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Estimating contemporary methane emissions from tropical wetlands using multiple modelling approaches

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Abstract

Methane gas makes a significant contribution to the greenhouse effect happening on the planet. In modern times, natural wetlands are the biggest source of methane gas as compared to other sources of natural origin. Emissions of methane gas from wetlands rely on the climate and have the ability to give a positive feedback to the changing climate. Nevertheless, there is lot of uncertainty associated with the strength of both the natural emissions and the feedback. Upscaling from site-based observations, process based models and inverse models have variable estimations of methane emission regionally as well as globally. Very few studies are available on tropical regions as compared to higher latitudes. This study has estimated methane emissions from tropical wetlands (30 degrees S to 30 degrees N) by extrapolation of fluxes based on wetland types using the Lehner and Doll (2004) wetland dataset. The information on the tropical wetland vegetation was also derived from the upscaling study carried out and was used to run a version of the LPJ-GUESS model developed for northern wetlands (LPJ-GUESS WHyMe) to estimate methane emissions from the tropics at a resolution of 0.5 degree latitude × 0.5 degree longitude. Modelled heterotrophic respiration from LPJ-GUESS (version 2.1) was also used to assess methane release from the tropics in a simple parameterisation in which a fixed carbon conversion factor was used to divert 4.15% of the respiration to methane release. The estimated annual methane emissions from tropical wetlands using upscaling of site based fluxes ranged from around 51 to 183 Tg CH_4 per year with largest emissions coming from 'swamp forest, flooded forest' wetland type. This range is largely in agreement with inverse modelling studies carried out in recent years. Modelled emissions from LPJ-GUESS WHyMe for the tropics was too high, at 566 TgCH_4 per year, whereas estimation from the simpler method using modelled heterotrophic respiration was 110 Tg CH_4 per year, which is also largely in agreement with inverse modelling studies carried out in recent years. Simulations with LPJ-GUESS WHyMe highlight the need for specific tropical wetland vegetation and their associated parameters, better water table calculations, seasonal inundation inputs, and more analysis of the factors governing the CO_2 to CH_4 production ratio in tropical regions. These factors combined could reduce the emissions to more reasonable values.

Keywords – Physical Geography, Ecosystem analysis, Upscaling, Modelling, Tropical wetlands, Methane emissions, LPJ-GUESS

Abstrakt/Sammanfattning

Metangas bidrar med en signifikant andel till den rådande växthuseffekten på jorden. I nutid är den största källan till utsläpp av metangas våtmarker i jämförelse med andra naturliga utsläppskällor. Emissioner av metangas från våtmarker är beroende av klimatet och har den egenskapen att ge en positiv återkoppling till klimatändringen. Icke desto mindre finns det dock stor osäkerhet associerat med både storleken på de naturliga utsläppen och hur mycket dess återkoppling är. Uppskalning från lokalbaserade observationer, processbaserade modeller och inverse modeller har olika uppskattningar på metanutsläpp, såväl regionalt som globalt. Väldigt få studier finns tillgängliga från tropiska områden jämfört med högre breddgrader. Den här studien har beräknat metanutsläpp från tropiska våtmarker (30 grader S till 30 garder N) genom att extrapolera flöden baserade på våtmarkstyper med våtmarksdataset från Lehner och Doll (2004). Information om den tropiska våtmarksvegetationen härstammar även från uppskalningstudier och användes till att köra en version av LPJ-GUESS utvecklad för nordliga våtmarker (LPJ-GUESS WHyMe), för att uppskatta metanemissioner från tropikerna med en upplösning på 0,5 grader latitud * 0,5 grader longitud. Modellerad heterotrof respiration från LPJ-GUESS (version 2.1) användes också för att beräkna metanutsläpp från tropikerna med en enkel parametrisering, i vilken en fix koldioxidfaktor användes till att avleda 4,15 % av respirationen till metanutsläpp. De från uppskalningsmetoden beräknade årliga etanemissionerna i tropiska våtmarker varierade mellan ca 51 till 183 Tg CH_4/år, där de största utsläppen kom från typer av våtmarker som sumpskog och översvämmad skog. Detta intervall stämmer bra överens med de från inverse modellering utförda under de senaste åren. Beräknade emissioner från LPJ-GUESS WHyMe i tropikerna var betydligt större, nämligen 566 Tg CH_4/år, medan beräkningar från den enklare modellerade heterotrofa respirationen var 110 Tg CH_4/år, vilket också stämmer bra överens med studier gjorda de senaste åren av inverse modellering. Simuleringar utförda med LPJ-GUESS belyser behovet av specifik tropisk våtmarksvegetation och relaterade parametrar, till exempel bättre beräknade grundvattennivåer, årliga översvämningsdata och mer analys av de faktorer som styr förhållandet mellan CO_2 och produktion till metan i tropiska områden. Dessa faktorer kombinerade skulle kunna minska utsläppen till mer rimliga värden.

Nyckelord–Geographi, Uppskalning, Modellering, Tropisk våtmark, Metanutsläpp, LPJ-GUESS

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Abbreviations

GHGs	Green House Gases
CRU	Climate Research Unit
GLWD	Global Lakes and Wetlands Database
PFTs	Plant Functional Types
TrBE	Tropical Broad-leaved Evergreen
TrH	Tropical Herbaceous
NPP	Net Primary Production
Estmax	Maximum Establishment Rate of Vegetation
WTPmax	Maximum Capacity of Vegetation to Sustain Inundation
GPP	Gross Primary Production
NEE	Net Ecosystem Exchange
NOAA	National Oceanic and Atmospheric Administration
GMD	Global Monitoring Division
TEM	Terrestrial Ecosystem Model
WMEM	Wetland Methane Emission Model

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Estimating contemporary methane emissions from tropical wetlands using multiple modelling approaches

1.1 Introduction

Methane, a Kyoto gas, ranks third in abundance in regard to the greenhouse gases (GHGs) present in the atmosphere of the earth, succeeding water vapour and carbon dioxide. Its action is around 25 times further effective as a greenhouse gas as compared to carbon dioxide (IPCC 2007), on a hundred-year timescale. Hence, comparatively minute variations in its concentration can have significant influence on the climate. Methane is accountable for 20 % of the man-made direct radiative forcing (IPCC 2001). Its presence in the atmosphere has risen around 2.5 times since the preindustrial era. This rise is still ongoing, though at a decreasing rate (IPCC 2007). Wetlands are the major natural source of release of methane to the atmosphere. Although a big proportion of these emissions occur in tropical areas, there have not been many studies on tropical wetlands of natural origin (Nahlik & Mitsch 2010). Wetlands release around 25% of the contemporary methane emissions globally due to extended inundated environments and resulting anaerobic conditions which is typical of these ecosystems (Mitsch & Gosselink 2007), while man made sources contribute most of the rest of the emissions (Whalen 2005).

One of the ways to better understand both the impact and origin of the amount of methane in the earth's atmosphere throughout the past and in the future is to improve the modelling of this gas from natural wetlands since they appear to have an important role in impacting the varying concentrations of methane in the atmosphere. Several models simulate the carbon cycle and its impact on future climate change. One of the well-evaluated models is named the LPJ-GUESS model. Its present state does not have methane emissions from tropical wetlands. Hence, the work of this thesis will be to model contemporary methane emissions from tropical wetlands using multiple modelling approaches and to move in the direction of adding methane emissions from tropical wetlands to the LPJ-GUESS model by assessing its ability to estimate fluxes of methane in the observed range using two alternative approaches.

1.2 Aim

The aim of this thesis is to estimate the magnitude of contemporary methane emissions from the tropical wetlands using upscaling of site-based observations, and to assess the ability of LPJ-

GUESS WHyMe to provide estimations of methane fluxes from the tropical wetlands within the range of the observations.

1.3 Specific objectives

This thesis seeks to perform the following specific tasks.

- Carry out upscaling of methane emissions from tropical wetlands using values from literature and a map of tropical wetland types.
- Carry out simulations of methane emissions from tropical wetlands using the LPJ-GUESS WHyMe model.
- Calculate methane emissions from tropical wetlands using heterotrophic respiration output from the LPJ-GUESS model v2.1.
- To compare the results of the above approaches with observations derived from other upscaling, process-based modelling and inverse modelling methods.

2.0 Theoretical background

2.1 Methane

Methane gas has the second largest radiative forcing of the long-lived GHGs following carbon dioxide (Ramaswamy et al 2001). It interacts with infrared radiation and consequently leads to ‘greenhouse warming’. According to IPCC (2007), the global mean abundance of this gas in the year 2005, determined at the network of 40 surface air flask sampling sites managed by NOAA/GMD in the northern as well as in southern hemisphere was $1,774.62 \pm 1.22$ ppb. Compared to the last 6,50,000 years, the contemporary levels of methane in the atmosphere have never been previously experienced (Spahni et al 2005). Table 1 below highlights the sources and sinks of this gas in the atmosphere. It is seen from this table that natural emissions of methane from wetlands are estimated at between 100 and 231 Tg CH_4 per year.

Table 1. Sources, sinks and atmospheric budgets of CH_4 ($TgCH_4\ yr^{-1}$)[a]

Reference	Hein et al 1997[b]	Houwel ing et al 2000[b]	Olivier et al 2005	Wuebbles and Hayhoe 2002	Scheehle et al 2002	J. Wang et al 2004[b]	Mikaloff Fletcher et al 2004 a[b]	Chen and Prinn 2006[b]	TAR	AR4
Base year	1983-1989	-	2000	-	1990	1994	1999	1996-2001	1998	2000-2004
Natural sources	-	**222**	**-**	**145**	**-**	**200**	**260**	**168**	-	-
Wetlands	231	163	-	100	-	176	231	145	-	-
Other Natural sources[c]	-	59	-	45	-	24	29	23	-	-
Anthrop-ogenic Sources[d]	**361**	**-**	**320**	**358**	**264**	**307**	**350**	**428**	-	-
Total Sources	**592**	**-**	**-**	**503**	**-**	**507**	**610**	**596**	**598**	**582**
Imbalance	+33	-	-	-	-	-	-	-	+22	+1
Sinks										
Soils	26	-	-	30	-	34	30	-	30	30[e]
Tropospheric OH	488	-	-	445	-	428	507	-	506	511[e]
Stratospheric loss	45	-	-	40	-	30	40	-	40	40[e]
Total Sink	**559**	**-**	**-**	**515**	**-**	**492**	**577**	**-**	**576**	**581**[e]

Notes:

a Table shows the best estimate values.

b. Estimates from global inverse modelling (top-down method).

c. Other natural sources include termites, ocean, hydrates, geological sources, wild animals and wild fires. All studies do not include all of them.

d.Anthropogenic sources include energy, coal mining, gas, oil, industry, landfills & waste, ruminants, rice agriculture, biomass burning, C3 vegetation and C4 vegetation. All studies do not include all of them.

e. Numbers are increased by 1% from the TAR according to recalibration described in Chapter 2, IPCC 2007,The Physical Science Basis.

Source: Summarized from Chapter 7, IPCC 2007, The Physical Science Basis.

2.2 Wetlands

According to the Ramsar Convention on Wetlands, (in Ramsar, Iran, 1971) wetlands are broadly defined in Article 1.1 as, "areas of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water the depth of which at low tide does not exceed six metres." The definition also includes (Article 2.1), " …riparian and coastal zones adjacent to the wetlands, and islands or bodies of marine water deeper than six metres at low tide lying within the wetlands".

According to Mitsch and Gosselink (2007), it is difficult to have a complete definition for a wetland but official definitions have been made by various national organizations throughout the world. Internationally, the Ramsar Convention, 1971 adopted a broad definition of wetlands. They have also mentioned that these definitions are used in science as well as management, and they further state that since wetland features vary persistently from aquatic to land ecosystems, there is absence of any specific, commonly acknowledged definition for wetlands. Absence of such a specific definition has perplexed and is the reason for irregularity in the administration, categorization, listing and recording of these wetland ecosystems.

The definition of a wetland often comprises of three key parts.

1. They have water at the surface or in the root region.
2. They possess an exclusive soil state that is distinct from neighboring uplands.
3. Wetlands sustain vegetation such as bryophytes, which is used to the wet conditions. On the other hand, wetlands are distinguished by the lack of vegetation that is intolerant to flood conditions. (Mitsch and Gosselink 2007)

They are distributed all over the globe from Arctic to tropical areas as well as from low-lying areas to high altitude areas (Wania 2007). Since the preceding 20 years, numerous researchers (Matthews and Fung 1987; Aselmann and Crutzen 1989; Stillwell-Soller et al 1996; Prigent et al. 2001; Lehner and Doll 2004) have gathered information by making use of local or global maps of vegetation data or the type of soil, or based on lake distribution or the landscape classification obtained from satellite data on the distribution of wetlands. Inspite of all this, recently existing maps of wetland distribution even now seem to be startlingly lacking (Wania 2007). An analysis of the Ramsar Wetlands Convention deduced that available data are unable to give a dependable assessment of the global coverage of wetlands (Finlayson and Davidson 1999). Latest research of lowlands in West Siberia puts forward that wetland records undervalue the real coverage of these ecosystems by 44-55% and some maps of wetland obtained from satellite underrate the area of wetland by 77-98% (Frey and Smith 2007; Wania 2007). Difficulty regarding keeping a check on the distribution of wetland appears to be associated with the seasonality aspect of the wetland coverage and the remoteness or dispersed nature of few wetlands, which makes investigation at ground or from space hard as well as time consuming and costly (Wania 2007).

Notwithstanding all these difficulties in analyzing the real coverage the wetlands, the fact that substantial amounts of wetlands exist in the tropics is quite clear from studies such as Matthews and Fung (1987) which says that wetlands are concentrated in tropical/subtropical regions (20 degrees N to 30 degrees S) and boreal regions. According to the Aselmann and Crutzen (1989) study, significant areas of wetlands occur in a tropical belt between 10 degrees north and 20 degrees south, and in boreal areas between 50 degrees and 70 degrees north.

2.3 Types of Wetland

Various terms used for the wetland types considered in this study are:

Bog- "A peat-accumulating wetland that has no significant inflows or outflows and supports acidophilic mosses, particularly *Sphagnum"* (Mitsch & Gosselink 2007).

Marsh- Wetland which is often or always flooded and distinguished by emergent flora which is herbaceous in nature and is suitable for totally saturated soil. An European vocabulary identifies marshes as having mineral soil substrate and there is no peat collection (Mitsch & Gosselink 2007).

Swamp - "Wetland dominated by trees or shrubs (United States definition). In Europe, forested fens and wetlands dominated by reed grass (*Phragmites*) are also called swamps" (Mitsch & Gosselink 2007).

Brackish wetland – 'Brackish' word refers to sea and estuary waters with salinity level ranging from 0. 5 to 30.0 percent because of the salts present in the ocean. Use of this terminology for inland wetlands and habitats in deep water must not be done (Cowardin et al 1985). Tiner R W

(1993) mentions in his book, "Brackish marshes develop upstream of salt marshes where significant amounts of fresh water dilute sea water to create moderately to slightly salty environments. The average salinity in this region range from moderately high (18 parts per thousand, ppt.) to essentially fresh (0.5 ppt.). Consequently, plant composition is extremely varied. Brackish marshes are found along coastal rivers upstream of the salt marshes or near the mouth of coastal rivers with heavy fresh water discharge that empty into bay and sounds with low tidal ranges."

Floodplain- Reid and Wood (1976:72,84) refer to floodplains as "The floodplain is a flat expanse of land bordering an old river….Often the floodplain may take the form of a very level plain occupied by the present stream channel, and it may never, or only occasionally, be flooded . . . It is this subsurface water [the ground water] that controls to a great extent the level of lake surfaces, the flow of streams, and the extent of swamps and marshes."

Fen- Moore P D (2006) defines fen to be a wetland consisting mainly of herbaceous vegetation, where water is provided from the discharge of ground water. They describe it as rheotrophic which implies that it obtains its nutrient elements from flow of ground water as well as precipitation. The water table of this wetland type is at the surface of the soil or underneath it during the summer season.

Additional definitions of various kinds of wetlands are given in Appendix A below.

According to Mitsch & Gosselink (2007), since there is an absence of a definite terminology for these wetland types, much of the former words convey the sense and denotation to users who have already known them. These general terms sometimes do not communicate the identical expression meant for a particular sort of a wetland within the world-wide society of scientists. They further point towards the lack of corresponding terms in different languages for various wetlands and also highlight the bewilderment in definition because of diverse applications of the word for alike kind of wetlands due to the varied uses in regions or continents. Still two points are stressed by them regarding the practice of widespread expression in grouping the types of wetland. They mention that any categorization that is dependent on general terms, consists of subjectivity. Since features of physical and biotic form are always varying from one kind of wetland to the other. Secondly, they highlight that the diverse wetlands in various regions may be communicated by the same expression. According to them, since these general terms are being applied incessantly even in technical writings, they recommend the usage with care and keeping concern for the readers worldwide.

2.4 Methane emissions from global and tropical wetlands

Wetlands behave as sink as well as source regarding their carbon dynamics. Wetlands possess substantial carbon sequestration capacity due to their ability to retain carbon through permanent burial (Mitsch & Gosselink 2007). Taking greenhouse gases into consideration, they can be source or sink for carbon dioxide, methane or nitrous oxide gas. They can be a sink for one gas but a source for another depending on their complicated biogeochemistry (Friborg et al 2003). Human impacts such as intensified nutrient loading, draining, in-filling, inundation, burning and altering vegetation can also transform them from sinks and convert them to sources. Wetlands are small sources of carbon dioxide and nitrous oxide but large sources of methane (National Climate Change Process 1999). Tables 1 (above) and 2 below clearly show wetland to be a significant source for methane gas to the worldwide emissions budget.

Table 2. Inputs from wetlands to yearly worldwide greenhouse gas emissions

Greenhouse Gas	Wetland Emissions	Total Global Emissions	% Contribution
Carbon Dioxide	8.5 Tg yr^{-1} (1)	7000 Tg yr^{-1} (2)	0.12
Nitrous Oxide	0.133 Tg yr^{-1} (3)	7.1 to 12.7 Tg yr^{-1} (4)	0.8 to 1.4
Methane	113 Tg yr^{-1} (5)	540 Tg yr^{-1} (5)	21

(1) Gorham 1991
(2) Houghton 1990
(3) Freeman et al 1993
(4) Davidson 1991
(5) Bartlett and Harriss 1993
(Note: 1 Tg = 10^{12} g)
Source: As given in National Climate Change Process 1999

In a study by Bousquet et al (2006) to measure the processes responsible for fluctuations in emissions of methane between 1984 and 2003 by making use of an inversion model of atmospheric transport and chemistry, results suggested that emissions from wetland dominated the inter-annual fluctuations of the sources of methane with the exception of 1997-1998 El Nino event. Such studies further stress the importance of wetlands as a source for methane emissions in the atmosphere.

A wetland CH_4–climate feedback study by Gedney et al (2004) estimated that the emission rate of methane from wetlands would almost double in the next century. On coupling it to a climate model, this very important rise in the emissions will lead to a escalation of mean temperature globally of 0.14-0.20 K which is 3.7- 4.9 % of the total projections of the rise in temperature by 2100. The IPCC (2007) also mentions that emissions of methane gas from wetlands rely hugely on the climate and have the ability to give a positive feedback to the changing climate.

The study by Matthews & Fung (1987) reported global yearly emissions of methane gas to be 110 Tg CH_4 from wetlands and estimated that around 25% of the total emissions are coming from tropical/subtropical peat-poor swamps falling within 20 degrees north to 30 degrees south. Another study by Aselmann and Crutzen (1989) estimated methane emissions from wetlands of natural origin by extrapolation of measured flux rates of methane to a global scale to give a global annual estimation of 40-160 Tg CH_4. They also mention the subtropics falling between 20 and 30 degrees north and the tropics between 0 and 10 degrees south to be the regions responsible for the largest amount of emissions. Recent work by Bloom et al (2010) estimated that wetlands in the tropical regions give 52 to 58 % of the wetland global methane emissions.

2.5 Methane production in wetlands

Carbon present in wetlands undergoes changes in various aerobic and anaerobic processes taking place there. The chief aerobic process is aerobic respiration whereas major anaerobic mechanisms include fermentation and methanogenesis. Methanogenesis is the production of methane by the particular microbes termed methanogens, which employ carbon dioxide as an acceptor of electron or utilize an organic compound with small molecular weight for example, from a methyl group. The mechanism takes place in the form of following equation.

$$CH_3COO + 4H_2 \longrightarrow 2CH_4 + 2H_2O$$

Formation of this gas needs a highly reduced environment having a redox potential under -200 mV when electron acceptors such as O_2, NO_3 and SO_4 left at last have also undergone reduction reaction (Mitsch & Gosselink 2007).

Methane formation in wetlands is influenced by factors such as the rate and form of the organic matter accumulation and its breakdown. The chief sources of carbon for the production of methane in wetlands is the easily decomposable carbon in the soil, litter, exudates from roots, decomposing roots, biomass which grows in water and allochthonous waste present in the anaerobic zone (Neue et al 1997). According to Patel & Roth (1977), methane formation in wetlands is negatively impacted by the presence of the high amount of sodium chloride. They mention the value to be around 0.18 M. Koyama et al (1970) also points out the sulphate presence in the seawater consisting of lower amount of salt preventing the formation of methane.

