K.-Y., Kellomäki, S., Barr, A.G., 2007. Total and Component Carbon Fluxes of a Scots Pine Ecosystem from Chamber Measurements and Eddy Covariance. Ann Bot 99, 345–353.
367. Zhang, M., Yu, G.-R., Zhang, L.-M., Sun, X.-M., Wen, X.-F., Han, S.-J., Yan, J.-H., 2010. Impact of cloudiness on net ecosystem exchange of carbon dioxide in different types of forest ecosystems in China. Biogeosciences 7, 711–722.
368. Zhang, M., Yu, G.-R., Zhuang, J., Gentry, R., Fu, Y.-L., Sun, X.-M., Zhang, L.-M., Wen, X.-F., Wang, Q.-F., Han, S.-J., Yan, J.-H., Zhang, Y.-P., Wang, Y.-F., Li, Y.-N., 2011. Effects of cloudiness change on net ecosystem exchange, light use efficiency, and water use efficiency in typical ecosystems of China. Agricultural and Forest Meteorology 151, 803–816.
369. Zheng, H., Zhao, X., Zhao, T., Chen, F., Xu, W., Duan, X., Wang, X., Ouyang, Z., 2011. Spatial–temporal variations of methane emissions from the Ertan hydroelectric reservoir in southwest China. Hydrological Processes 25, 1391–1396.