Methane produced by methanogenesis is oxidized by obligate methanotropic bacteria as per the equation below:

$CH_4 \rightarrow CH_3OH \rightarrow HCHO\text{-} \rightarrow HCOOH \rightarrow CO_2$

(Mitsch and Gosselink 2007)

These methanotrophs are plentiful in the boundary of floodwater-soil and also in the rhizosphere of wetland vegetation (Neue et al 1997). The amount of emitted methane from the wetland is then the absolute outcome from the processes of methanogenesis and methane oxidation (Mitsch and Gosselink 2007).

Emissions of methane gas to the atmosphere from the soils present in wetlands lacking oxygen occurs by three methods, namely by the diffusion of dissolved methane gas, by gas bubble ebullition and through plants consisting of aerenchyma tissue (Neue et al 1997). According to Boon (1999), it is estimated that the vascular system of emergent plants might be responsible amid 50 and 90 percent release of the total production of methane from a wetland consisting of vegetation.

2.6 Various approaches to methane flux estimation

The IPCC (2007) list three methods regarding the assessment of the emissions of methane gas:

(a) Extrapolating from the flux which is determined directly (Upscaling)
(b) Bottom-up approach in modelling (Process-based Modelling)
(c) Top-down approach (Inverse modelling)

2.6.1 Upscaling

Upscaling of methane flux refers to the extrapolation of flux, which is measured per unit area per unit time and is multiplied with the entire area in consideration to obtain the flux from the area considered in that time. According to Aselmann and Crutzen (1989), extrapolating fluxes can be quite uncertain. Bartlett and Harriss (1993) have also suggested that the extrapolation of flux from one wetland area to another might have significant inaccuracy in them. They have also proposed to establish confidence in the method. According to them, a statistical categorization of the inconsistency in space is essential inside the habitat as well as between the habitats when a small number of flux measurements is extrapolated to bigger regions having a similar habitat. They have also highlighted that this kind of sampling is hardly ever performed in such studies, which makes it hard to determine confidence limits. Nevertheless, this method provides global estimations from upscaling of methane fluxes measured at particular sites.

2.6.2 Bottom up Models

Process based models are an effort to include the various processes (physical, biological, geological and chemical) responsible for emitting methane in a mechanistic manner. Cao et al (1996) had pointed out the uncertainty prevailing in the estimation of methane emissions at a regional as well as worldwide scale (in spite of a growing number of measurements of flux rates of methane) due to the unsatisfactory knowledge of the spatial extent of wetlands and a lack of robust measurements, as the majority of the studies measured the gas at an area smaller than a square meter and during few months. They also highlight the lack of studies documenting measurements for a period larger than a year. According to them, having these constraints renders it doubtful that trustworthy assessments of the contemporary fluxes of methane have been obtained by extrapolating the values measured at points to local or worldwide scale. Cao et al (1998) also highlight the limited capacity of the regular method of, “measure and multiply” for computing methane emissions at local as well as periodic scales. They mention the great variations in the methane emissions, including uncertainties, as the reason for this abovementioned limitation.

Ecosystem models are important for modelling the processes involved in the emission of methane from wetlands taking care of the various factors such as temperature, water table depth, substrate availability, to name a few, affecting the emission processes in order to better assess the wetland methane emissions and forecast their response to the ongoing climate change (Cao et al 1998). According to Wania (2007), simulating emissions of methane in process based modelling must include four vital mechanisms. The first is the distribution of existing and accessible substrate of carbon to the microorganisms termed methanogens that produce methane gas in the absence of oxygen as a byproduct of their metabolism. The second process is the production of methane. The third and fourth mechanisms include methane oxidation and the transport of methane, respectively.

Several models for the emission of methane gas exist with varying levels of intricacy. Wania (2007) has done a detailed review of methane emission models and mentioned Christensen et al (1996), Granberg et al (1997), Kettunen et al (2000) and Kaplan (2002) to be entirely empirical. She further describes Segers and Leffelaar (2001 a), Granberg et al (2001 a) and Kettunen (2003) as mechanistic, but quite exhaustive or examined for just a single site. She refers to Cao et al (1996), Cao et al (1998), Walter et al (1996), Walter and Heimann (2000), Walter et al (2001 a, b), followed by Potter et al (1997) and Zhuang et al (2004) as process-based models having undergone testing locally or globally. She has highlighted these models of regional or global applications not only to be mechanistic to differing extents but also relying on certain empirical calculations for the processes, and requiring varying quantities of data as input.

2.6.2.1 An overview of two extensively employed bottom-up models

a) Cao et al (1996) model

The wetland methane emission model (WMEM) described by Cao et al (1996) is based upon the hypothesis that the amount of methane production per unit time should be limited by the accessibility of the substrate which is formed from the primary production process of the plant and breakdown of organic matter, which is controlled by the ecological aspects. Equilibrium between production and oxidation processes of methane decides the emission rate of methane gas into the atmosphere. Their model employs four carbon pools, which are living vegetation consisting of carbon, soil carbon, carbon that is decomposed and carbon as methane. They mention that the flow of carbon between these compartments were presupposed to be regulated by three factors, which were the size of the donor compartment, by definite parameters associated with the features of the pools involved and by aspects of environment such as radiation from the sun, temperature and moisture present in soil. Cao et al (1996) also mention that processes such as net primary production (NPP), soil accumulating the litter carbon and breakdown of the organic form of carbon were computed using the Terrestrial Ecosystem Model (TEM). Raich et al (1991) and McGuire et al (1992) explain the TEM model in detail. In the WMEM given by Cao et al (1996), the position of the water table and temperature were regarded as chief ecological characteristics controlling the methane production.

To run the wetland methane emission model given by Cao et al (1996), the information on independent variables required, such as the location, area, soil, vegetation and climate of wetlands present worldwide, were arranged within a Geographical Information System database which was georeferenced and possessed a resolution of 0.5 degree latitude $\times$ 0.5 degree longitude. The input dataset on temperature, precipitation and cloudiness was from the International Institute of Applied System Analysis (IIASA) terrestrial climate data set having values, which are monthly averages for the long-term and the same resolution as for the georeferenced database. The approach of Raich et al (1991) was used to compute plant photosynthesis and the study by Matthews and Fung (1987) was used to obtain information on wetland location, area and vegetation. The model simulates wetlands drawn from Matthews and Fung (1987) considering them as inundated as well as moist/dry tundra considering them as non-inundated. Cao et al (1996) mentions that the description of initial-state values regarding various vegetation categories were employed in the computations of the model as Melillo et al (1993) and McGuire et al (1992) have done for their global ecosystem model.

One of the primary differences between LPJ-GUESS and the Cao et al (1996) model is that processes such as vegetation characteristics, net primary production, the deposition of litter carbon into the soil and organic carbon decomposition are simulated in the LPJ-GUESS model itself whereas in the Cao et al (1996) model, these processes are calculated using another model as mentioned above.

b) Walter et al (2001 a) model

Walter et al (1996) published an independent methane emission model in the same year. Its application at the global scale has been described in Walter et al (2001 a). Wania (2007) has highlighted that there are variations between their 1996 and 2001 a version. Walter et al (2001 a) used data from various sources as inputs to the model. Data from Matthews and Fung (1987) has been used for the location of wetlands worldwide. Global data sets of vegetation and soil characteristics were used for estimating globally applicable model parameters. Vegetation dependent parameters comprised of depth of the soil, rooting depth and effectiveness of plant mediated transport. A parameter dependent on soil characteristics is relative pore space. Walter et al (2001 a) mentions their model to be sensitive to climate and can be used to examine the changes brought about by climate in the emissions of methane from natural wetlands. In the model, methane gas production rate is affected by two factors, which are soil temperature and net primary productivity. Net primary productivity is considered as a criterion for evaluating presence and accessibility of carbon in its organic form for producing the methane gas. Yearly total NPP at a grid cell is used from the global terrestrial carbon cycle model Biosphere-Energy Transfer and Hydrology (BETHY) given by Knorr (1997) which computes the net primary productivity for a group of vegetation types which is based on the Wilson and Henderson–Sellers (1985) vegetation map. Their model also consists of a hydrologic model that is used to perform the modelling of the variations of the water table due to the climate in wetlands. Walter et al (2001 a) mentions the use of a simple water balance equation to calculate the water table position daily. The input variables used for model forcing are total daily precipitation, 2-metre air temperature and net incoming radiation from the sun at the surface at every six hours. They mention the spatial resolution to be 1 degree by 1 degree. High hydraulic conductivity and rising water retention potential with the increase in depth are the suppositions for this hydrologic model used in their global model for methane emissions.

Wania (2007) gives a clear comparison between the Cao et al (1996) and Walter et al (2001 a) models, highlighting Walter's model as being more mechanistic than Cao's model. She also highlights the drawbacks of the Walter's model in the sense of needing more data for input, which becomes a weakness when applying the model globally and in the modelling of past and future emissions. Wania (2007) has further pointed out its usage for carrying out modelling in definite sites, emphasizing the fact that essential parameters for input are identified but is clearly skeptical about its applications globally. In contrast to LPJ-GUESS, Walter et al (2001 a) does not calculate net primary productivity by itself, and instead uses another model to generate NPP as its input.

2.6.3 Inverse Modelling

In contrast to the above approach, studies such as Lelieveld et al (1998), Houweling et al (1999) and Chen and Prinn (2006) have used an inverse modelling approach, which includes observations of the amount of methane in the atmosphere and also atmospheric chemistry transport models to find emissions of methane. IPCC (2007) highlights this approach to be depending upon observations of the methane concentrations that are distributed in space and time and in a few situations, collection of atmospheric isotopes. IPCC (2007) has also pointed out this approach to be comprising of observations from aircraft and satellites such as in Xiao et al (2004) and Frankenberg et al (2005) & (2006).

Wania (2007) mentions the helpful aspect of this kind of modelling is that it is free of the assumptions regarding the mechanisms employed in process based models in giving the assessment of the emissions of the methane gas and the values can be matched with the measured figures of the amount of methane in the atmosphere. Wania (2007) also highlights the limitation of these top-down models due to their dependence on observations of methane in the atmosphere being used as input and hence cannot envisage emissions of this gas. Nevertheless, she points at the assistance they provide in lessening the uncertainties coming up due to process-based models by the aiding in comprehending the results from these mechanistic models.

Bousquet et al (2006) mention the quantitative association of methane measurements in the atmosphere to the sources and sinks at the local level (regional) with an inverse modelling approach. This study also mentions measurements in the atmosphere for long periods and also state that these kind of model gives vital information for estimating the tendencies in the emissions of this gas presently, at the range varying worldwide to the subcontinental level. Nevertheless, this study also emphasizes the difficulty of applying this method in a region or at the level of a nation due to the uncertainties existing in the effluxes from the surface and OH distribution and thus points to the need of numerous group of observations spatially as well as temporally.

Frankenberg et al (2005), whose work consists of top-down approach, have highlighted that observations from space permit the detection of spatial and temporal fluctuations in the concentrations of methane in the atmosphere worldwide, which leads to recognition of the sources which are already known and also the unearthing the unknown ones, specifically in the areas that has insignificant sampling through the prevailing surface measurement networks. Several studies using inverse modelling approach have been carried out which give a range of methane emissions from various sources.

2.6.4 The LPJ-GUESS Model and its methane module

LPJ-GUESS is the Dynamic Global Vegetation Model (DGVM), which simulates the vegetation dynamics of land ecosystems. It models the growing processes including the struggle for resources of the plant at an individual level. Competition for sunlight among the adjacent plants is impacted by the variations in the height, depth, area and leaf area index of the plants. Every single plant carries out its distribution of carbon which is assimilated to its leaf mass, fine root mass and sapwood mass. The height and diameter development is regulated by the division and provision of carbon as well as the conversion of the sapwood to the heartwood. Plant Functional Types (PFTs) represent the vegetation in the model. PFTs include both woody plants (trees and shrubs) and grass types. Every individual fits into one kind of PFT and thus each PFT groups individuals with similar traits. Each PFT is represented by particular parameters specifying its establishment, phenology, distribution of carbon, allometry, endurance of low light conditions, rates of photosynthesis and rates of respiration due to which these PFTs have their own niches in the environment, which are denoted by bioclimatic limits and physiological optima, and struggle for water and light resources amongst themselves which characterizes the modelled vegetation (Smith et al 2001). The model requires input data i.e. monthly climate data such as air temperature, total precipitation, fractional sunshine hours and wet days and data regarding description of the type of the soil and the yearly value of the atmospheric carbon dioxide mixing ratio worldwide. Modelling of the mechanisms is carried out at a daily, monthly or yearly time step as required (Smith et al 2001; Wania et al 2009 a).

Smith et al (2001) describes two ecosystem models, individual based (LPJ-GUESS cohort or individial mode) and area based (LPJ-GUESS population mode). The individual based model differs from the area based model in terms of the dynamics and structure of vegetation. Contrary to the former, where each individual plant or cohort is separate from the other, individuals of each PFT in the area based model do not possess individual features but instead represent an average of the PFT population in each grid cell. They also mention that the schemes controlling phenology, plant photosynthesis, water balance, respiration, leaf and root turnover, allocation of carbon and tree allometry are same for both model configurations. The detailed processes of the model are described in Smith et al (2001).

This individual based model (LPJ-GUESS) on comparison with the population mode (LPJ-DGVM) in Smith et al (2001) has been found to perform well in those parts where overlapping of evergreen and deciduous types have been found. It also did well in regions, which suffered from water scarcity seasonally and would have a tendency to support grasses as compared to trees that cannot accept drought. They also mention better model performance when dealing of mechanisms at a single plant level, specifically for the struggle for light resources and death due to stress. The findings of Smith et al (2001) puts forward that the simulation of the structure and function of ecosystems might be benefitted by following an individual-based approach to changing aspects of vegetation for studies ranging from regional to continental scale resolution.

LPJ-GUESS v 2.1 has been developed to model northern (high latitudes) peatland hydrology, permafrost dynamics and peatland vegetation and is called LPJ-GUESS Wetland Hydrology (LPJ-GUESS WHy) (Paul Miller, private communication) using processes as given in Wania et al (2009 a, b) where the DGVM used by them is called LPJ-WHy (LPJ-Wetland Hydrology). Wania (2009 a) has adapted LPJ-DGVM to model the changes in temperature depending upon the depth of the soil to find out the depths of the active layer of permafrost and the presence of permafrost within 2 m of soil from above. The hydrology module of LPJ (Gerten et al 2004) was divided for locations without peatlands and for organic soils. For former, the existing hydrology scheme was adapted so that modelling of freeze-melt cycles takes place. For the latter, they used a fresh parameterization that they mention takes into account the diplotelmic nature of peat, which is an acrotelm and catotelm (Ingram 1978; Wania et al 2009 a) in peatlands. Certain outcomes of snow ageing were introduced in the management of the surface snowpack of the model so that snow density alters with snow age rather than being constant, permitting variations in the features of thermal insulation.

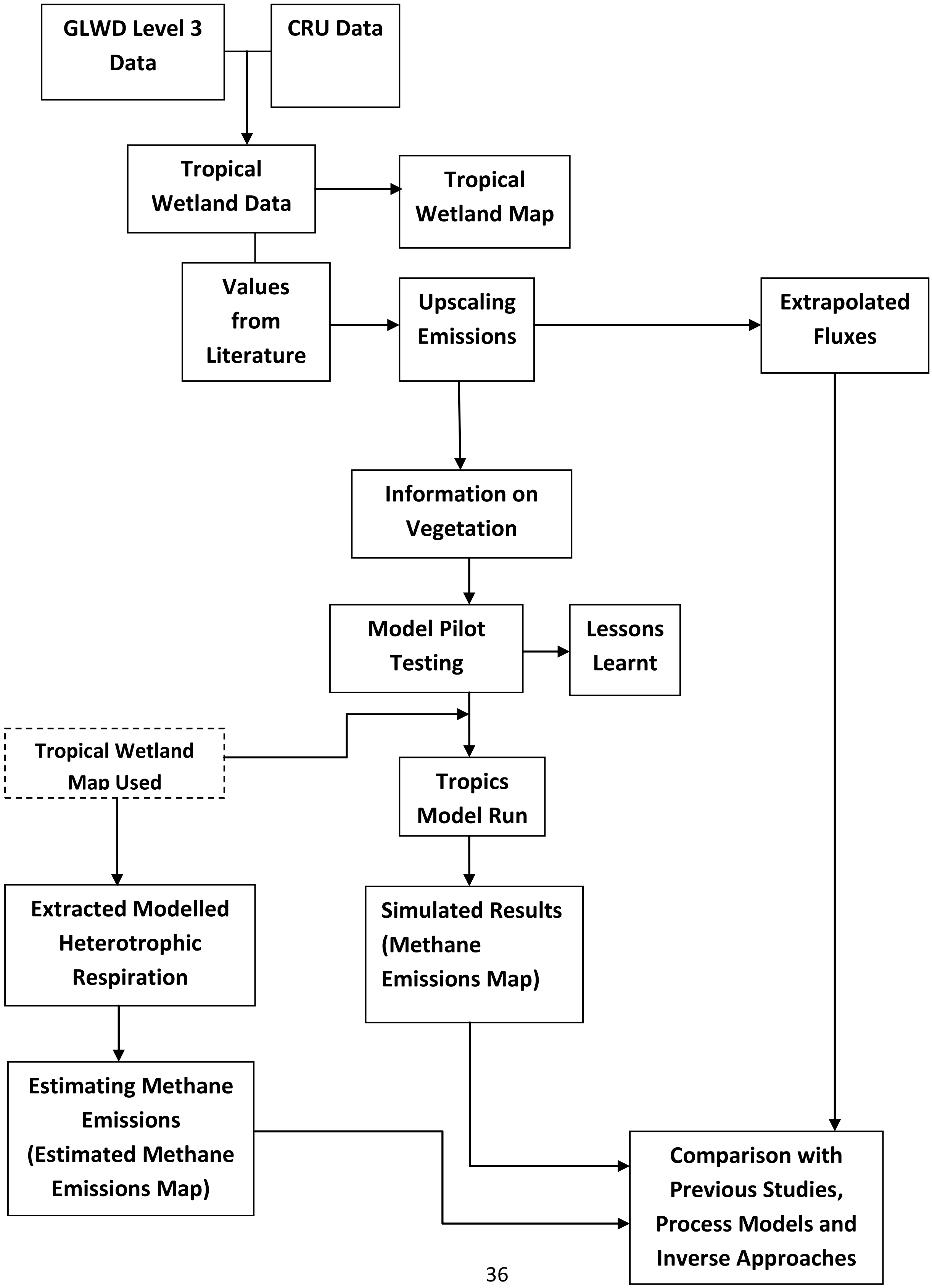
Apart from inclusion of modifications to physical land surface processes which manage temperature of the soil, position of the water table, depth of the active layer and distribution of permafrost (Wania et al 2009 a), vegetation related changes were added to the model as described in Wania et al (2009 b). Two more PFTs growing specifically in peatlands in the model are introduced namely C_3 graminoids that can survive inundation and include species such as *Carex*, *Eriophorum*, *Juncus* and *Typha* and the other PFT is *Sphagnum* mosses. They have also added inundation stress mechanism for PFTs in peatlands. Every PFT in the model is given a water table threshold beyond which they feel stress due to flooded conditions. Gross Primary Production (GPP) per month is reduced by an inundation stress factor per month, which is based on two factors i.e. the total days the PFT had felt stress and a parameter determining the extent of maximum survival duration for the flooded condition in terms of days per month. Other important features added by Wania et al (2009 b), is the slowing down of decomposition of the carbon pool under flooded conditions and the inclusion of a root exudates pool.

LPJ-WHyMe (LPJ Wetland Hydrology and Methane) is a further development of LPJ-WHy and is used to simulate methane emissions from northern peatlands (Wania et al 2010). The model LPJ-GUESS WHy (LPJ-GUESS Wetland Hydrology) is also developed in the same way as to simulate methane emissions from northern peatlands and the model is called LPJ-GUESS WHyMe (LPJ-GUESS Wetland Hydrology and Methane) (Paul Miller, personal communication). Wania et al (2010) describe LPJ-WHyMe in detail and explain the process based approach of the model in modelling methane emissions from peatlands, though they have also expressed the use of a number of empirical relationships and parameters. Simulation of methane production, the transportation processes of methane by diffusion, plant-mediated transport and ebullition and also the oxidation process of methane takes place in the model. Hence, a methane model (sub-model) has been incorporated into DGVM, which involves the active interplay within hydrology, temperature of the soil, vegetation and methane processes (Wania et al 2010). LPJ-WHyMe has the establishment of the "potential carbon pool for methanogens", as Wania et al (2010) denote it that comprises of exudates of root and material from vegetation, which can breakdown simply and a small degree of decayed extra recalcitrant organic matter. Carbon classified as heterotrophic respiration in LPJ is handled in different manners in LPJ-WHyMe for locations having a presence or absence of peatlands. For locations without peatlands, heterotrophic respiration is transferred to carbon dioxide flow to the atmosphere whereas for peatland sites, the carbon from decomposition contributes to the potential carbon pool that is accessible for methanogenic archaea. The above mentioned potential carbon pool is supplied over various layers of the soil depending on the root biomass distribution which is then divided into carbon dioxide and methane. Please refer to Wania (2010) for further details.

The present study uses the LPJ-GUESS WHyMe model without any changes and reparameterisation for tropical areas, and will be applied for the first time to the tropics. This model incorporates all of the LPJ-WHyMe developments described above (Paul Miller, personal communication).

3.0 Material and Methods

3.1 Flowchart of methodology used in the study



The tropical wetland data was extracted from Global Lakes and Wetlands Database (GLWD) Level 3 dataset (Lehner and Doll 2004) by using Arc GIS 9. The data was processes in a C++ program using the Climatic Research Unit (CRU) dataset (0.5×0.5 degree grid) (Mitchell and Jones 2005) to get the tropical wetlands in the same 0.5×0.5 degree grid. The program also calculated the type of wetlands and the fraction of wetlands in each grid along with the total area of each grid across the tropical region, considering the decrease in the area of the grids towards the poles. This data was used to derive a tropical wetland map in Arc GIS. Values from literature of methane emissions from various wetland types along with the tropical wetland data were used for upscaling methane emissions. Studies used for upscaling emissions also gave the information on vegetation of those sites, which were useful for adjusting the LPJ-GUESS WHyMe model for simulating methane emissions. Pilot testing for a few sites was carried out and the lessons learnt from them were useful for running the model for the entire tropics using the tropical wetland information. The resulting simulated methane emissions from LPJ-GUESS WHyMe were used to produce a tropical wetland methane emissions map. The tropical wetland information was also used to extract modelled heterotrophic respiration values from LPJ-GUESS model v 2.1, which were used to estimate methane emissions using a simpler approach (Refer 3.11) and a second map for the estimated tropical wetland methane emissions was produced.

3.2 The GLWD Level 3 dataset

The wetland dataset used in the study is the GLWD Level 3 (lakes and wetlands grid) (Lehner and Doll 2004). It is a global map in raster format (grid) at 30-second resolution consisting of lakes, reservoirs, rivers and various wetland types. Each grid cell represented a specific water body. Detailed information on it can be found in Table 3 below. The geodetic reference system of the dataset is the North American Datum of 1987 on Clarke's ellipsoid. It was assigned WGS-84 as its false datum. Classes 1, 2, 3, 8 and 9 as mentioned in Lehner and Doll (2004) are not used in the study.

Table 3. Classification of the GLWD Level 3 dataset

Value of the cell	Class
1	Lake
2	Reservoir
3	River
4	Freshwater Marsh, Floodplain
5	Swamp Forest, Flooded Forest
6	Coastal Wetland
7	Pan, Brackish/Saline Wetland
8	Bog, Fen, Mire
9	Intermittent Wetland/Lake
10	50-100% Wetland
11	25-50% Wetland
12	Wetland Compex (0-25%)

sNote: Total Wetlands as per Lehner and Doll (2004) –Classes 3-12
Source: Lehner and Döll (2004)

3.3 Study Area

The area chosen for this study is tropics, which have been defined as extending from 30 degrees South to 30 degrees North for the purpose of this study. A broad range of latitudinal bands has been selected for the tropical region with the purpose of including a large extent of wetlands and avoiding exclusion of wetlands in the subtropical regions. The spatial extent of wetlands for the subtropical/tropical region as mentioned by Maltby and Turner (1983) is 4.8×10^6 km^2 whereas Matthews and Fung (1987) specifies it to be 1.9×10^6 km^2. Aselmann and Crutzen (1989) find it to be 2.1×10^6 km^2 (Mitsch and Gosselink 2007, page 46, Table 3.1). A definition of tropical zone differs within the studies. Wetlands present in the tropical areas may be temporary and just occurring in specific seasons or may be everlasting in natural conditions (Bartlett and Harriss

1993). They have also mentioned that the degree of flooding keeps changing substantially during the year in the wetlands, acknowledging fluctuations in precipitation to be the chief reason for alterations in the seasons in the tropical areas. High temperature and radiation from the sun leads to characteristically high primary production rates. Large areas having periodic inundation might be found in the floodplains of Amazon and other huge rivers in the tropical region, where the areas consisting of forests have been modified by periodic flooding, for example, their species have been acclimatized to those conditions.

3.4 CRU Dataset

Another dataset used is the CRU TS 3.0 climate dataset (Mitchell and Jones 2005) consisting of surface air temperature, total precipitation, fractional sunshine hours from cloud cover percentage and the number of wet days from the CRU climatology per month for the tropics (30 degree south to 30 degree north) in a 0.5 degree $\times$ 0.5 degree gridded dataset. The geodetic reference system used for the dataset is WGS 84 and the coordinate system used is latitude and longitude.

3.5 Methane fluxes site-based data

The data from site based observations used in this study for extrapolation for the entire tropics have been taken from various studies carried out using different measurement techniques ranging from 1988 to 2010. Methane fluxes were measured using diffusion chambers, gas-sampling methods, closed recirculating chambers, gradient techniques, closed chamber techniques and static chamber techniques. One of the studies used for upscaling has used remote sensing for estimation of inundated areas. The specific details regarding the particular technique used by the studies can be found in Tables 4-7 below.

3.6 Heterotrophic respiration data modelled from LPJ-GUESS v2.1

Heterotrophic respiration data from the years 1990-2006 as simulated by LPJ-GUESS v2.1 using the CRU dataset as forcing were used to estimate methane emissions using a fixed carbon conversion factor to convert a set fraction of the modelled heterotrophic respiration to methane emission (Paul Miller, unpublished data).

3.7 Data extraction and Upscaling

The GLWD-Level 3 dataset was projected as WGS 84. A text document was produced from the information contained in every pixel of the dataset which is at 30 second $\times$ 30 second resolution, essentially consisting of the location of that pixel in latitude and longitude as well as the wetland category. This was possible by converting the raster dataset to point data having the grid values (wetland category) and the x and y coordinates of every point. This finally produced the text file consisting of location of every point dataset in latitude and longitude as well as their wetland category. The data was selected for the tropical belt only. This text document was finally used in a C++ program which for every latitude and longitude value on the 0.5 degree grid (used by CRU dataset) finds out the number of pixels in the GLWD dataset falling in the same latitude and longitude grid cell and calculates the percentage coverage of each wetland category in the GLWD dataset. Code for the C++ program can be found in Appendix B below. The program also calculates the area of each tropical grid cell in km^2, making required adjustments for the spherical shape of the Earth as the size of the grid cells decreases towards the poles. The area has been calculated assuming Earth to be a perfect sphere. A wetland map was produced from the data in Arc GIS for the tropics. As the dataset consisted of various wetland categories, maps representing different wetland categories were also produced. Out of the various wetland categories given in Lehner and Doll (2004), upscaling for the methane emission values from various studies in tropical areas was carried out for four categories of wetlands, namely, the Fresh water Marsh, Floodplain category; the Swamp Forest, Flooded Forest category; the Coastal wetland category and the Pan, Brackish/Saline wetland category. Three other, less well-defined categories from Lehner & Doll (2004) were also upscaled. An assumption was made regarding their category type to be falling anywhere between the above four wetland categories. These three less well-defined categories (Wetland class 10, 11 and 12 from the Table 3 above) were given an approximate range of values for emissions from them by using upscaled emissions from the mentioned four wetland categories (the Fresh water Marsh, Floodplain category; the Swamp Forest, Flooded Forest category; the Coastal Wetland category and the Pan, Brackish/Saline wetland category).

The River class though mentioned as wetland in Lehner and Doll (2004) was excluded from the study considering the focus of the study on various other types of wetlands. Bog, Fen and mire were also excluded due to their negligible area as compared to other wetland types. Intermittent wetlands were excluded due to the limitation of literature available on them.

3.8 Description of sites used in upscaling

Methane emission values used for upscaling wetland classes were taken from various sites. These sites were chosen corresponding to each wetland class. Their selection over other sites is purely based on the amount of literature available for them. Measurements per unit area (m^2) per unit time (year) of methane emissions from three studies covering different parts of the tropics i.e. one site from Costa Rica (Nahlik and Mitsch 2010), a second from the Central Amazon Basin, South America (Melack et al 2004; Nahlik and Mitsch 2010) and a third site from India (Mallick and Dutta 2009) were used to upscale the entire area of tropics falling in the Fresh water Marsh, Floodplain category. Similarly, extrapolations from sites i.e. La Selva from Costa Rica (Nahlik and Mitsch 2010), Orinoco river, floodplain in Venezuela (Smith et al 2000), Lago Calado in the Amazon basin, Brazil (Bartlett et al 1988) and Vargem Grande in Amazon Basin, Brazil (Devol et al 1988) belonging to Swamp Forest, Flooded Forest category were used for upscaling. Coastal wetland sites were represented by Lothian island of Sunderban mangrove forest, India (Mukhopadhay et al 2002), Pichavaram mangroves, India (Purvaja and Ramesh 2000) and Pulicat Lake, India (Shalini et al 2006). Laguna Guaniquilla, Cabo Rojo in Puerto Rico (Sotomayor et al 1994) and salt affected areas and salt pans existing in the coastal wetland ecosystem of Pichavaram mangroves, India (Purvaja and Ramesh 2001) were used for upscaling emissions for the Pan, Brackish/Saline wetland class.

3.9 Pilot-testing for LPJ-GUESS WHyMe simulations for methane emissions

The knowledge gained from this upscaling approach was used to define the tropical wetland vegetation in the LPJ-GUESS WHyMe model by adopting the existing PFTs to tropical areas. Currently, the model has two kinds of PFTs for tropical trees i.e. Tropical broad-leaved evergreen (TrBE) and Tropical broad-leaved raingreen (TrBR) along with a Tropical Herbaceous (TrH) PFT for herbaceous vegetation such as for C_3 and C_4 grasses. As there is no definite plant functional type for tropical wetlands in LPJ-GUESS WHyMe, the PFTs TrBE and TrH (C_3 and C_4 grasses) were assumed to be the potential wetland vegetation. Hence, to simulate the methane emissions for these pilot sites, approximations for the vegetation characteristics such as the type of leaf, inundation stress, maximum establishment rate of vegetation and tolerance of shade have been used in the model (Refer Appendix C) using the existing characteristics of the TrBE and TrH PFTs in LPJ-GUESS v2.1, but relaxing these PFTs' tolerance of inundation to allow them to exist in areas with high water tables. The wetland hydrology of Wania et al (2009 a) was used throughout, though the upper limit of the water table depth was relaxed to allow water tables up to 50 cm above the soil surface. Pilot testing was carried out for four wetland categories, namely the Fresh water Marsh, Floodplain category; the Swamp Forest, Flooded Forest category; the Coastal wetland category and the Pan, Brackish/Saline wetland category. Earth site in Costa Rica and La Selva site in Costa Rica were used as pilot testing sites for the Fresh water Marsh, Floodplain category and the Swamp Forest, Flooded Forest category. Pichavaram Mangroves site in India was used as pilot testing site for the Coastal wetland category as well as the Pan, Brackish/Saline wetland category due to the overlapping characteristics of these wetland classes. These three sites were also used for upscaling methane emissions from the respective wetland categories. Panama site was also used as a pilot testing site for the tropics though it was not used for upscaling emissions. This site used the same vegetation parameters which were used for marsh and swamp wetland categories. Their selection over other sites is purely based on the amount of literature available for them. The analysis of the pilot testing results was carried out for soil temperature and water table position. The modelled methane emissions from LPJ-GUESS WHyMe were compared with the field observations.

3.10 Simulating methane emissions using LPJ-GUESS WHyMe for tropical wetlands

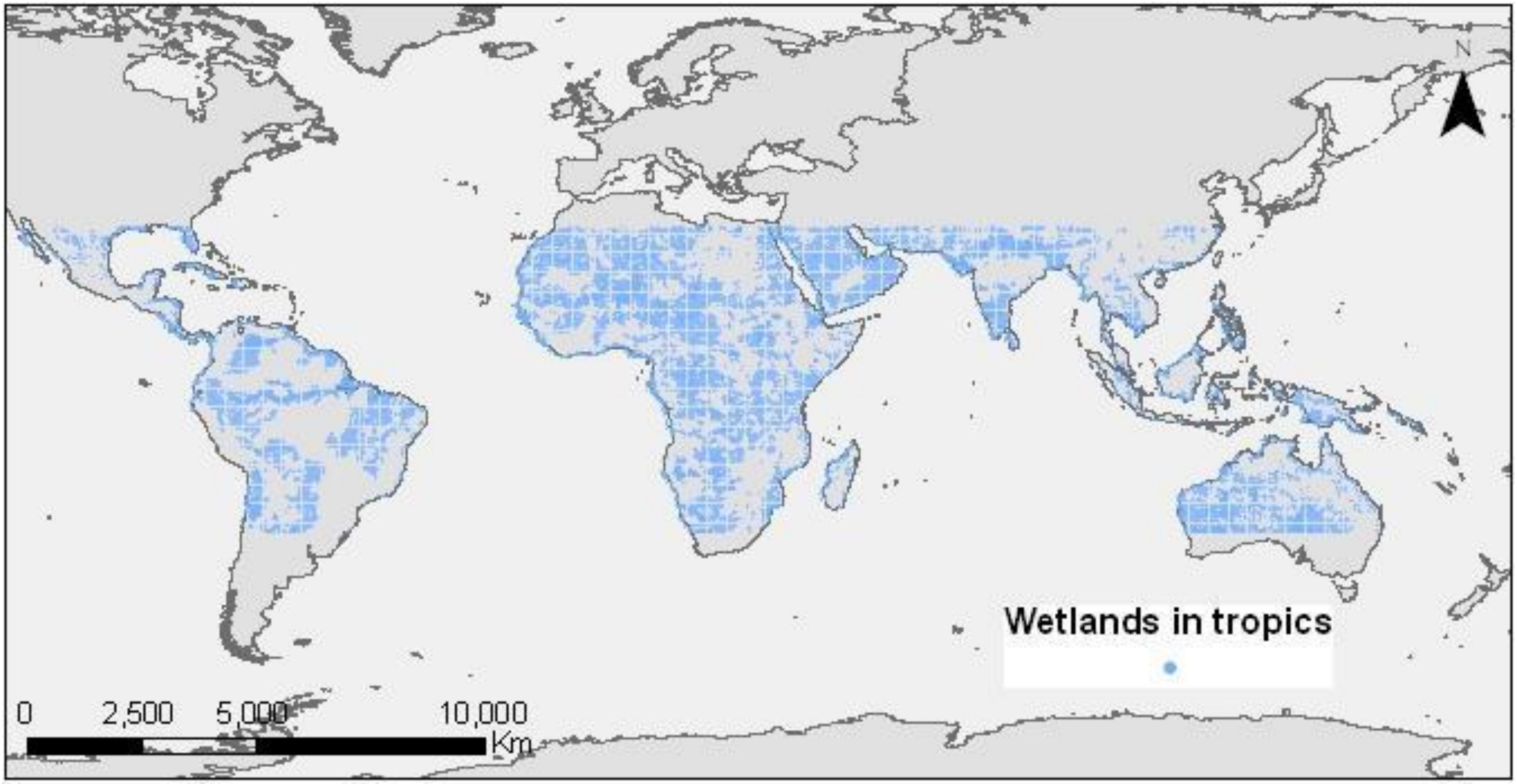
Based on the pilot testing results, the model was run in a 0.5 degree × 0.5 degree simulation with the data on tropical wetland distribution extracted in this study from the GLWD Level 3 dataset of Lehner and Doll (2004). It was assumed that inundated parts in the grid remain the same throughout the year. The model was forced with a CRU TS 3.0 climate dataset providing monthly input data of surface air temperature, total precipitation, fractional sunshine hours from cloud cover percentage and a count of wet days for the tropics (30 degrees south to 30 degrees north) in the 0.5 degree × 0.5 degree gridded dataset. A spin up run for 500 years was carried out to get both vegetation and soil carbon pools to their equilibrium long term values. Similar runs regarding the vegetation aspects were carried out as it was done for the pilot testing of the tropical sites. Rice paddies are not included in the model run (not represented in LPJ-GUESS) and only the natural wetland classes of Lehner and Doll (2004) excluding the river class; the bog, fen, mire class and the intermittent wetland class were used in the calculation of methane emissions.

3.11 Estimating emissions from modelled heterotrophic respiration output

LPJ-GUESS v2.1 has recently been run globally with a generic set of PFTs in order to generate its global benchmarks, which include such quantities as globally averaged GPP, NPP, NEE, soil carbon pools and water runoff. The results fall within the range of values reported in other studies (Paul Miller, private communication). Simulated heterotrophic respiration values were extracted from the LPJ-GUESS v2.1 benchmark runs for the tropics and methane emissions were estimated from those values by assuming that a fixed fraction of the respiration was emitted as methane instead of carbon dioxide. This study assumed this fixed carbon conversion factor to be 0.0415. The inspiration for this method and the value of the carbon conversion factor has been taken from the recent results of Spahni et al (2011 discussion paper). The sites used for pilot testing methane emissions from LPJ-GUESS WHyMe simulations were also used to find out the estimated emissions from modelled heterotrophic respiration output of LPJ-GUESS v2.1. The results of estimated emissions for the pilot testing sites are given along with the results of modelled methane emissions from LPJ-GUESS WHyMe.

4.0 Results

4.1 Tropical Wetland Maps



Map 1-Wetlands in tropics

Note: Plotted as latitude longitude in degrees from the gridded dataset.
The scale does not apply for the entire map.

Map 1 above shows the occurrence of wetlands in tropics. Note that the symbols are not drawn to scale. This map shows all wetland classes mentioned in the Lehner and Doll (2004) dataset excluding rivers; bog, fen, mire and intermittent wetland/Lake class.

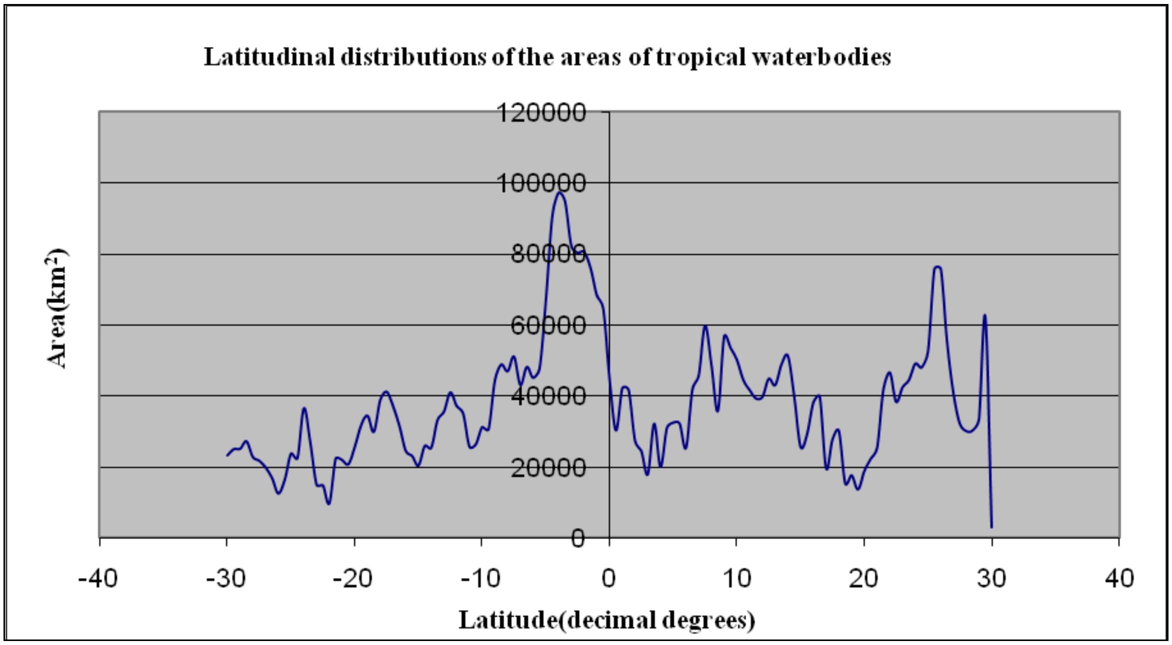
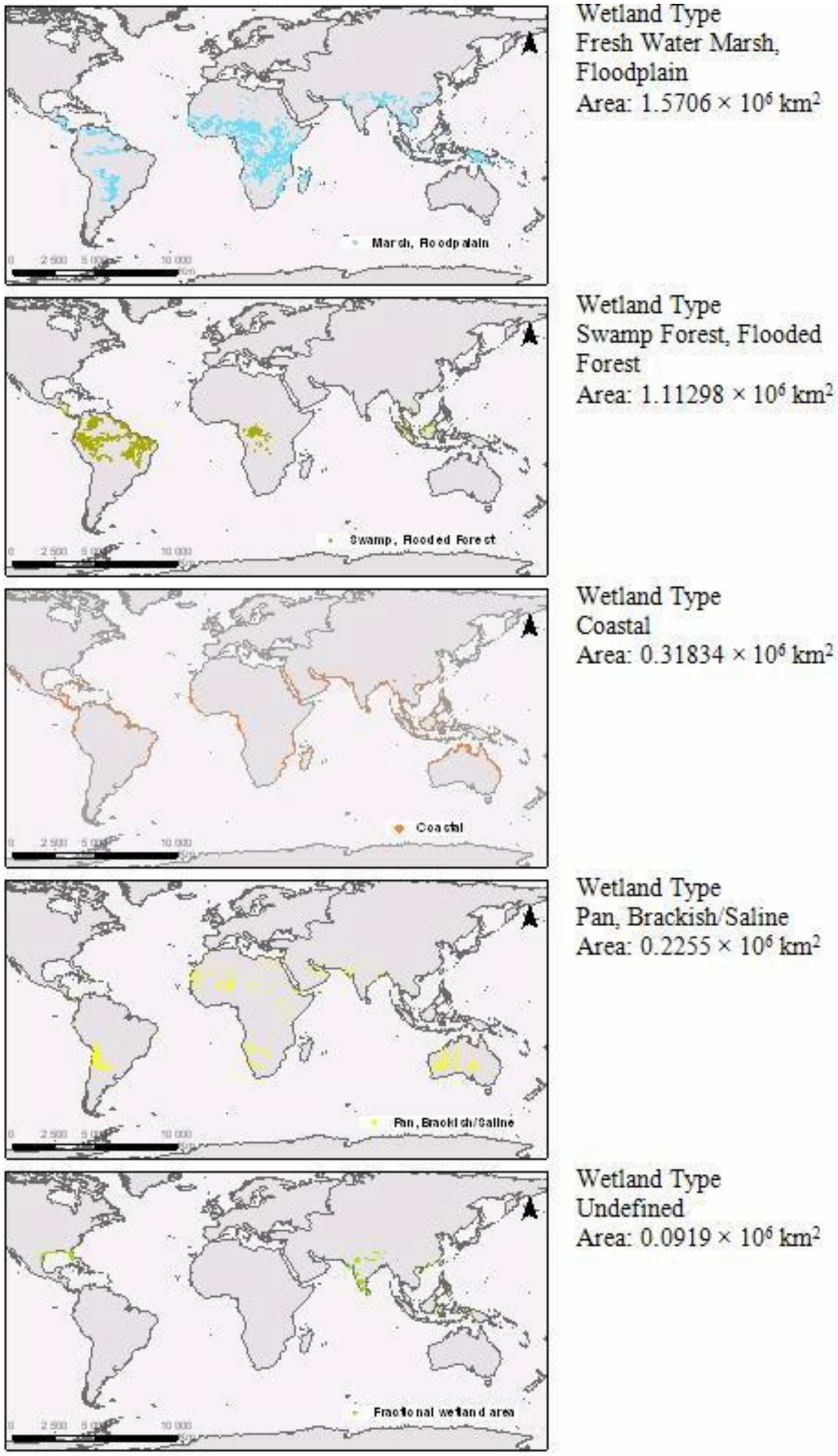


Figure 1: The areal distribution of waterbodies across 30 degrees S to 30 degrees N consisting of the all the classes as given in Table 3 above (calculated using the Lehner and Doll 2004 GLWD Level 3 dataset).