Appendix 1:
Hydropower reservoirs included in the study; page 1 of 2

	Reservoir - Name	*Country*	*Region*	*Flooded yr*	*Sample yr*	*Age*	*Area*	*NEE of CO2*	*NEE of CH4*	*Biome*	*source*
	NORTH AMERICA										
1	Aluoette	Canada	British-columbia	1928	2002	74	17	407		boreal	Tremblay 2005
2	Arrow-Lower	Canada	British-columbia	1969	2002	33		1032	-6.6	boreal	Tremblay 2005
3	Buntzen	Canada	British-columbia	1914	2002	88	2	-1411		boreal	Tremblay 2005
4	Duncan	Canada	British-columbia	1965	2002	37	72	810	-10.0	boreal	Tremblay 2005
5	Jones	Canada	British-columbia	1952	2002	50	5	213		boreal	Tremblay 2005
6	Seven Mile	Canada	British-columbia	1979	2002	23	4	731	-113.0	boreal	Tremblay 2005
7	Stave	Canada	British-columbia	1911	2002	91	62	-602		boreal	Tremblay 2005
8	Whatsan	Canada	British-columbia	1951	2002	51		5	-5.8	boreal	Tremblay 2005
9	Williston-Finlay	Canada	British-columbia	1961	2002	41	1761	-704		boreal	Tremblay 2005
10	Williston-Parsnip	Canada	British-columbia	1969	2002	33	1761	-1758		boreal	Tremblay 2005
11	Williston-Peace	Canada	British-columbia	1979	2002	23	1761	-920		boreal	Tremblay 2005
12	Grand Rapids	Canada	Manitoba/Ontario	1968	2007	39		-624	-0.6	boreal	Demarty 2009
13	Great Falls	Canada	Manitoba/Ontario	1928	2002	74	10	-5754	-15.3	boreal	Tremblay 2005
14	Jenpeng	Canada	Manitoba/Ontario	1979	2007	28		-316	-1.1	boreal	Demarty 2009
15	Kettle	Canada	Manitoba/Ontario	1970	2007	37	337	-514	0.0	boreal	Demarty 2009
16	McArthur Falls	Canada	Manitoba/Ontario	1965	2007	42	115	-367	0.0	boreal	Demarty 2009
17	Pine Falls	Canada	Manitoba/Ontario	1952	2002	50	9	-3404	5.0	boreal	Tremblay 2005
18	Seven Sisters Fall	Canada	Manitoba/Ontario	1931	2002	71	21	-4979		boreal	Tremblay 2005
19	Slave Falls	Canada	Manitoba/Ontario	1937	2002	65		-4086	-113.0	boreal	Tremblay 2005
20	Baskatong	Canada	Ontario/Quebec	1927	2002	75	413	-1161	-3.2	boreal	Tremblay 2005
21	Bersimis	Canada	Ontario/Quebec	1959	2002	43	978	-1485	-0.1	boreal	Tremblay 2005
22	Cabonga	Canada	Ontario/Quebec	1928	1996	68	667	-1381	-13.9	boreal	Tremblay 2005
23	Caniaposcau	Canada	Ontario/Quebec	1984	2003	19	4318	-669	-9.8	boreal	Tremblay 2005
24	Eastmain-1	Canada	Ontario/Quebec	2006	2007	1		-2426		boreal	Demarty 2009
25	EOL	Canada	Ontario/Quebec	1979	2003	24		-1161	-3.8	boreal	Tremblay 2005
26	Gouin	Canada	Ontario/Quebec	1964	1999	35	1570	-665	-2.7	boreal	Tremblay 2005
27	Lac St-Jean	Canada	Ontario/Quebec	1956	2003	47		-1480		boreal	Tremblay 2005
28	Laforge 1	Canada	Ontario/Quebec	1993	1995	2	1288	-2062	-27.3	boreal	Tremblay 2005
29	Laforge 2 (b)	Canada	Ontario/Quebec	1993	2000	7	260	-892		boreal	Tadonléké 2011
30	Laforge 2 (c)	Canada	Ontario/Quebec	1984	2003	19	260	-833	-7.4	boreal	Tremblay 2005
31	La Grande 1	Canada	Ontario/Quebec	1979	2003	24	70	-1667	-8.8	boreal	Tremblay 2005
32	La Grande 3	Canada	Ontario/Quebec	1984	2003	19	2420	-1707	-8.1	boreal	Tremblay 2005
33	La Grande 4	Canada	Ontario/Quebec	1983	2003	20	765	-1178	-10.8	boreal	Tremblay 2005
34	Manic 1	Canada	Ontario/Quebec	1951	1999	48		-3054	-11.3	boreal	Tremblay 2005
35	Manic 2	Canada	Ontario/Quebec	1965	1999	34	124	-848	-6.0	boreal	Tremblay 2005
36	Manic 3	Canada	Ontario/Quebec	1971	1999	28	236	-306	-1.1	boreal	Tremblay 2005
37	Manic 5	Canada	Ontario/Quebec	1964	2003	39	1950	-1407	-6.1	boreal	Tremblay 2005
38	Manic 5 (b)	Canada	Ontario/Quebec	1964	1999	35	1950	-2327		boreal	Tadonléké 2011
39	Opinaca	Canada	Ontario/Quebec	1980	1993	13		-3450	-8.0	boreal	Kelly 1994
40	Opinaca	Canada	Ontario/Quebec	1980	2003	23		-1885		boreal	Tremblay 2005
41	Outaouais	Canada	Ontario/Quebec	1962	2003	41		-1282		boreal	Tremblay 2005
42	Outardes 3	Canada	Ontario/Quebec	1969	1999	30		-85	-0.1	boreal	Tremblay 2005
43	Outardes 4	Canada	Ontario/Quebec	1968	2003	35	650	-2187	-0.9	boreal	Tremblay 2005
44	Rivière-des-Prairies	Canada	Ontario/Quebec	1929	2007	78		-665	-0.5	boreal	Demarty 2009
45	Robertson	Canada	Ontario/Quebec	1994	2003	9		-1408	-6.1	boreal	Tremblay 2005
46	Robert-Bourassa	Canada	Ontario/Quebec	1975	1994	19	2835	-1400	-13.0	boreal	Kelly 1994
47	Robert-Bourassa (b)	Canada	Ontario/Quebec	1975	2003	28	2835	-1706	-7.9	boreal	Tremblay 2005
48	Robert-Bourassa (c)	Canada	Ontario/Quebec	1975	2002	27	2835	-1415		boreal	Tadonléké 2011
49	Robert-Bourassa (d)	Canada	Ontario/Quebec	1975	2007	32	2835	-661	0.1	boreal	Demarty 2009
50	Sanite-Marguerite 3	Canada	Ontario/Quebec	1998	2003	5		-5484	-2.7	boreal	Tremblay 2005
51	Sanite-Marguerite 3 (b)	Canada	Ontario/Quebec	1998	1999	1		-6703		boreal	Tadonléké 2011
52	Toulnoustouc	Canada	Ontario/Quebec	1957	2003	46		-1393	-0.1	boreal	Tremblay 2005
53	Upper Salmon 1	Canada	Newfoundland	1967	2003	36		-1906		boreal	Tremblay 2005
54	Upper Salmon 2	Canada	Newfoundland	1983	2003	20		-1923		boreal	Tremblay 2005
55	Hinds	Canada	Newfoundland	1980	2003	23		-2105		boreal	Tremblay 2005
56	Cat Arm	Canada	Newfoundland	1985	2003	18	53	-2257		boreal	Tremblay 2005
57	Sandy	Canada	Newfoundland	1925	2003	78		-2510		boreal	Tremblay 2005
58	F. D. Roosevelt	USA	WA	1942	2001	59	324	462	-3.2	boreal	Suomis 2004
59	Dworshak	USA	ID	1973	2001	28	69	1195	-4.4	boreal	Suomis 2004
60	Wallula	USA	OR	1954	2001	47	2	349	-9.0	boreal	Suomis 2004
61	Shasta	USA	CA	1944	2001	57	120	-1247	-9.5	temperate	Suomis 2004
62	Oroville	USA	CA	1968	2001	33	64	-1026	-4.2	temperate	Suomis 2004
63	New Melones	USA	CA	1979	2001	22	51	1186	-7.1	temperate	Suomis 2004