Values for the area are summed in steps of 0.5 degrees. The three fractional wetland classes of the dataset namely, 50-100% wetland, 25-50% wetland and Wetland complex (0-25% wetland) did not have a well-defined spatial coverage ratio as mentioned in Lehner and Doll (2004). Those three classes of wetland have been considered with their full capacity of inundation in Figure 1, which plots the zonal distribution of the areas of tropical waterbodies and shows the maximum coverage just south of the Equator.



Map 2. The wetland classes used in this study

Note-Plotted as latitude, longitude in degrees

The various categories of wetland classes are shown in Map 2. The region where each wetland class has been shown might also overlap with the other wetland class in the map, since the data shown is the 0.5 degree resolution data which is used in this study, and each grid cell may contain multiple Lehner and Doll (2004) wetland types (Dataset available for wetland classes was at a very fine resolution (30 second $\times$ 30 second)). The undefined wetland classes of the Lehner and Doll (2004) dataset i.e. namely, 50-100% wetland, 25-50% wetland and wetland complex (0-25% wetland) (Refer Table 3), specify fractional areas of those wetlands and have been integrated together as one wetland class in Map 2.

4.2 Upscaling Results

Total wetland area of the tropics, calculated by summing all the wetland types as mentioned in the Lehner and Doll (2004) dataset for the tropical zone (30 degrees S-30 degrees N) excluding 'River' wetland class was approximately 3.7×10^6 km^2. The area was also computed for each respective wetland type in the tropics, which is shown in Figure 2 below.

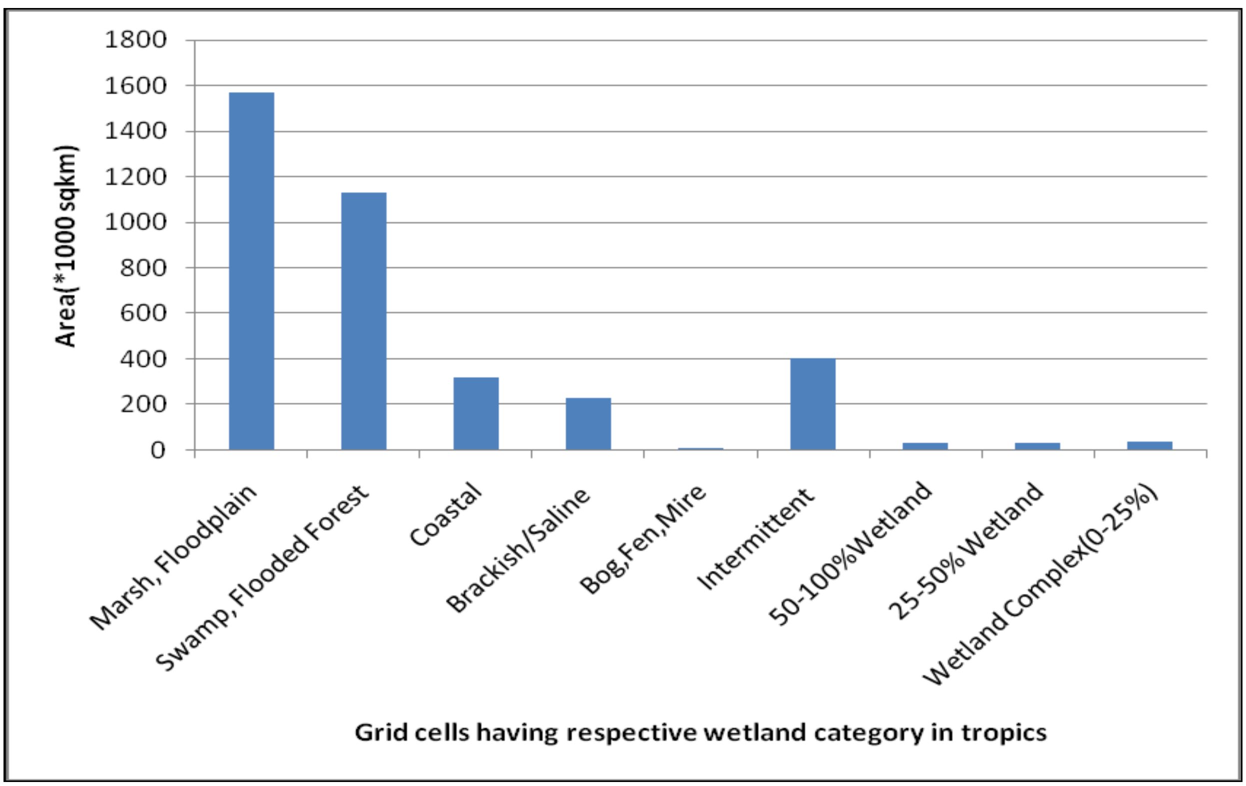


Figure 2: Area wise distribution of different wetland types in the tropics

Figure 2 clearly depicts the dominating Fresh water Marsh, Floodplain category in the tropics followed by Swamp, Flooded forest category. Out of the total wetland area present in the tropics, Figure 3 below represents the area considered for upscaling in this study. Wetland classes 8 and 9 of Lehner and Doll (2004), namely, 'Bog, Fen, Mire' and 'Intermittent wetland/Lake' have been excluded from the upscaling carried out. As seen in Figure 2, 'Bog, Fen, Mire' seemed to have negligible area as compared to other wetland classes and hence was excluded from the study. Though intermittent wetland/Lake class had considerable area of 0.4×10^6 km^2, it was also not considered for the upscaling due to the vagueness of the type of wetland and also the lack of published studies on methane fluxes for this type of wetland.

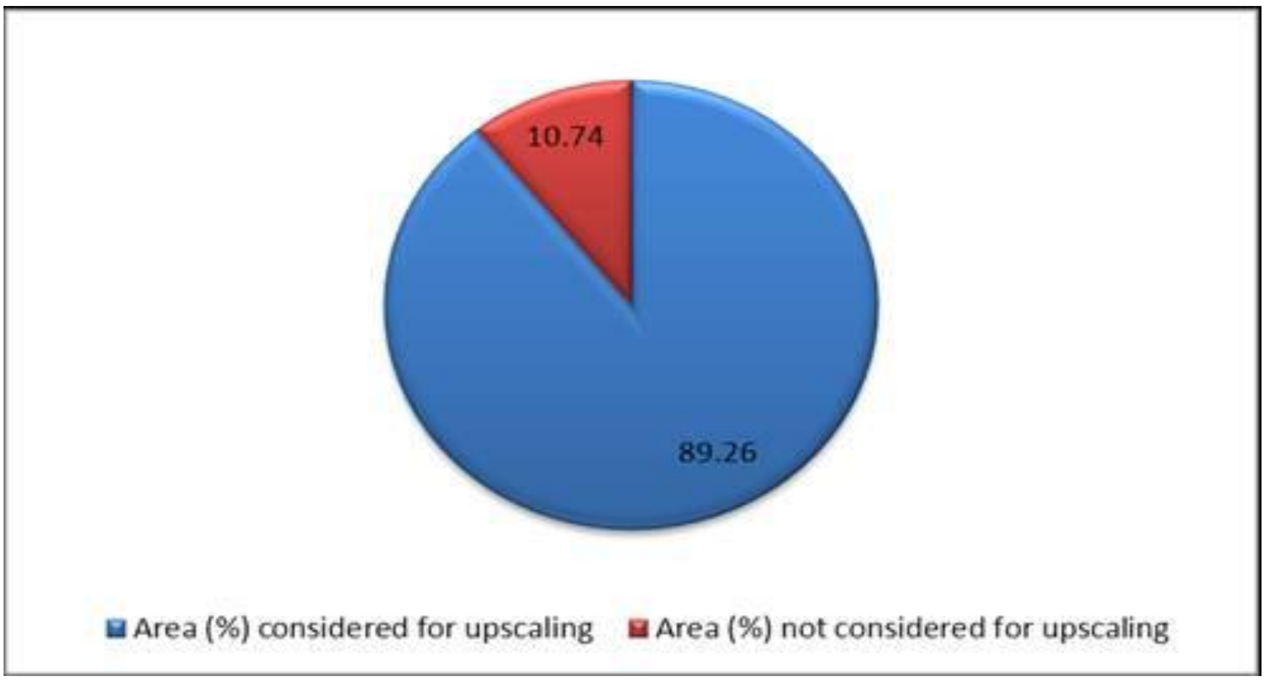


Figure 3. The percentage of wetland area considered for the upscaling approach

Out of the total wetland area for the tropics i.e. 3.7×10^6 km^2, area of 3.34×10^6 km^2 amounting to around 89 % was used for the upscaling approach whereas 0.40×10^6 km^2 representing about 11 percent of the wetland area was excluded from this approach.

Table 4- Observation sites along with published methane emissions for the Fresh water Marsh, Floodplain category

Wetland type (as mentioned in study)	Study	Measurement Technique	Site	Reported value	Emissions $gCH_4m^{-2}yr^{-1}$
Forested Marsh	Nahlik and Mitsch (2010)	Diffusion chamber	Earth, Costa Rica	$91mgCH_4\text{-}Cm^{-2}day^{-1}$	44
Forested Floodplain*	Melack et al (2004)	Remote Sensing (Inundation and seasonal vegetation) by Melack et al 2004 Chamber Technique (methane measurements by Devol et al 1990)**	Central Amazon Basin, South America	$105gCH_4\text{-}Cha^{-1}day^{-1}$	4
Freshwater, Floodplain	Mallick and Dutta (2009)	Gas sampling method	Bhaleshwa Lake, Floodplain of River Yamuna, Northern outskirts of Delhi, North India	(-0.36 ± 0.27) to (-0.664 ± 0.27) $mgCH_4m^{-2}hr^{-1}$ (Sept-Jan) (129.82 ± 19.08) to (2.986 ± 0.14) $mgCH_4m^{-2}hr^{-1}$ (Feb-Apr) (-2.074 ± 1.34) to (0.075 ± 0.007) $mgCH_4m^{-2}hr^{-1}$ (May-July)	38.74-137.75

* Wetland type as well as other details as referenced in Nahlik and Mitsch (2010)

**Measurement technique as mentioned in Melack et al (2004)

Table 5- Observation sites along with published methane emissions for the Swamp Forest, Flooded Forest category

Wetland type (as mentioned in study)	Study	Measurement Technique	Site	Reported value	Emissions $gCH_4m^{-2}yr^{-1}$
Rain Forest Swamp	Nahlik and Mitsch (2010)	Diffusion Chamber	La Selva, Costa Rica	$601mgCH_4\text{-}Cm^{-2}day^{-1}$	293
Flooded Forest*	Smith et al (2000)	Diffusion Chamber	Orinoco River, Floodplain, Venezuela	$7mmolCH_4m^{-2}day^{-1}$	42
Flooded Forest*	Bartlett et al (1988)	Closed, recirculating chamber	Lago Calado, Amazon Basin, Brazil	$192mgCH_4m^{-2}day^{-1}$	70
Flooded Forest*	Devol et al (1988)	Diffusion Chamber	Vargem Grande,Amazon Basin, Brazil	$110\ mgCH_4m^{-2}day^{-1}$	40

* Wetland type as well as other details as referenced in Nahlik and Mitsch (2010)

Table 6- Observation sites along with published methane emissions for the Coastal Wetland category

Wetland type (as mentioned in study)	**Study**	**Measurement Technique**	**Site**	**Reported value**	**Emissions $gCH_4m^{-2}yr^{-1}$**
Mangroves	Mukhopadhay et al (2002)	Gradient Technique	Lothian Island, Sundarban Mangrove forest, India	6.46×10^{-3} $\mu gCH_4m^{-2}s^{-1}$ (Feb-May) 4.46 $\mu gCH_4m^{-2}s^{-1}$(Jun-Sep) -4.53 $\mu gCH_4m^{-2}s^{-1}$ (Oct-Jan) Pre-monsoon(Feb-May) Monsoon(Jun-Sep) Post-Monsoon(Oct-Jan)	-0.67
Mangroves	Purvaja and Ramesh (2000)	Closed Chamber Technique	Pichavaram Mangroves	7.4 $mgCH_4m^{-2}hr^{-1}$	44.6-89.7
Estuary	Shalini et al (2006)	Chamber Method	Pulicat Lake, South India	$8gCH_4m^{-2}y^{-1}$	8

Table 7- Observation sites along with published methane emissions for the Pan, Brackish/Saline Wetlands category

Wetland type (as mentioned in study)	**Study**	**Measurement Technique**	**Site**	**Reported value**	**Emissions $gCH_4m^{-2}yr^{-1}$**
Natural Coastal Brackish Mangrove Lagoon(semi enclosed)	Sotomayor et al (1994)	Static Chamber Technique	Laguna Guaniquilla,Cabo Rojo, Puerto Rico	1.2 $gCH_4m^{-2}yr^{-1}$	1.2
Salt affected areas & Salt Pans	Purvaja and Ramesh (2001)	Static Chamber Technique	Pichavaram Mangroves, coastal wetland ecosystem, India	7.38 $mgCH_4m^{-2}hr^{-1}$ (Monthly average)	64.65

As is shown from Tables 4-7 above, there is a wide range of methane emissions for each class of wetland depending upon the measurements reported from various studies. To aid the comparison all reported values have been converted to fixed units of $gCH_4m^{-2}year^{-1}$, and have been reported in the final column in each table. A range for the total, annual methane emissions for each of these four tropical wetland types was then computed by multiplying the lowest and highest observed values from Tables 4-7 by their respective areas, as shown in Figure 2. Apart from these emissions, wetland classes 10, 11 and 12 i.e. namely, 50-100% wetland, 25-50% wetland and wetland complex (0-25% wetland) give emissions varying from (-) 0.06 to around 27 Tg CH_4 per year (The negative sign indicates that the classes act as a methane sink rather than a source). Emissions for these classes have been calculated using the areas at their class centers i.e. the total area of class 10 wetland has been calculated by assuming that 75% of the area assigned to this class is actually a wetland. Similarly, for class 11 it was assumed that 37.5 % and for class 12, 12.5% of its assigned area was assumed to be a wetland. Since there was no further information on the kind of wetland for these categories, their methane emissions have been presumed to be the average of the four wetland classes shown in Figure 4.

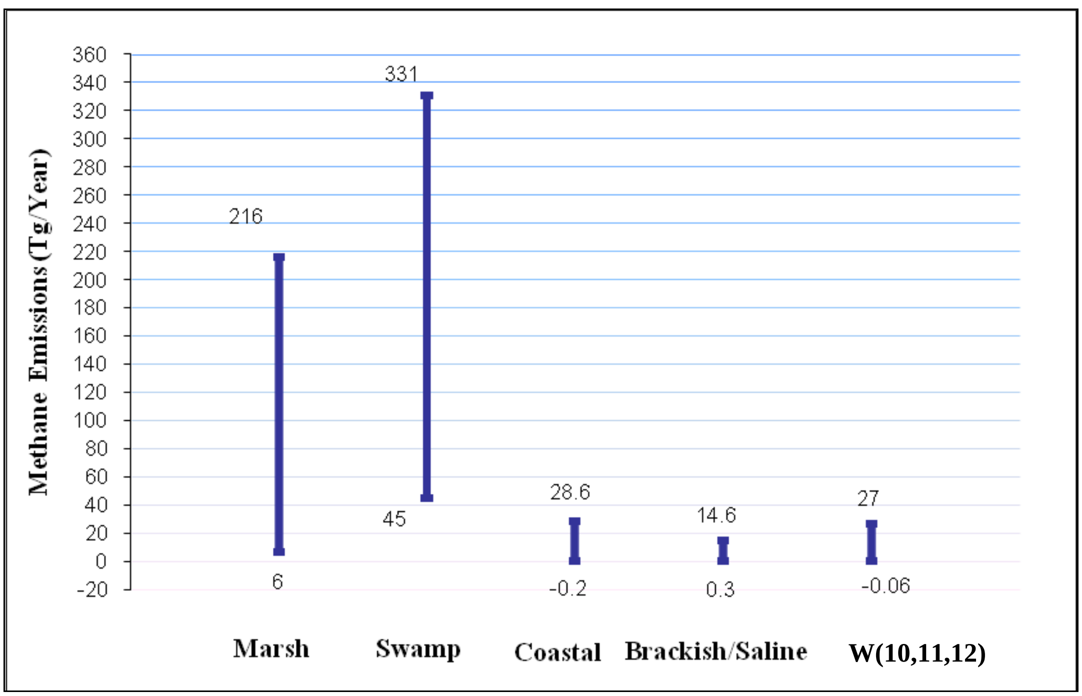


Figure 4: Upscaled methane emissions from wetland categories

Summing the results from these categories, it is found that the total methane emissions from the tropical wetlands (excluding ‘River’, ‘Bog, fen, mire’ and ‘Intermittent wetland/Lake’) lies between 51 and 617 Tg CH_4 per year. The higher values in this range of emissions are an overestimation as compared to the available literature (e.g. see Table 1 above). As seen in Tables 4-7, there seems to be an exceptionally high value for each wetland type. After removing the exceptionally high values from each of the marsh, swamp and coastal categories, the higher range estimated for tropical wetland methane emissions only for these four categories drops to approximately 177 Tg CH_4 per year. Adding emissions from wetland classes 10, 11 and 12, (-0.06 to 6.43 Tg CH_4 per year after once again calculating their emissions using the values from the main categories excluding exceptionally high values) gives the total methane emissions from the tropical wetlands to be around 51 to 183 Tg CH_4 per year. This range is largely consistent with the values reported in section 2.4 above, though the higher range is still perhaps an overestimation, given that total, global methane emissions from wetlands range between 100 and 231 Tg CH_4 per year (Table 1).

4.3 Pilot testing of LPJ-GUESS WHyMe for chosen sites

The pilot testing sites were chosen for these wetland classes (i.e. Fresh water Marsh, Floodplain (wetland class 4), Swamp Forest, Flooded Forest (wetland class 5), Coastal wetland class (wetland class 6) and Pan, Brackish/Saline wetland class (wetland class 7). The Earth site in Costa Rica was chosen for the marsh category (see Table 4), the La Selva site in Costa Rica was chosen for the swamp category (see Table 5) and Pichavaram Mangroves on the south-east coast of India was selected for the coastal and saline categories (see Table 6 & 7). These sites were selected to represent respective wetland types. The same site was chosen for the coastal and saline category as these sites possessed similar vegetation and several other overlapping characteristics. The specific choice of these sites over others for each wetland class is purely based on the amount of information available for them. The pilot testing for Panama site (wetland site) in the tropics was also carried out using the information from Walter and Heimann (2000).

Before performing pilot testing of the methane emissions for the sites, environmental variables of the sites such as temperature and precipitation were compared with that of the CRU dataset used to drive the LPJ-GUESS model. Comparison was carried out for the two sites i.e. Earth and La Selva, representing the marsh and swamp categories, respectively. Values for the environmental variables for these two sites were taken from Nahlik & Mitsch (2010).

Table 8: A comparison of environmental variables in the field to those used to drive the model for the Earth site in Costa Rica

Variables	Field observation (Nahlik and Mitsch 2010)	CRU data
Mean Annual Air Temperature (degree centigrade)	Shallow wetland: 29.1+-0.6 Deep wetland: 27.9+-0.4	24.12 (1999-2006 average)
Mean Annual Precipitation (mm/year)	3463+-731 (Given as mean 10 year annual rainfall in mm/yr)	4277.20 (1999-2006 average)

Table 9: A comparison of environmental variables in the field to those used to drive the model for the La Selva site in Costa Rica

Variables	Field observation (Nahlik and Mitsch 2010)	CRU data
Mean Annual Air Temperature (degree centigrade)	Shallow wetland: 25.5+-0.2 Deep wetland: 25.7+-0.2	22.7 (1999-2006 average)
Mean Annual Precipitation (mm/year)	4639+-618 (Given as mean 10 year annual rainfall in mm/yr)	3774 (1999-2006 average)

Tables 8 and 9 confirm that the mean annual values for temperature and rainfall in LPJ-GUESS WHyMe were reasonable for the sites to be pilot tested. Hence, pilot testing for simulations were carried out for the methane emissions.

4.3.1 Earth Site, Costa Rica

This wetland site falls in 10º13′0″ N, 83º34′16″ W with a tropical humid climate having a size of 116 ha with an average 10-year annual rainfall of 3463 ± 731 $mmyr^{-1}$ and within a restored humid forest landscape (Refer Table 4).

Simulation of the methane emissions from LPJ-GUESS WHyMe model with varying vegetation types included as well as with varying vegetation characteristics was carried out. The resulting environmental variables such as soil temperature and water table position are shown in Figures 5 and 6 below.

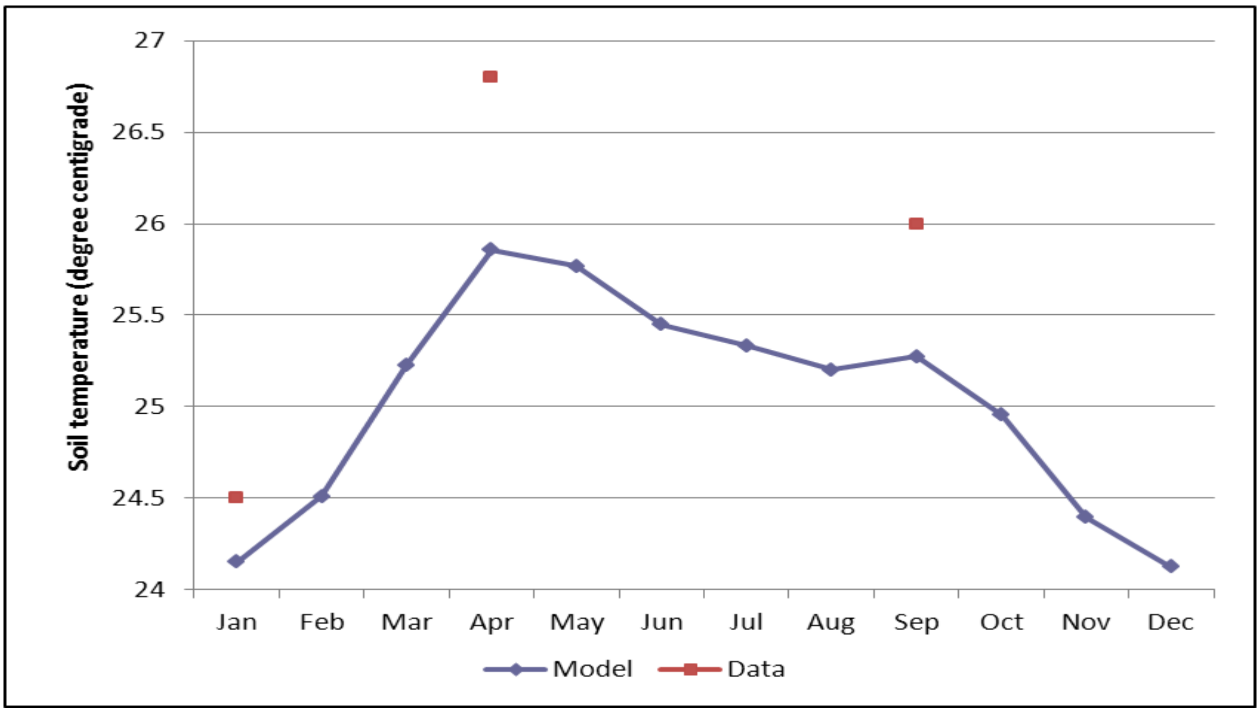


Figure 5: Comparison between modelled and observed soil temperature (degree centigrade) for the Earth site. The model results are monthly averages for seven years (2000-2006) for the soil temperature at 25 cm depth. The observed data (Nahlik and Mitsch 2010) shows the average temperature of the soil at 5 cm depth.

On comparison with the observed field data for the year 2007 from Nahlik and Mitsch (2010), it is seen that the simulated values as shown in the Figure 5 show a similar pattern of rising from January onwards towards the month of April. April is the month with the highest soil temperature after which the temperature starts declining. Even the values simulated as shown in the Figure 5 are quite close to the field observations, which have a mean value of about 25.6 degree centigrade for the shallow areas of wetland and around 25.1 degree centigrade for the deeper parts of the wetland. The slight underestimation of monthly temperatures could be due to the different depths considered and/or the fact that the air temperature forcing data from CRU is slighly lower than the values observed at the site (Table 8).

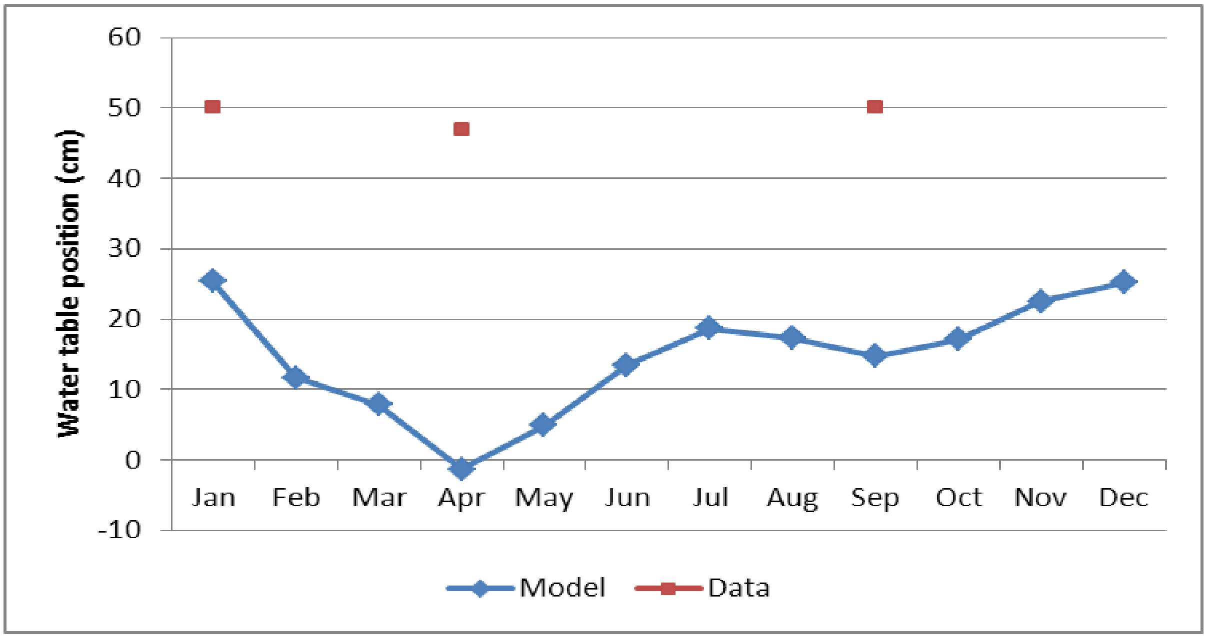


Figure 6: Comparison between modelled and observed water table position (cm) for the Earth site. The model shows a monthly average for seven years (2000-2006) for the water table position. Observational data (Nahlik and Mitsch 2010) shows the mean values.

On comparison with the observations carried out for the year 2007 in the study from Nahlik & Mitsch (2010), the simulated water table position seems to be underestimated for this site. However, a similar pattern of decline from January onwards towards the month of April and then a rise from April onwards was observed in 2007. The study reports the mean water depth for the Earth site to be around 50 cm above the surface. The rate of change of water table position is entirely different as the field data shows a change of around 2 to 3 cm from January to April and to September whereas the model simulates the water table position declining directly from around 25 cm to below soil surface in April and then again rising by about 19 cm beyond which it further declines towards the month of August.

4.3.1.1 Simulated methane emissions for the Earth site

Since we did not have information regarding the tree coverage on the Earth site, methane emissions were simulated for three different conditions with regard to the treatment of the trees in LPJ-GUESS WHyMe. The first condition had no trees at the site modelled whereas the second had few trees, which were modelled by setting the maximum establishment rate (Estmax) for tropical trees to be 0.01 individuals m^{-2} $year^{-1}$. In the third simulation, tree establishment was further increased to 0.05 individuals m^{-2} $year^{-1}$. In the second and third condition for modelling, the maximum water table position tolerance (WTPmax) for the trees was kept to 100 mm, above which the trees were assumed to suffer from anoxia, with reduced photosynthesis as a result (Wania et al 2009 b). Grasses were in all the cases for every pilot testing site were assumed to tolerate water table positions up to 500 mm above the soil surface. Methane emissions were simulated in varying conditions as mentioned above to find out the effect of vegetation dynamics and composition on the emissions. As a complement to the LPJ-GUESS WHyMe pilot testing simulations, the methane emissions were also estimated in a simple manner by using the heterotrophic respiration output by LPJ-GUESS v2.1 (Refer 3.11).

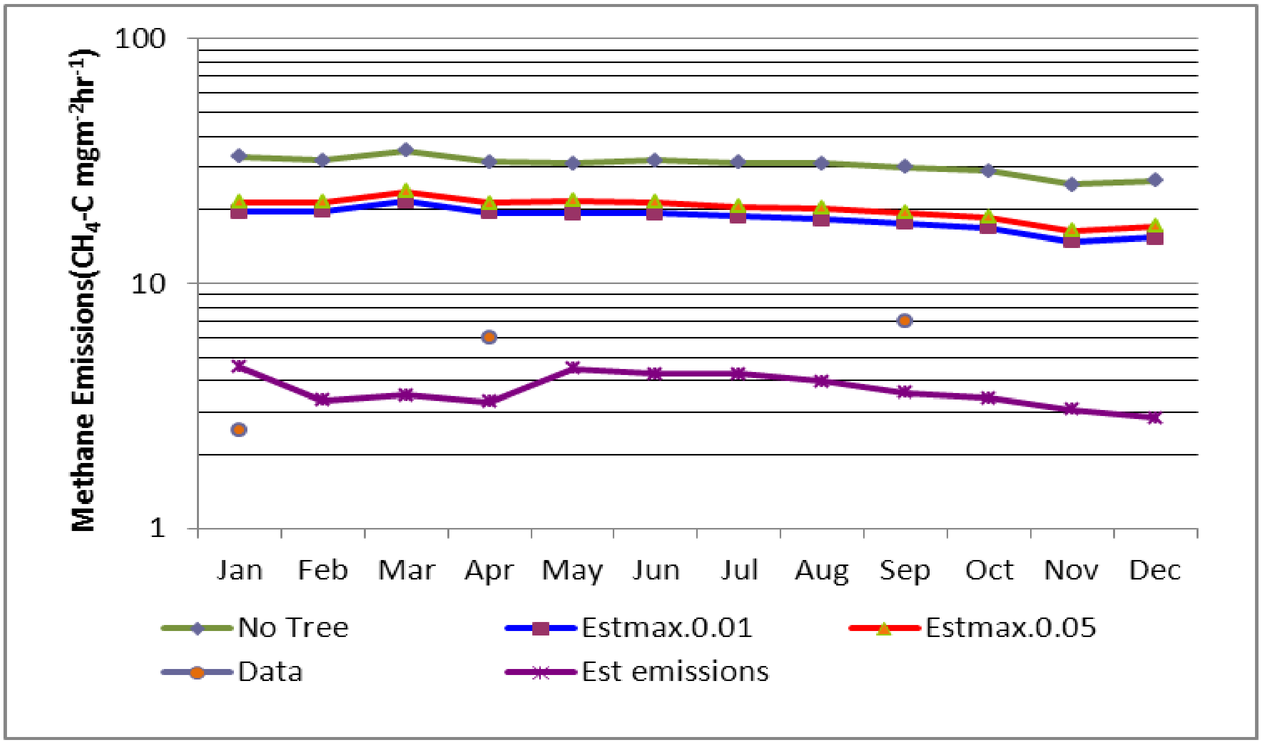


Figure 7: Comparison between modelled methane emissions (LPJ-GUESS WHyMe) with varying vegetation compositions and model configurations along with the observed data (Nahlik and Mitsch 2010) for the Earth site. No tree, max establishment rate 0.01 individuals $m^{-2}year^{-1}$ and 0.05 individuals $m^{-2}year^{-1}$ (Estmax.0.01 and Estmax.0.05) are varying scenarios of simulations which show monthly average for seven years (2000-2006) for the methane emissions (Methane emissions are reported on a log scale in CH_4-C mg $m^{-2}hr^{-1}$ for the purpose of comparison with field data). Est emissions are the methane emissions estimated from modelled heterotrophic respiration output from LPJ-GUESS v2.1.

A comparison of simulated methane emissions has been carried out with the observations for the various months for the year 2007 from the Nahlik and Mitsch (2010) study. Field observations show rising emissions through the year. Simulated emissions rise until March from where it starts declining. The model did not capture the spike in emissions during high precipitation months (July and November for year 2007) as mentioned in the study. The model also did not capture the negative methane emissions represented for the Earth site in the study indicating methane oxidation. Also, the values simulated for methane emissions are very high as compared to the range of around 2 to 8 CH_4-C $mgm^{-2}hr^{-1}$ reported in the study. However, estimated emission values using heterotrophic respiration (Est emissions) are quite close to the observed data values (See discussion for details).

Table 10. Yearly methane emissions simulated from LPJ- GUESS WHyMe in $gCH_4m^{-2}yr^{-1}$ for the Earth site

Years	No trees	Maximum establishment rate for trees (Est max) 0.01 individuals m^{-2} $year^{-1}$	Maximum establishment rate for trees (Est max) 0.05 individuals m^{-2} $year^{-1}$
2000	333	171	228
2001	369	187	261
2002	338	185	218
2003	358	273	231
2004	369	238	228
2005	347	214	235
2006	346	220	240
Average	351	212	235

Note-The study has used $gCH_4m^{-2}yr^{-1}$ and Tg CH_4 per year units throughout. Different units at other places have been used for the purpose of comparison with field data.

The annual estimation from the study, Nahlik and Mitsch (2010) carried out over a 29 month period from 2006 to 2009 mentions the yearly value of methane emissions to be 44 $gCH_4m^{-2}yr^{-1}$ whereas the modelled scenarios are much higher (Table 10). Methane in the no tree simulation is highest as this scenario has the biggest litter pool as well as the fast soil carbon pool, both of which form potential carbon pool for methanogens. The dominant herbaceous vegetation (represented as grasses in the model), being more productive, had higher NPP which leads to more litter, and hence more substrate or potential carbon for methanogens. The highest litter pool also leads to the largest fast soil carbon pool as compared to the other two scenarios. The no tree simulation had most of the carbon in soil as compared to the vegetation whereas in the simulations with trees there was a lot more carbon in vegetation, and less in the soil. The scenario with maximum establishment rate of 0.05 individuals m^{-2} $year^{-1}$ has slightly higher methane emissions than the scenario with maximum establishment rate of 0.01 individuals m^{-2} $year^{-1}$ as the scenario with more trees has slightly higher NPP, which then leads to slightly higher methane emissions due to greater root exudates, and leaf turnover.

4.3.2 La Selva, Costa Rica

This wetland site falls in 10º25′49″N, 84º0′37″W with a tropical wet climate having a size of 3 ha with an average 10-year annual rainfall of 4639 ± 618 mmyr^{-1} and within a primary rainforest landscape (Refer Table 5).

Similarly, pilot testing of this site was also carried out from LPJ-GUESS WHyMe model with varying vegetation composition as well as with varying vegetation characteristics. The resulting environmental variables such as soil temperature and water table position are shown in Figures 8 and 9 below.

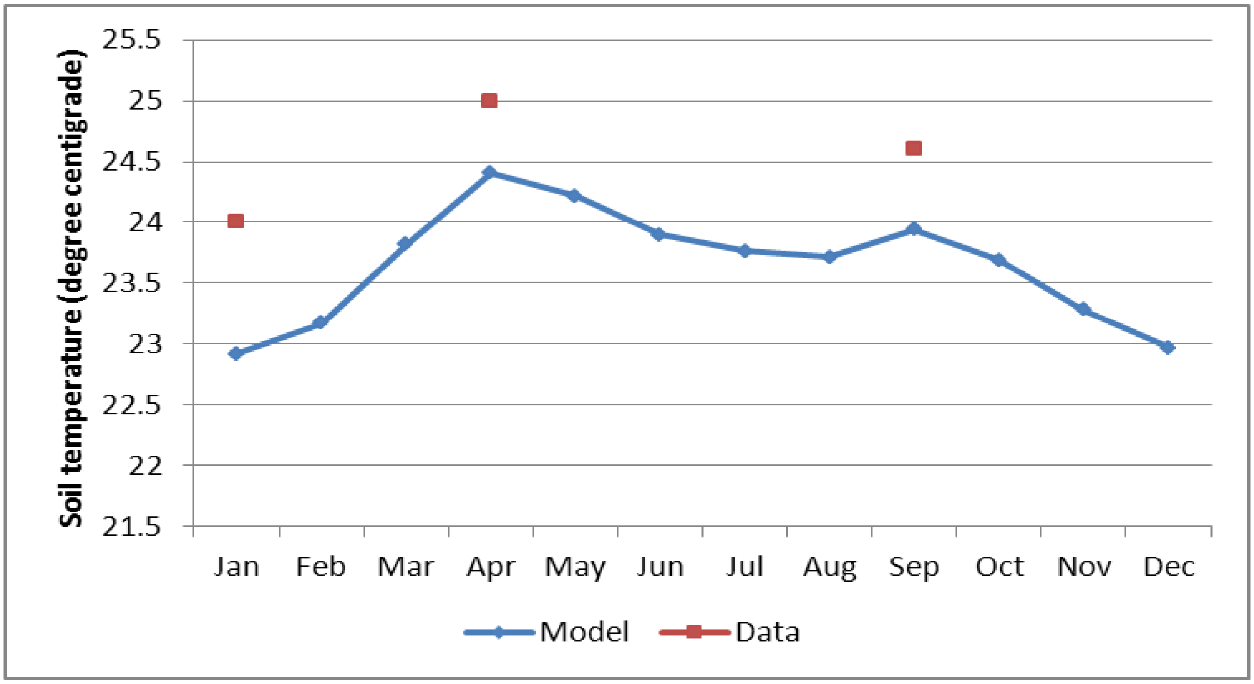


Figure 8: Comparison between modelled and observed soil temperature (degree centigrade) for the La Selva site. The model shows monthly averages for seven years (2000-2006) for the soil temperature at 25 cm depth. Observational data (Nahlik and Mitsch 2010) shows the average temperature of the soil at 5 cm depth.

Field data of soil temperature at 5cm (degree C) show an increasing trend from January until April and a decrease towards September from April onwards (Field data is available for January, April and September months only). The modelled soil temperatures compare well to the data from the study by Nahlik and Mitsch (2010). Study reports the mean soil temperature at 5 cm to be around 24.5 degree C for the shallow part of wetland and 25 degree C for the deep part of the wetland and soil temperature at 10 cm to be around 24.5 degree C in the shallow part and 24.9 in the deep part of the wetland (their study divided the site into various transects).