Appendix 1:
Hydropower reservoirs included in the study; page 2 of 2

	Reservoir - Name	*Country*	*Region*	*Flooded yr*	*Sample yr*	*Age*	*Area*	*NEE of CO2*	*NEE of CH4*	*Biome*	*source*
	SOUTH AMERICA										
64	Tucurui (a)	Brazil	Amazonas	1985	1998	13	2850	-10433	-205.4	tropical	Santos 2006
65	Tucurui (b)	Brazil	Amazonas	1985	1999	14	2850	-6516	-13.4	tropical	Santos 2006
66	Samuel (a)	Brazil	Amazonas	1989	1998	9	559	-8087	-183.6	tropical	Santos 2006
67	Samuel (b)	Brazil	Amazonas	1989	1999	10	559	-6087	-27.2	tropical	Santos 2006
68	Samuel (c)	Brazil	Amazonas	1989	2004	15	559	-3345	-24.4	tropical	Abril 2005
69	Miranda (a)	Brazil	Amazonas	1997	1998	1	51	-4980	-262.4	tropical	Santos 2006
70	Miranda (b)	Brazil	Amazonas	1997	1999	2	51	-3796	-45.9	tropical	Santos 2006
71	Três Marias (a)	Brazil	Amazonas	1961	1998	37	1040	142	-328.2	tropical	Santos 2006
72	Três Marias (b)	Brazil	Amazonas	1961	1999	38	1040	-2369	-64.3	tropical	Santos 2006
73	Barra Bonita	Brazil	Amazonas	1963	1998	35	312	-6434	-19.2	tropical	Santos 2006
74	Barra Bonita (b)	Brazil	Amazonas	1963	1999	36	312	-1537	-22.6	tropical	Santos 2006
75	Segredo	Brazil	Amazonas	1992	1998	6	82	-4789	-9.9	tropical	Santos 2006
76	Segredo	Brazil	Amazonas	1992	1999	7	82	-601	-7.9	tropical	Santos 2006
77	Xingó	Brazil	Amazonas	1994	1998	4	60	-9837	-30.0	tropical	Santos 2006
78	Xingó	Brazil	Amazonas	1994	1999	5	60	-2440	-50.2	tropical	Santos 2006
79	Itaipu	Brazil	Amazonas	1982	1998	16	1549	-1205	-12.9	tropical	Santos 2006
80	Itaipu	Brazil	Amazonas	1982	1999	17	1549	-864	-8.5	tropical	Santos 2006
81	Serra da Mesa	Brazil	Amazonas	1996	1998	2	1784	-1316	-121.0	tropical	Santos 2006
82	Serra da Mesa	Brazil	Amazonas	1996	1999	3	1784	-3972	-105.0	tropical	Santos 2006
83	Balbina	Brazil	Amazonas	1989	2004	15	2360	-3344	-33.7	tropical	Guérin 2006
84	Balbina (b)	Brazil	Amazonas	1989	2011	22	2360	-3300	-47.0	tropical	Kemenes 2011
85	Furnas	Brazil	Cerrado region	1963	2007	44	1342	-528		tropical	Roland 2010
86	Mascarenhas de Moraes	Brazil	Cerrado region	1957	2007	50	250	-1672		tropical	Roland 2010
87	Luiz Carlos Barreto De Carvalho	Brazil	Cerrado region	1969	2007	38	47	-2817		tropical	Roland 2010
88	Manso	Brazil	Cerrado region	2000	2007	7	360	-3895		tropical	Roland 2010
89	Funil	Brazil	Cerrado region	1969	2007	38	27	5853		tropical	Roland 2010
90	Petit Saut	French Guiana		1994	2003	9	365	-5765	-46.0	tropical	Abril 2005
	ASIA										
91	Nam Ngum	Lao PDR		1971	2009	38	370	704		tropical	Chanudet (2011)
92	Nam Leuk	Lao PDR		1999	2009	10		-1365		tropical	Chanudet (2011)
93	Hong Feng	China		1958	2007	49	57	-660		temperate	Wang 2011
94	Baihua	China		1960	2007	47	15	-1056		temperate	Wang 2011
95	Xiuwen	China		1960	2007	47		-2068		temperate	Wang 2011
96	Hongyan	China		1971	2007	36		-986		temperate	Wang 2011
97	Three Georges Dam	China		2006	2011	5	1045		-6.2	temperate	Chen 2011
98	Ertan	China		1998	2009	11	101		-2.8	temperate	Zheng et. al. (2011)
	EUROPE										
99	Skinnmeddselet	Sweeden	North	1989	2001	12		-880		boreal	Åberg 2004
100	Lokka (a)	Finland		1967	1994	27	418	-1056		boreal	Huttunen 2003
101	Lokka (b)	Finland		1967	1995	28	418	-1980	-33.6	boreal	Huttunen 2003
102	Porttipahta	Finland		1970	1995	25	214	-1540	-3.5	boreal	Huttunen 2003
103	Lake Wohlen	Switzerland		1920	2007	87	4		-156	temperate	Eugster 2011

Appendix 2:
Decision tree for identification of appropriate tier-level for land converted to antoerh land-use category (example given for land converted to forest land, LF)