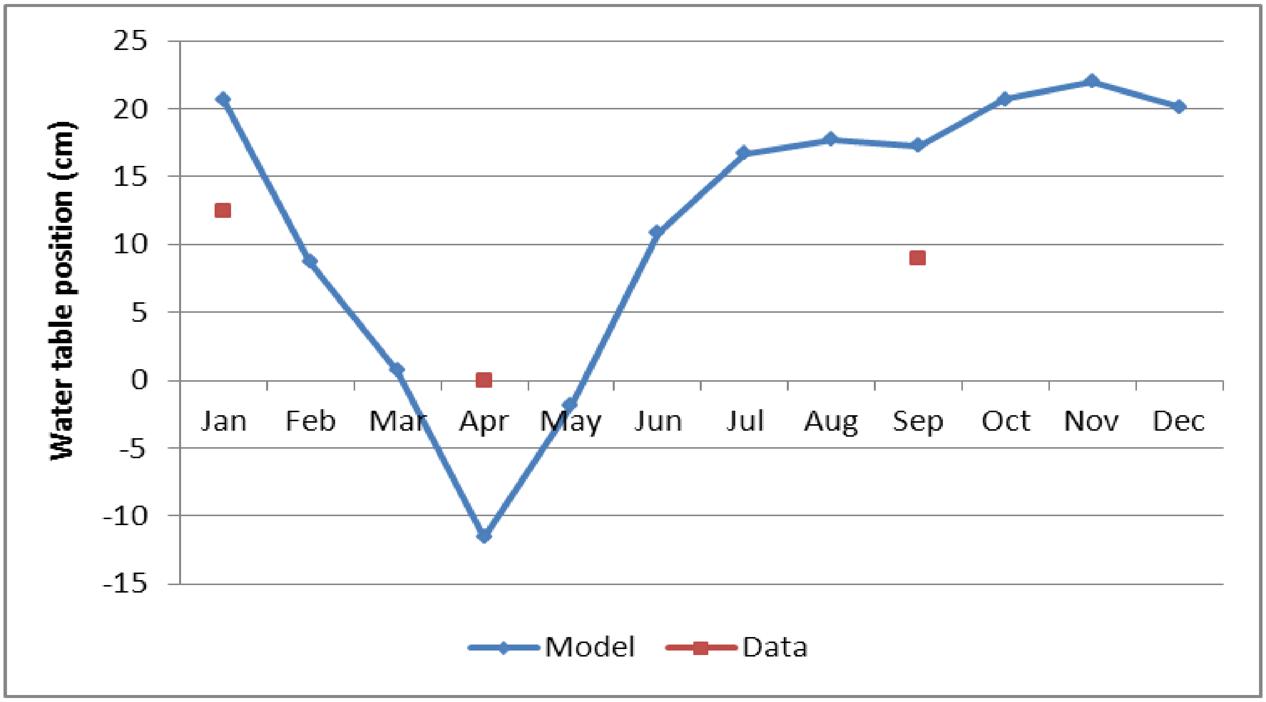


Figure 9: Comparison between modelled and observed water table position (cm) for the La Selva site. Model shows monthly average for seven years (2000-2006) for the water table position. Observational data (Nahlik and Mitsch 2010) shows the mean values.

A similar pattern is observed on comparison with the water table observations from the site for the year 2007 reported by Nahlik and Mitsch (2010). Water levels decrease from January towards April and then rise again towards the month of September (Field data is available only for January, April and September months). The mean water level reaches 0 cm during the month of April in the field data (i.e. at the surface) whereas the model simulates the water table position to be below the surface i.e. around 12 cm below. This period with the lowest water table position occurs when the soil temperature reaches to its highest value at 25 cm depth (Figure 8) indicating drying up of the water during the hottest month. Average water depth values for the 29 month sampling period from 2006 to 2009 for this site was around 9 cm for the shallow part of wetland and 20 cm for the deep part of wetland.

4.3.2.1 Simulated Methane emissions for the La Selva site

Modelling of methane emissions for this site was performed for four different scenarios to examine the sensitivity of the methane emissions due to the type of vegetation (trees, C_3 and C_4

grasses) in the wetland site, as well as due to the property of water tolerance capacity in inundation conditions for the vegetation.

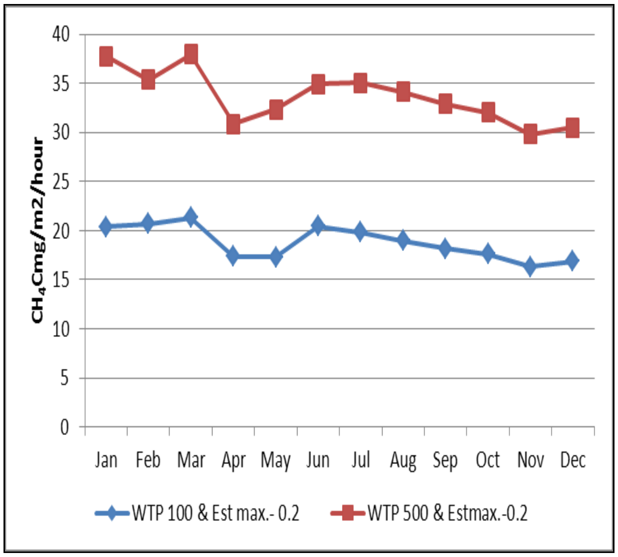


Figure 10: Methane emissions for varying vegetation property

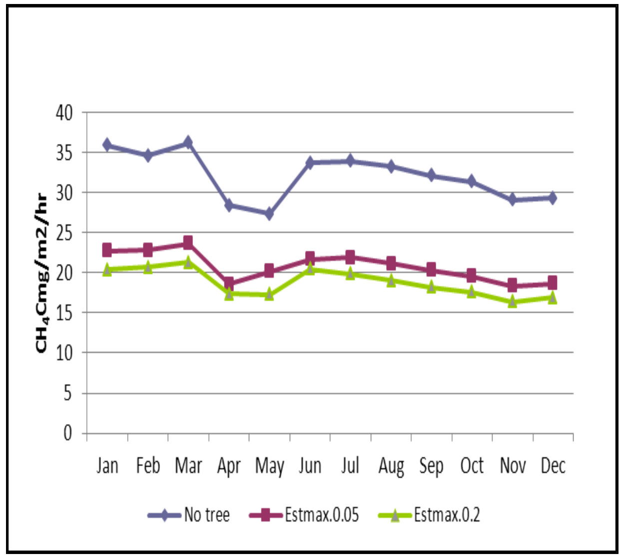


Figure 11: Methane emissions for varying vegetation composition

Figures 10 and 11 above shows the emissions as monthly averages of seven years (2000-2006) simulated by LPJ-GUESS WHyMe. Figure 10 illustrates the emissions at different water tolerance capacity in inundation conditions of vegetation i.e. at 100 mm and 500 mm when establishment rate of trees is 0.2 individuals m^{-2} yr^{-1}. Figure 11 demonstrates varying emissions in three different vegetation scenarios, namely those without trees and with trees having maximum establishment rates of 0.2 (Estmax 0.2) and 0.05 (Estmax 0.05) individuals m^{-2} $year^{-1}$. Clearly, both vegetation characteristic and vegetation composition influences the emissions of methane gas from the site. NPP and hence methane emissions increase when the vegetation is more tolerant of inundation (Figure 10), whereas having vegetation with higher NPP and faster turnover also tends to increase emissions (Figure 11).

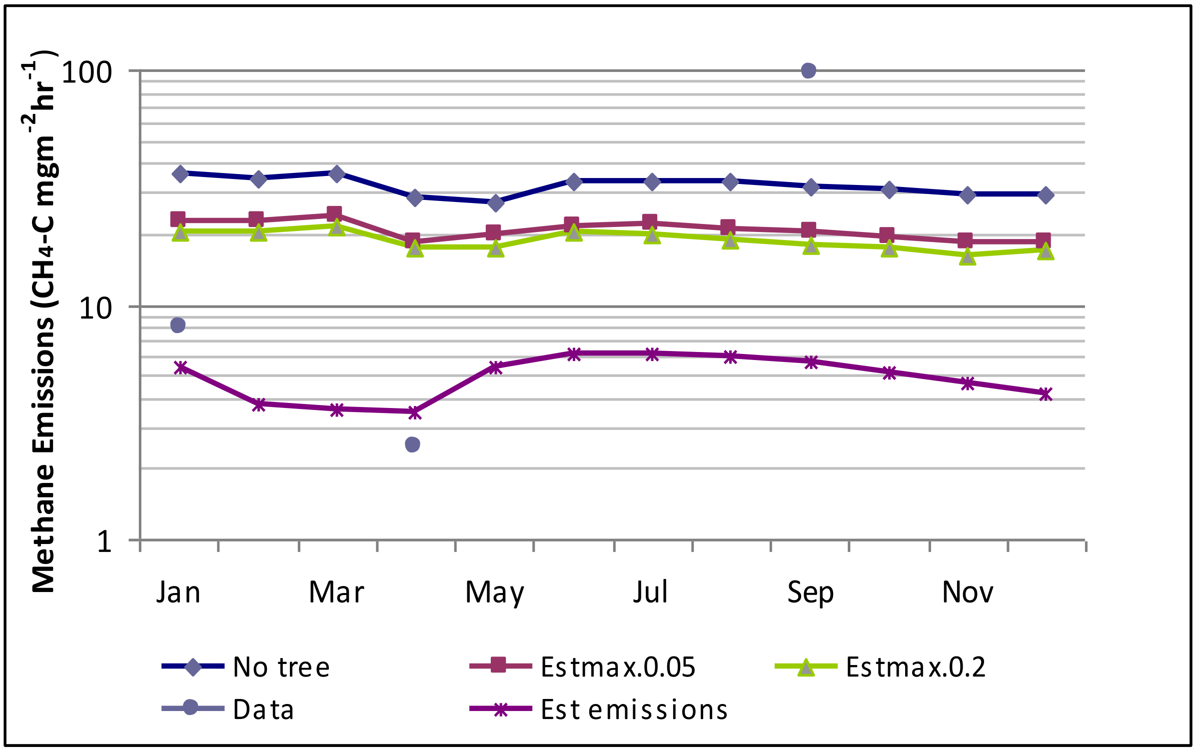


Figure 12: Comparison between modelled methane emissions (LPJ-GUESS WHy Me) with varying vegetation composition and observed data (Nahlik and Mitsch 2010) for mean methane emissions for the La Selva site. No tree, max establishment rate 0.2 (Estmax 0.2) and 0.05 (Estmax 0.05) are varying scenarios of simulations which shows monthly average for seven years (2000-2006) for the methane emissions (Methane emissions are reported on a log scale in CH_4-C mg $m^{-2}hr^{-1}$ for the purpose of comparison with field data). Est emissions are the methane emissions estimated from modelled heterotrophic respiration output from LPJ-GUESS v 2.1.

On comparison of seven yearly averages for each month (simulations from LPJ-GUESS WHyMe) and observations of mean methane emissions for the year 2007 from the study performed by Nahlik and Mitsch (2010), it is seen that the study shows average methane emissions to be decreasing from January until April and then they rise again from April until September. September shows the highest emissions of methane carbon in the field observations (Field data is available for January, April and September only). The model simulations though show decreasing emissions from January to April but do not capture the higher value of methane emissions in September. The study reports that average methane emissions in the field ranged from -2.8 to 297 mg CH_4-$Cm^{-2}h^{-1}$ at the La Selva site but the model did not capture the negative values of methane emission as mentioned in the study. Estimated methane emission values (Est emissions) seem to be close to the observed data for the first half (around four months) of the year.

Table 11. Yearly methane emissions simulated by LPJ-GUESS WHy Me in $gCH_4\ m^{-2}yr^{-1}$ for the La Selva site, with differing inundation tolerances in modelled vegetation.

Years	Estmax 0.2 and WTPmax: 500mm	Estmax 0.2 and WTPmax: 100mm
2000	246	189
2001	380	212
2002	555	226
2003	472	224
2004	388	201
2005	340	210
2006	331	252
Average	**387**	**216**

It is seen in Table 11 that methane emissions are higher for the scenario with trees having higher water tolerance capacity in inundation conditions i.e. in this case 500 mm as compared to 100 mm. This is due to the fact that trees having a lower tolerance to flooding (eg.WTP max = 100 mm) suffer anoxia early which restricts their photosynthesis and thus their productivity, whereas the trees with higher water tolerance capacity have higher productivity. Higher productivity leads eventually to a bigger carbon pool for methanogens, which leads to more methane emissions.

Table 12. Yearly methane emissions simulated by LPJ GUESS WHy Me in $gCH_4m^{-2}\ yr^{-1}$ for the La Selva site with different establishment rates of trees.

Years	**No Tree**	**Estmax 0.05 and WTPmax: 100mm**	**Estmax 0.2 and WTPmax: 100mm**
2000	346	253	189
2001	369	260	212
2002	359	221	226
2003	389	243	224
2004	375	224	201
2005	380	219	210
2006	370	256	252
Average	**370**	**239**	**216**

The highest methane emissions in the no tree scenario have been observed as compared to scenarios with trees having different establishment rates of individuals. This follows the same reasoning as given above for the Earth site (Refer 4.3.1.1). The scenario with trees having a higher establishment rate of individuals, Est max.0.2 (0.2 individuals $m^{-2}year^{-1}$) has, however, slightly less emissions as compared to the other scenario of trees i.e. Est max. 0.05 (0.05 individuals $m^{-2}year^{-1}$) (Table 12) due to the slightly lower total NPP when Est max. is 0.2. This is partly due to the lowered NPP of C_4 grasses, due to the increased competition and shading by trees when trees establish in greater numbers. The reduction in C_4 grasses both reduces the annual carbon input for methanogens, and restricts the possibility for plant-mediated transport through the aerenchyma of C_4 grasses (Wania et al 2009 b). The study by Nahlik and Mitsch (2010) estimate annual methane emissions from measurements carried over a 29 month period from 2006 to 2009 to be 293 g $CH_4\ m^{-2}\ yr^{-1}$.

4.3.3 Panama site

This site is situated in Central Panama (81 degrees West and 8 degrees North) having a swamp type of wetland. The dominant vegetation of the site is *Raphia taedigera* (palm) and the annual mean temperature of the site is 27ºC (Keller 1990; Walter and Heimann 2000).

Pilot testing of this wetland site in simulating methane emissions was also carried out from LPJ-GUESS WHyMe model with varying vegetation composition. The resulting environmental variable such as water table position is shown in Figure 13 below.

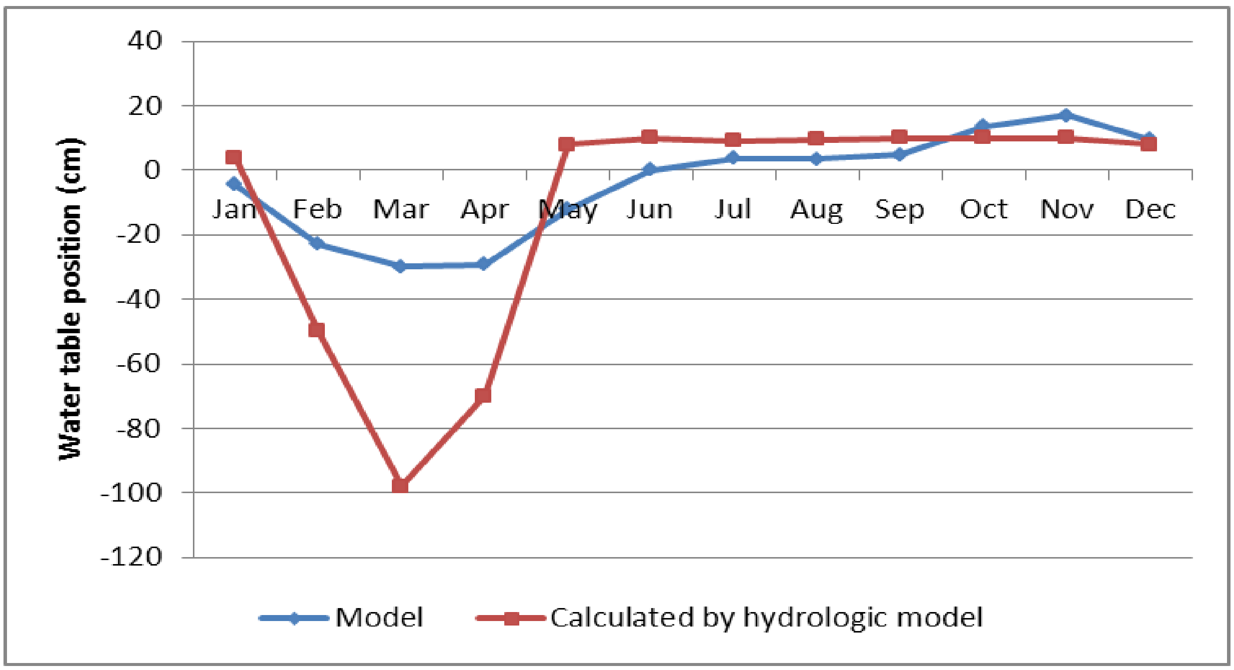


Figure 13: Comparison between modelled LPJ-GUESS WHyMe and calculated hydrologic model water table position (cm). LPJ-GUESS WHyMe shows monthly averages for seven years (2000-2006) for the water table position. Values for the calculated hydrologic model water table position have been plotted approximately by manually measuring the values from Walter and Heimann (2000), (their Figure 7.b, page no. 757). Values have been measured and plotted for the middle of the month assuming that it applies to the whole month.

Due to the absence of field data, the simulated water table level by LPJ-GUESS WHyMe has been compared with calculated water table level by a hydrologic model (Walter 1998) which is driven by the ECHAM4 model (Roeckner et al 1996) as described in Walter and Heimann (2000). On comparison, it is seen that simulated water table position by LPJ-GUESS WHyMe follows the similar pattern of moving below 0 cm for the months of January, February and March and then rising again from March onwards. Even the pattern of moving downwards during the month of December (as seen in Walter and Heimann (2000), Figure 7b) has also been captured in the LPJ-GUESS WHyMe simulation. There are differences, such as the peak in the months of October and November in the LPJ-GUESS WHyMe simulation. The water table position calculated by hydrologic model reaches above 0 cm (i.e. the soil surface) in May as compared to the LPJ-GUESS WHyMe simulation which goes above 0 cm in June. However, though, the pattern is similar, the water table position as calculated by the hydrologic model falls as low as around 100 cm below the soil surface. LPJ-GUESS WHyMe simulates its lowest values of around 30 cm below the soil surface during the same period. This limit is due to the restrictions of the existing wetland hydrology scheme (Wania et al 2009 a), where the water table is not allowed to exceed a depth of 30cm below the surface.

4.3.3.1 Simulated Methane emissions for the Panama site

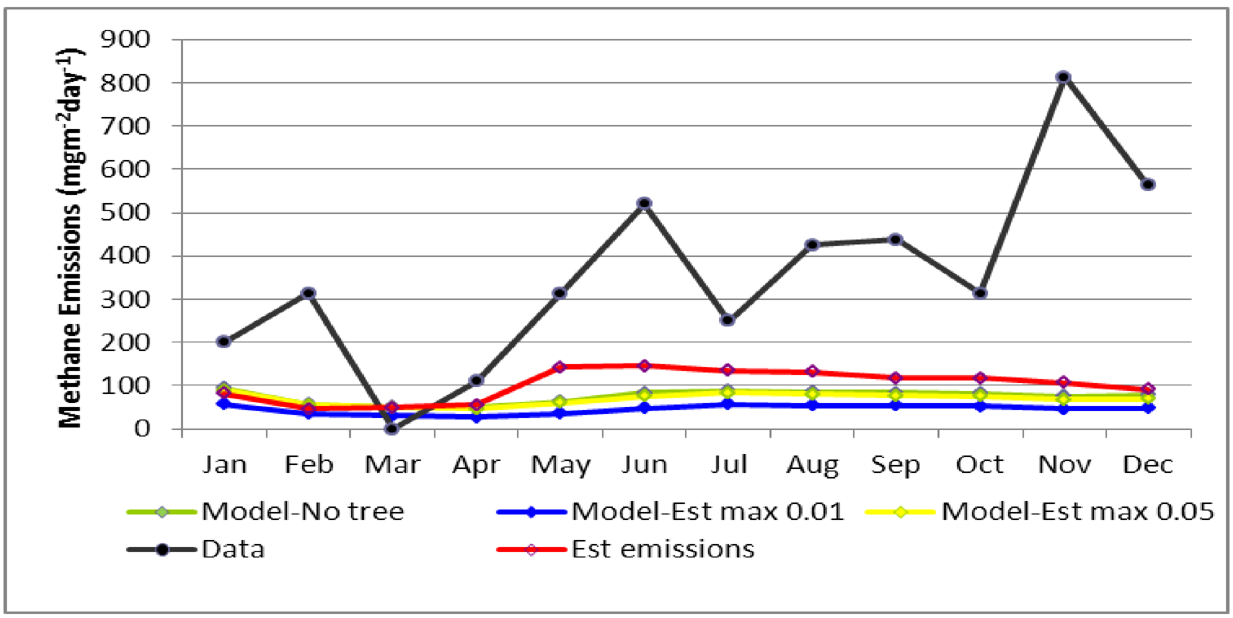


Figure 14: Comparison between modelled LPJ-GUESS WHyMe methane emissions with varying vegetation composition and observed data for methane emissions for Panama site. No tree, max establishment rate 0.01 and 0.05 are varying scenarios of simulations which show monthly averages for seven years (2000-2006) for the methane emissions. Values for the observed data have been plotted approximately by manually measuring the values from Walter and Heimann (2000), (their Figure 7.a, page no. 757). Est emissions are the methane emissions estimated from modelled heterotrophic respiration output from LPJ-GUESS v 2.1.

Analysing the LPJ-GUESS WHyMe methane emissions along with the observed emissions from Keller (1990) as shown in Walter and Heimann (2000), it is seen that LPJ-GUESS WHyMe simulates a release of methane even during the month of March when the observed dataset from Keller (1990) shows no release. The relatively high water table position simulated in LPJ-GUESS WHyMe for that month (Figure 13) seems to be the reason for the methane emissions even during that month. It is also observed that LPJ-GUESS WHyMe simulates lower methane values than the observational data from Keller (1990). On comparison, estimated methane emissions are also lower than the observed data. This site seems to have contradicting results as compared to the other sites (Figure 14) and an additional dataset is required for this site to further test it.

4.3.4 Pichavaram Mangroves

The Pichavaram mangroves lie on the south-east coast of India (11º27′N,79º47′E) having an area of around 1400 ha. The vegetation of the site comprises majorly of *Rhizophora*, *Avicennia*, *Bruguiera*, *Ceriops*, *Salicornia* and *Excoecaria* species. The annual average rainfall for the site is reported to be 96.60 mm (Purvaja and Ramesh 2000).

Pilot testing of this wetland site in simulating methane emissions was also carried out from LPJ-GUESS WHyMe model. The resulting environmental variables such as soil temperature and water table position are shown in Figures 15 and 16 below.

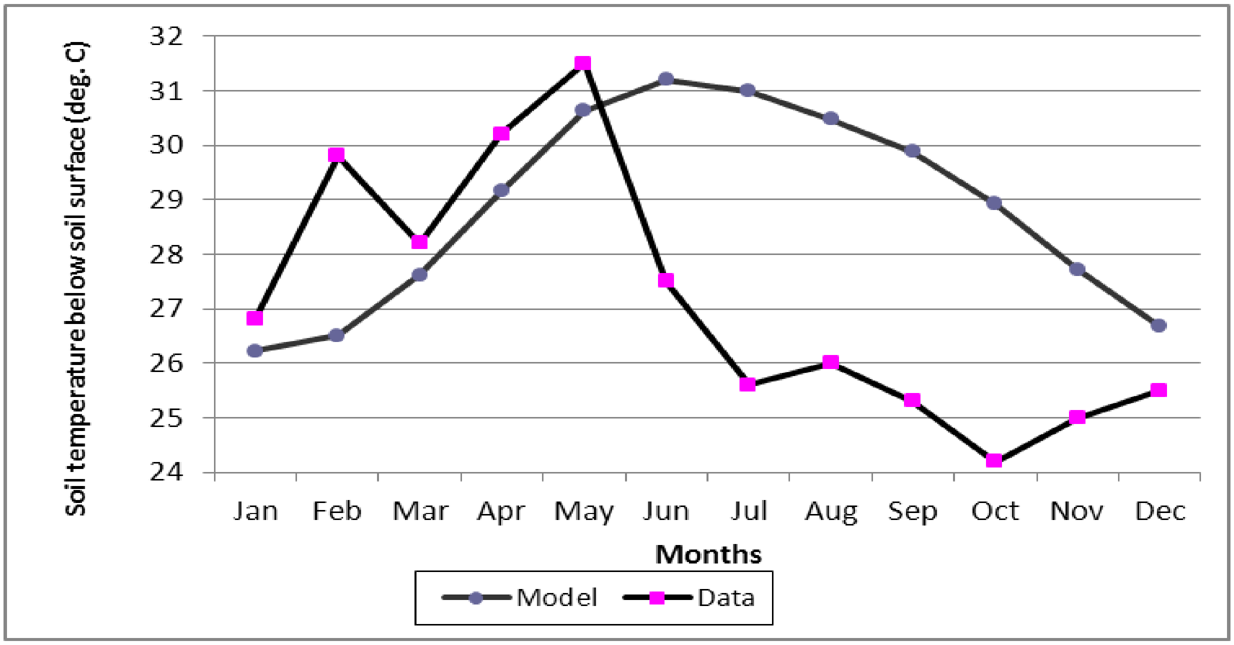


Figure 15: Comparison between modelled and observed soil temperature (degree centigrade). Model shows a monthly average for seven years for the soil temperature at 25 cm depth. The observed data (Purvaja and Ramesh 2000) shows soil temperature at 10 cm depth for a single day of the respective month and is assumed to apply for the whole month.

Seven year averages from 2000 to 2006 values have been considered for the simulated dataset. The observed dataset is for the year 1996, reported from field as mentioned in the study by Purvaja and Ramesh (2000). Comparing monthly data specifically, there are deviations from observations chiefly around second half of the year which may be due to the fact that values were only reported for one day per month. However, the model's annual average for seven years is 28.84 degree centigrade, which is similar to the annual average reported from field data, which is 27.10 degree centigrade.

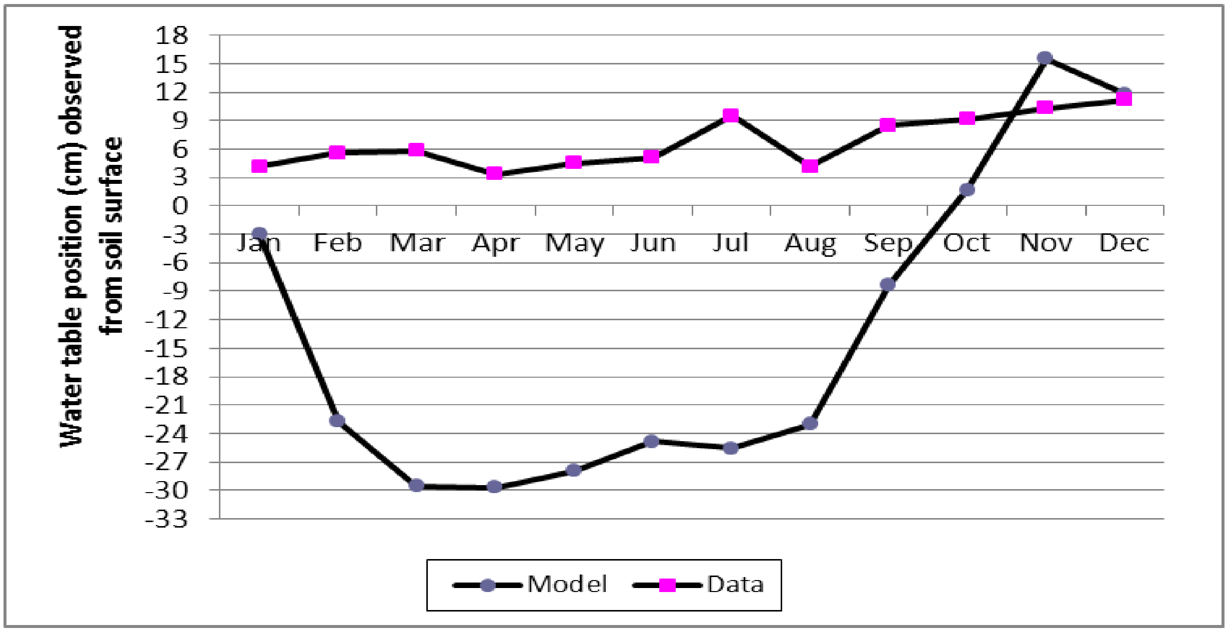


Figure 16: Comparison between modelled and observed water table position (cm). Model shows monthly average for seven years for the water table position. The observed data (Purvaja and Ramesh 2000) shows water table position measured for a single day of the respective month and is assumed to apply for the whole month.

The LPJ-GUESS WHyMe model does not capture the almost constant water table level of this coastal wetland consisting of mangroves. The model shows a water table below the soil surface for most of the year whereas the field observation data (Purvaja and Ramesh 2000) shows the water table above the soil surface throughout the year. This reflects the inability of the model to capture the coastal area's complex hydrology. The average annual value of the water table position reported from the field data is 6.90 cm above the surface.

4.3.4.1 Simulated Methane emissions for the Pichavaram Mangroves

According to the study carried out by Purvaja and Ramesh (2000), the water depth in the area fluctuates, getting as high as 3 to 4 m and as low as 30 to 50 cm with an average level of 1.56 m. However, the dataset for 1996 in this study shows an average water level of 6.90 cm (Figure 16). Nevertheless, this clearly indicates that the vegetation of this site is able to tolerate the flooding conditions of such high water levels. Simulations were therefore run with all vegetation being able to tolerate water levels (WTPmax) up to 500 mm above the surface and is shade intolerant in nature (There was not enough information regarding the shade tolerance property of mangroves present on the site).

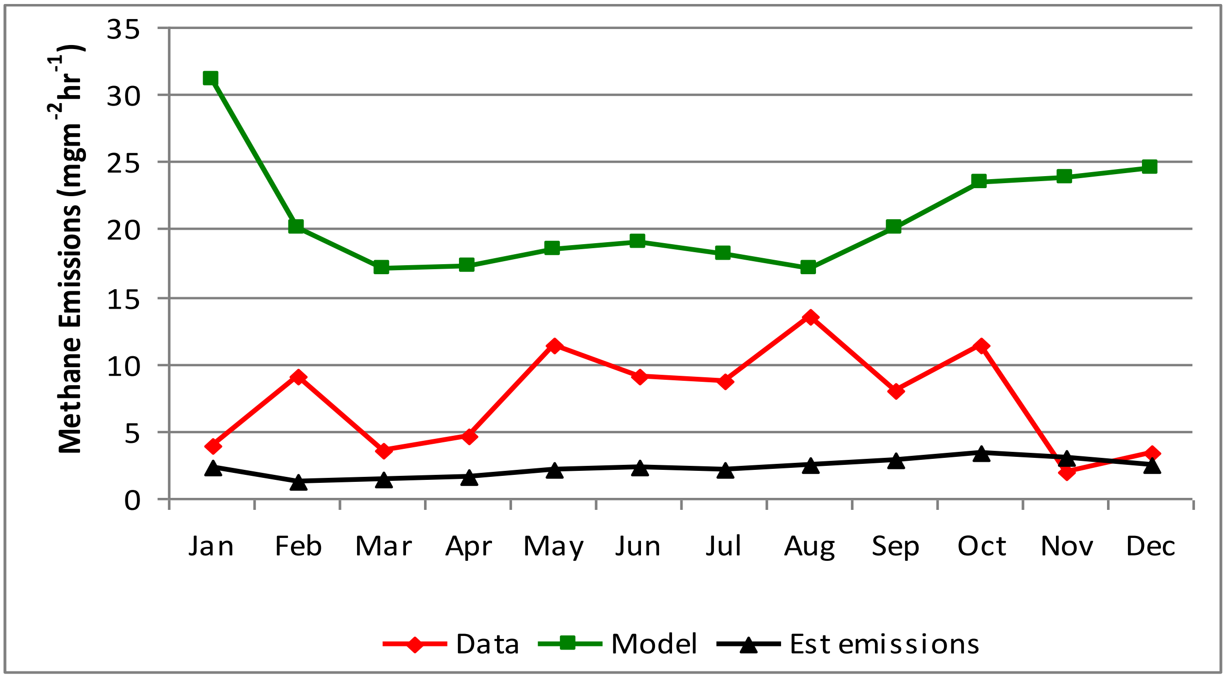


Figure 17: Comparison between modelled (LPJ-GUESS WHyMe) and observed (Purvaja and Ramesh 2000) methane emissions for Pichavaram Mangroves. The model shows monthly average for seven years whereas the observational data shows emissions measured for a single day of the respective month and is assumed to apply for the whole month. Methane emission units are converted to mgm^{-2} hr^{-1} for the purpose of comparison with the field data. Est emissions are the methane emissions estimated from modelled heterotrophic respiration output from LPJ-GUESS v 2.1.

The LPJ-GUESS WHyMe simulation for Pichavaram Mangroves was carried out with vegetation having a WTP max of 500mm. On comparison of simulated methane emissions with the field data of 1996 reported in Purvaja and Ramesh (2000), it is clearly seen in the above Figure 17 that there is no similarity in the seasonal trend of methane emissions from the site. Unlike the LPJ-GUESS WHyMe simulations, the estimated emissions from modelled heterotrophic respiration output values lie close to the observed data.

Table 13.Yearly methane emissions simulated by LPJ-GUESS WHyMe for the Pichavaram Mangroves site

Years	**Simulated annual methane emissions ($gCH_4m^{-2}yr^{-1}$)**
2000	190
2001	224
2002	171
2003	168
2004	173
2005	131
2006	206
Average	180

The Purvaja and Ramesh (2000) study gives a range of 44.6-89.7 $gCH_4m^{-2}yr^{-1}$ for the site with lower range of value falling in the high salinity zone whereas the higher range of value being emitted from the intermediate salinity zone (The study had reported the fluxes for the intermediate salinity zone and high salinity zone of the Pichavaram mangroves site). Thus, the simulations from LPJ-GUESS WHyMe reflect that the model is highly overestimating the methane values. The obvious reasons for this may be the inadequate hydrology for the coastal areas as well as the insufficient representation of the required plant functional types for the tropical wetlands.

4.4 LPJ-GUESS WHyMe Simulations for the Tropical Wetlands

Methane emissions were modelled for the tropical wetlands by running the LPJ-GUESS WHyMe model for those grid cells of the CRU datset which fall under the tropical wetland areas of the Lehner and Doll (2004) dataset (excluding 'River', 'Bog, Fen, Mire' and 'Intermittent wetland/lake' classes). Out of the total wetland area for the tropics as mentioned above (Refer 4.2), around 89% of it was considered for this simulation.

Wetland classes were first grouped into two major categories. One category comprised the marsh, floodplain and swamp, flooded forest wetland classes whereas the other category included coastal and pan, brackish/saline wetland classes. Model runs were carried out twice, once for each major category, with the difference being the woody vegetation included in both. For the former, this study includes moderately flood tolerant tropical broadleaved evergreen trees, with WTPmax limits of 100mm, and maximum establishment rates of 0.05 individuals m^{-2} $year^{-1}$ (see Sections 4.3.1 and 4.3.2 above). For the latter, the study includes two flood tolerant tropical broadleaved evergreen PFTs, both with WTPmax limits of 500mm, and differing only in their shade tolerance. All simulations included both C_3 and C_4 flood tolerant grasses. The resulting methane emissions from both the model runs of both the major categories were then combined. The emissions for the wetland classes 10, 11 and 12 were assumed to be the average of the emissions of both the major categories used in this tropical simulation.

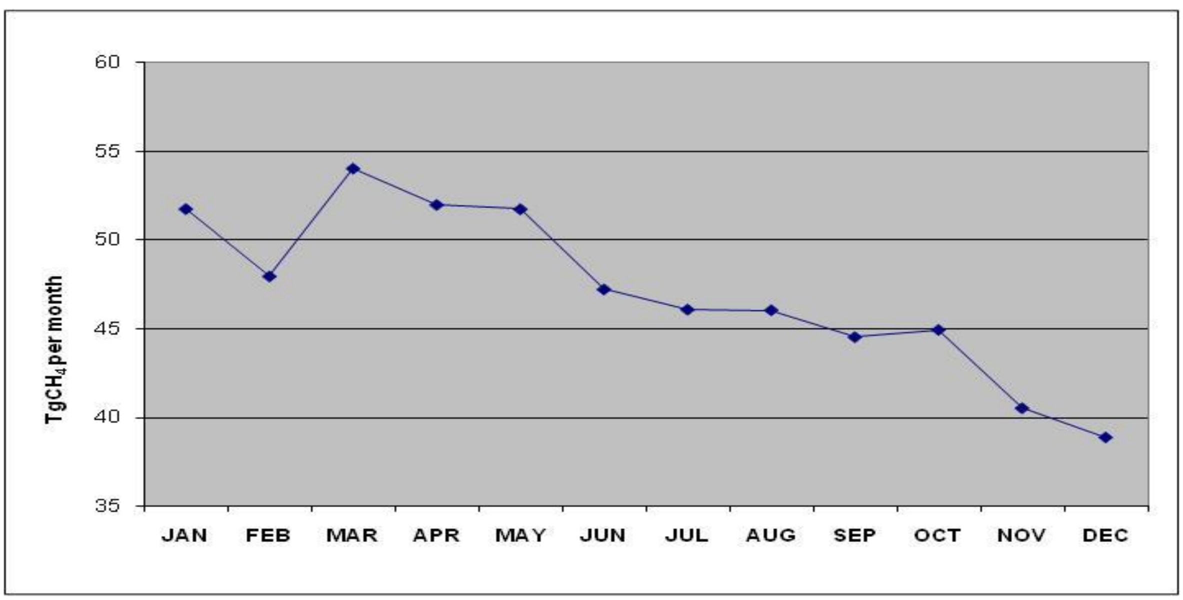


Figure 18: Simulated results for monthly average methane emissions (17 years) for the tropical wetlands

On simulating for the wetlands in the tropics, March and April were found to be the months with the highest methane emissions (see Figure 18). This simulation represents the emissions from all wetlands present in the tropics according to GLWD-Level 3 dataset of Lehner and Doll (2004) excluding 'River', 'Bog, Fen, Mire' and 'Intermittent wetland/lake' classes. The combined, simulated yearly emissions for the tropical wetlands considering the mentioned wetland classes is 566 Tg CH_4 per year. This value is similar to the upper range of values estimated in the simple upscaling exercise, before exceptional field observations were excluded, and represents a considerable overestimation of tropical wetland methane emissions.

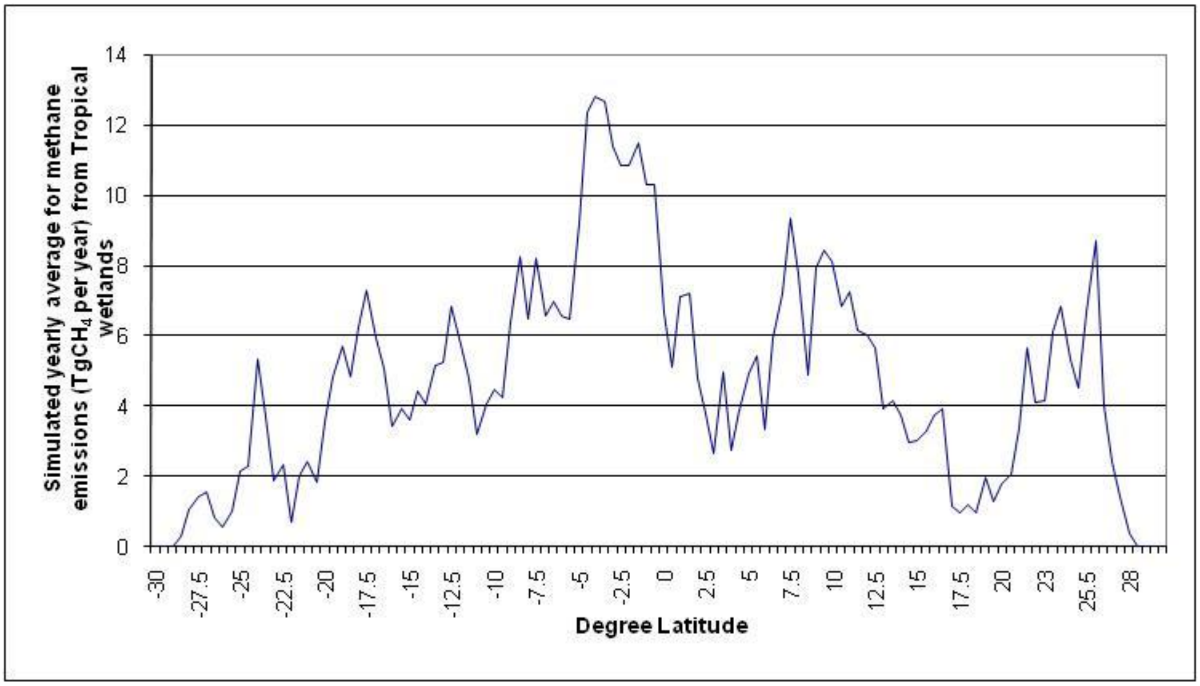
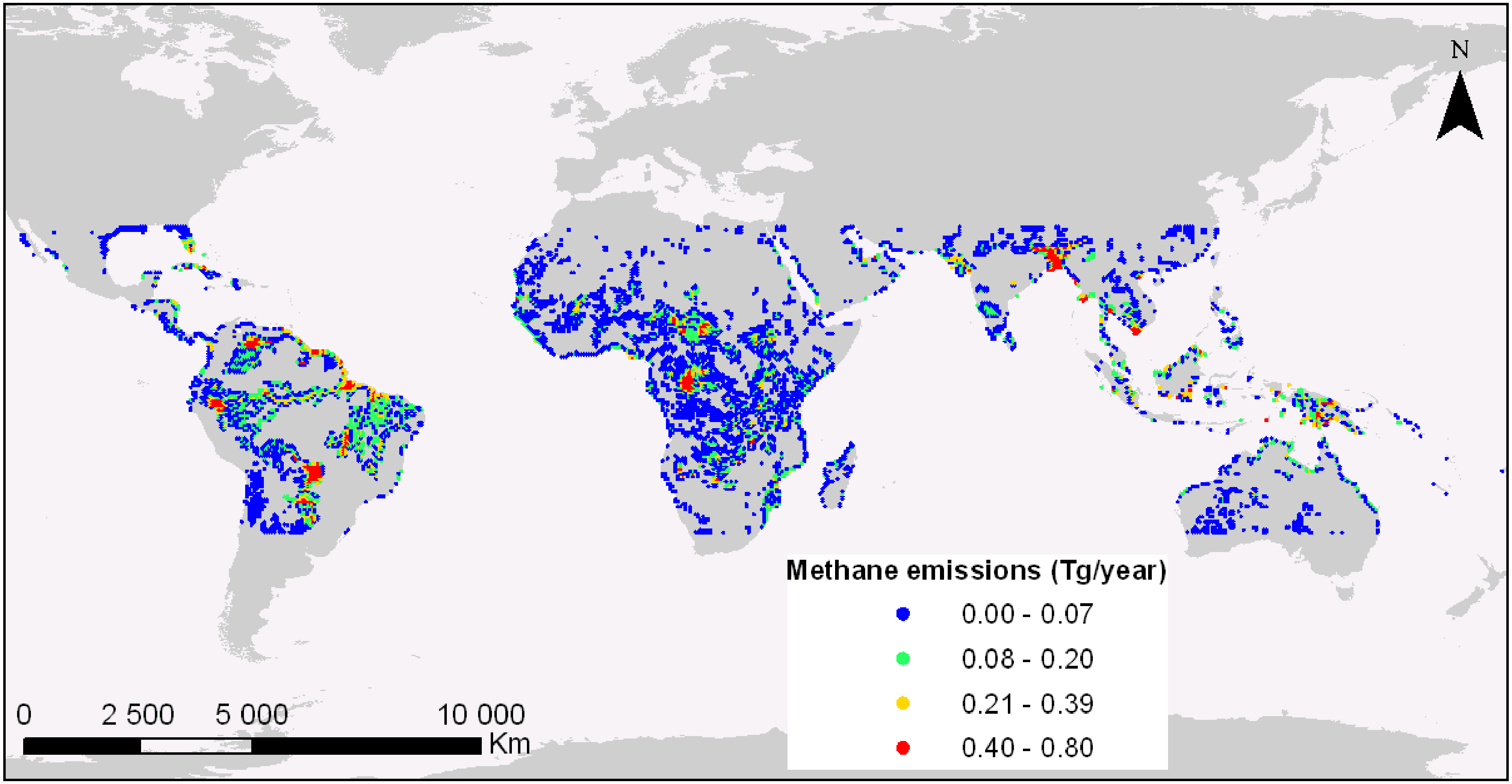


Figure 19: The latitudinal distribution of simulated methane emissions from tropical wetlands

Figure 19 shows the simulated yearly average (17 years) for methane emissions from LPJ-GUESS WHyMe for the tropical wetlands organized into latitude bands. There is a peak near the equator towards south. This corresponds to the similar peak observed in the latitudinal distributions of the areas of tropical waterbodies as seen in Figure 1.

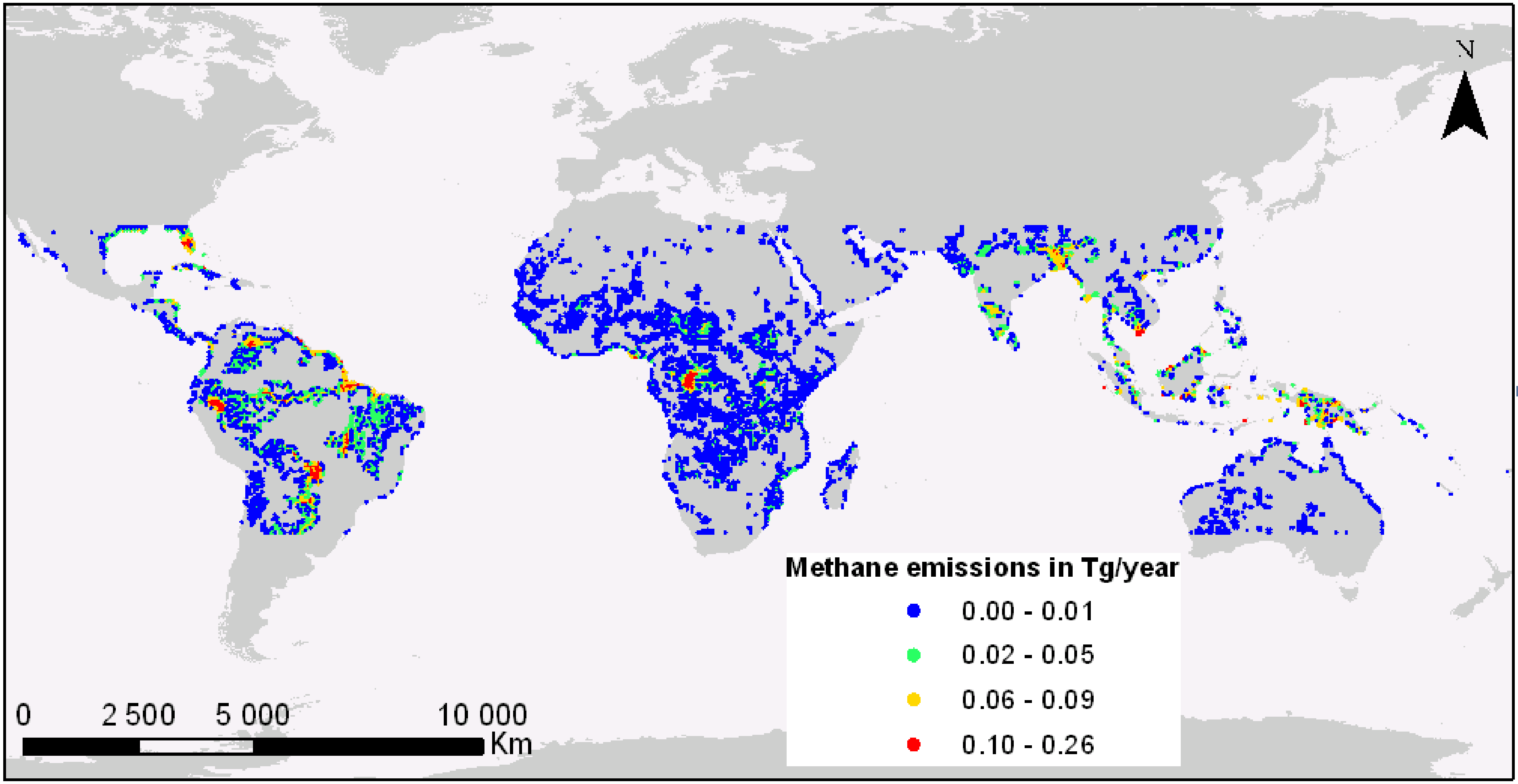


Map 3. Simulated methane emissions from LPJ-GUESS WHyMe, 1990-2006 average for tropical wetlands

Note- Plotted as latitude longitude in degrees and the scale does not apply for the entire map.
The symbols are not drawn to scale.

4.5 Estimating methane emissions from modelled heterotrophic respiration output

The recent paper by Spahni et al (2011, in discussion stage) used an approach of considering methane emission as a fraction of heterotrophic respiration for wetlands. Following the similar approach and using the same carbon conversion factor i.e. 4.15 % for estimating methane gas from the heterotrophic respiration values simulated by LPJ-GUESS v2.1 for the years 1990 to 2006 for the tropical wetlands, a map has been produced (map 4 below). The annual emissions estimated by this approach were 110 $TgCH_4$ per year.



Map 4. Estimated methane emissions from modelled heterotrophic respiration in LPJ-GUESS v2.1, 1990-2006 average.

Note- Plotted as latitude longitude in degrees and the scale does not apply for the entire map.
The symbols are not drawn to scale.
Both the Maps (3 and 4) have different scale of emissions.

On comparison of both the maps (3 and 4), the first being derived from LPJ-GUESS WHyMe by simulating methane emissions from tropical wetlands (Map 3) and the other from estimating methane emissions from heterotrophic respiration (Map 4), it is seen that the spatial emission pattern of methane gas from tropical wetlands has been captured by LPJ-GUESS WHyMe. The peak emissions have been observed in or near several countries such as Bangladesh, Cambodia, Central Africa, Venezuela and Brazil. The both maps show similar emission peaks in these areas though with considerable differences in magnitude as modelled emissions from LPJ-GUESS WHyMe show much higher emissions for the same areas as compared to the estimation of methane emissions from modelled heterotrophic respiration output. The almost similar pattern of emissions is also seen in Bloom et al (2010), Figure 3A where they have shown daily wetland methane emissions per unit area for 2003-2005 on a 3º × 3º grid.

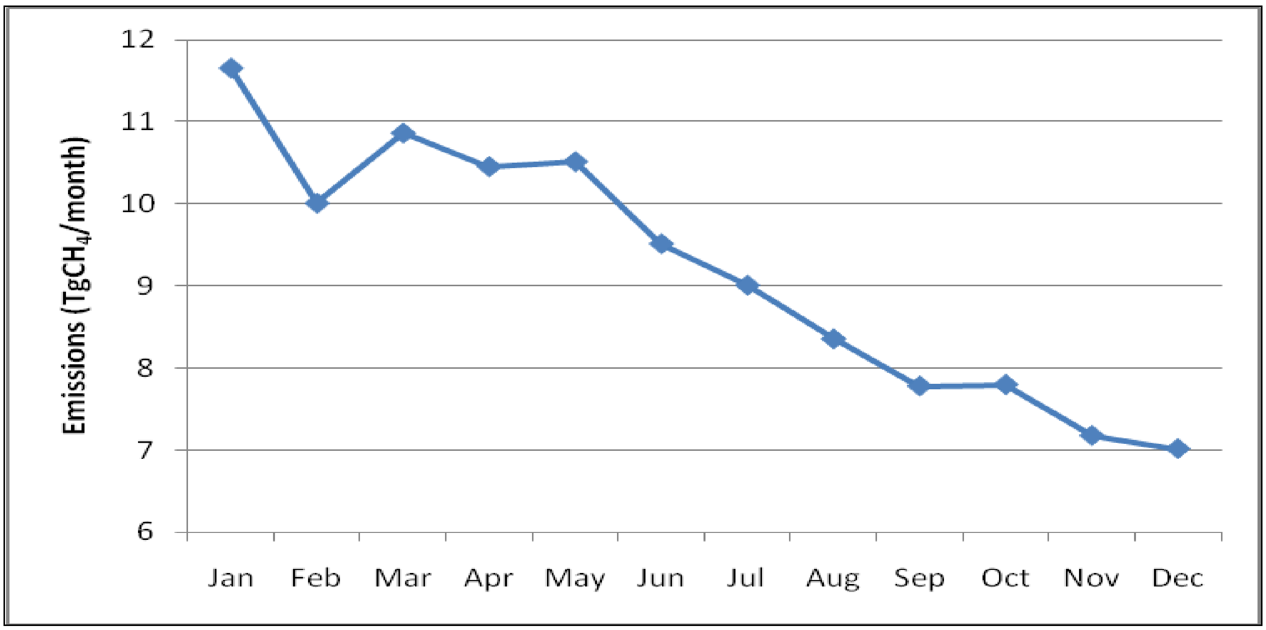


Figure 20: Seasonal variation of methane emissions as a fraction of heterotrophic respiration in wetlands in the tropics

As with LPJ-GUESS WHyMe model in Figure 18, Figure 20 also shows that the emissions seem to be higher towards the beginning of the year in general, and show a decreasing trend towards the last months of the year. This pattern may be due to the non-homogeneous litter distribution process as litter is collected at the year end and is included in the litter pool all together in the first month of the year due to which substrate for decomposition gradually lessens due to the diminishing litter in the coming months over the year. Lack of inundation variability may also be contributing to this pattern.

4.6 Comparison of various approaches

Table 14. Comparison of tropical wetland methane emissions using various approaches

Process Based Models ($TgCH_4$/year)	**Inverse based models ($TgCH_4$/year)**	**Reported in literature, derived from field measurements and extrapolation ($TgCH_4$/year)**
**Cao et al (1996) 51.4	Bergamaschi et al (2007) 138.4	Matthews and Fung (1987) *30 (approximation)
Walter et al (2001 a) *180 (mean annual)	Bousquet et al (2006) $^{\$\$}104 \pm 12 \pm 9$	Aselmann and Crutzen (1989) *46.5 (approximation)
Present study a) LPJ-GUESS WHyMe simulation 566 b) LPJ-GUESS estimation (Simpler approach) 110	Frankenberg et al (2005) $^{\$}68.5$	**Bartlett and Harriss (1993) 66
-	-	Present study a) Upscaling result 51-183

Note-Definition of tropics might vary among studies. Studies for which tropical zone is not mentioned use the same extent of tropics as is used by the present study.
*Approximations calculated from Figures for 30 degrees S to 30 degrees N given in respective studies as the definition of tropics varied between the studies
**Reported for Tropical regions (20 degrees N to 30 degrees S)
[$] Tropics vary from 15 degrees south to 15 degrees north.
[$$] ± 12 represents the first error which estimates the mean of the error determined by the inversion model used in the study and ± 9 refers to the second error estimate which represents the spread between the ensemble members of the 18 inversions carried out in the study.

5.0 Discussion

5.1 Upscaling of site based observations

The results of upscaling methane emissions are highly overestimated for the upper range but excluding the exceptional values lowers the upper range of values drastically from 617 to 183 Tg CH_4 per year. Even then, the upper range is extremely high in comparison to previous studies like Matthews and Fung (1987), and Aselmann and Crutzen (1989) (Table 14), which are also based on extrapolation of site flux observations giving the values of around 30 Tg CH_4 per year and 46.5 Tg CH_4 per year, respectively, for 30 degrees N to 30 degrees S (approximations calculated from figures given in the respective studies as the definition of tropics varied in studies). The methane emissions values given in such assessments depend on the wetland areas used for extrapolating the values. Matthews and Fung (1987) assume a wetland area of 1.9×10^6 km^2 for the wetlands in 30 degrees N to 30 degrees S whereas Aselmann and Crutzen (1987) have 2.1×10^6 km^2 for the same latitude belt (calculated from Table II, page 333, Aselmann and Crutzen 1987). Wetland data extracted in this study for 30 degrees N to 30 degrees S is from the Lehner and Doll (2004) global wetland dataset which according to Mitsch and Gosselink (2007) is amongst the latest and most complete assessments of wetland spatial coverage. The computed sum for their wetlands in the same latitudinal belt is 3.7×10^6 km^2 (excluding rivers which is also mentioned as wetland class in their data). Refer to methodology above for details. This study uses a wetland area of 3.34×10^6 km^2 for upscaling (excluding Bog, Fen and mire wetlands as well as intermittent wetlands) which is quite high as compared to the previous studies. On comparison with bottom up estimates, Cao et al (1996) gave a value of 51.4 Tg CH_4 per year based on the Matthews and Fung (1987) data on wetlands location and area. Another well known global application of a process based model for methane emissions from natural wetlands is Walter et al (2001 a) who used the same global wetland dataset from Matthews and Fung (1987) and give a higher value of around 180 Tg CH_4 per year (calculated from Figure 6, page 34,199 in Walter et al 2001a) which is quite close to the higher range of the upscaling results of this study. Though top down approaches such as Frankenberg et al (2005) and Bousquet et al (2006) give values of 68.5 and $104 \pm 12 \pm 9$ (± 12 representing the first error estimate whereas ± 9 representing the second error estimate) Tg CH_4 per year respectively, recent published literature gives a higher value of around 138.4 Tg CH_4 per year (Bergamaschi et al 2007) which is closer to upper value of the upscaling results of this study as compared to other inversion estimates.

5.2 Modelling tropical wetland methane emissions using LPJ-GUESS WHyMe

The total mean (1990-2006) annual methane emissions from the tropical wetlands simulated by the LPJ GUESS WHyMe model was 566 Tg CH_4 per year (Table 14). The LPJ-GUESS WHyMe model highly overestimates the methane values due to the lack of specific parameter values for emissions from tropical wetlands. Specific parameters for plant functional types for wetland vegetation in the tropics such as palm trees found in fresh water marshes (around the edges) and swamp forests and mangroves trees in coastal areas need to be incorporated more fully in the model. Palm trees require pinnately leaved and palmately leaved characteristics in the plant functional type belonging to tropical trees (based on the information on vegetation in tropical wetlands from upscaling studies). Tolerance of inundation stress also needs to be specific for the tropical areas. For example, the mangroves trees at the Pichavaram mangroves site, India, tolerated an average water level of 1500 mm which emphasises the need for such high WTPmax parameter values to be incorporated for the tropical vegetation in the coastal wetlands. However, for the current model even a WTPmax of 1000 mm for the vegetation is too high and caused the model to crash. Out of the two palm trees found on the sites, one of them is found in a partial shade environment, but LPJ-GUESS has only two shade tolerance categories, namely shade tolerant and shade intolerant. Such specific characteristics of tropical wetland vegetation need to be included in the model. The potential carbon pool for methanogens in the model is dependent on net primary production (Wania 2010, Figure 1), and the NPP of vegetation is greatly impacted by factors such as temperature, water, sunlight and nutrients (Neue et al 1997). Hence, all these might influence the potential carbon pool for methanogens through their contribution to NPP of the vegetation. Considering such factors, it is to be noted that modelling has been carried out with a version of LPJ-GUESS developed originally to simulate the wetland hydrology and methane emissions at northern latitudes. This is the first time that the model has been applied to tropical wetlands. Parameters values are therefore unknown and need to be optimised based on observations of hydrology and vegetation in these biomes. As an example of the sensitivity to parameter values chosen, the study notes the tests carried out with different establishment rates (Estmax) of tropical wetland trees. Pilot testing at a few sites with different establishment rates of trees in the tropical wetlands lead to different carbon pools, and different methane emissions (see, e.g, Figures 7, 11 & 12). The carbon pools form the basis of the substrate for methane production (Wania, 2010, Figure 1). Thus, there is a clear need for the parameter Est max to have a suitable value for getting the methane emissions to a more reasonable range. Similar arguments apply to other parameters affecting vegetation composition in LPJ-GUESS WHyMe.

On comparing simulated monthly average methane emissions (1990-2006) from LPJ-GUESS WHyMe (Figure 18) with the results of Ringeval et al (2010), who have carried out their simulations with the ORCHIDEE global vegetation model coupled with a process based wetland methane emission model (Walter et al 2001 a). Ringeval et al forced their model in one of their simulations using a fixed area of wetland which was the average annual area or average area for the methane release season thus considering no seasonal fluctuations in wetland area. This condition is similar to the simulation of the present study where seasonality of inundation is not captured as it is assumed that the grid cells are inundated throughout the year. Though the emission values in this study are highly overestimated (Figure 18), nevertheless a similar pattern (Ringeval et al 2010, Figure 4 c) is observed from January to June. The peak in emissions in October in their study is also captured in the present study.

With regard to the latitudinal emissions shown in Figure 19, Spahni et al (2011, discussion paper, Figure 4 b) have found a similar spike just south of equator (around 4 degrees S) in their calculations of the yearly net emissions of methane across the latitudes for their two scenarios for 2004. Their study calculated net methane emissions by considering emissions from northern peatlands, inundated wetlands, rice agriculture and wet mineral soil emissions (sources), the soil carbon uptake (a sink), weighted by their fraction of grid cell and area. On comparison of their annual emission value in their SC2 scenario around the highest peak observed in the latitudinal distribution (around 4 degrees S), it is almost twice of the value presented in this study for that latitude. Bloom et al (2010) have also found the highest peak near the equator in their latitudinal distribution for their normalised top down estimate for the years 2003-2005 (Figure 3 b) .

5.3 Estimating emissions from modelled heterotrophic respiration output

Methane emissions of 110 Tg CH_4 per year were calculated for the latitude belt of the tropics by using simulated values of heterotrophic respiration from LPJ-GUESS v2.1. The carbon conversion ratio used comprises in a crude sense the oxidation of methane while its surface transport and general flux tuning and the resulting value is quite close to the values given by Bousquet et al (2006) for the tropics using same definition of tropics as this study (Table 14). They gave a figure of $104 \pm 12 \pm 9$ Tg CH_4 per year where ± 12 and ± 9 refers to the first error and second error estimates of the study respectively.

Again a comparison of the seasonal emission pattern (Figure 20) with Ringeval et al (2010, Figure 4 c) reveals a similar pattern from January to June and also a similar peak in October, though the values are higher for these months. However, the peak observed in October has a lower value as compared to their study. These seasonal variations assume no seasonal fluctuations in wetland extent.

Spahni et al (2011, discussion paper) have pointed out that the carbon ratio of methane to carbon dioxide production is not fixed and is largely uncertain. The molar ratio of methane gas to carbon dioxide formation fluctuates from 0.001 to 1.7 for anaerobic conditions (Segers 1998, Wania et al 2010). Potter et al (1996) has used the ratio of 0.0001 to 0.1 for methane to carbon dioxide production which were based on the water table position (Wania 2010). Such a broad range of values emphasises the unpredictability of this ratio due to the chief reason that other acceptors of electrons, for example, nitrate and ferric ions, get reduced before the formation of methane (Segers 1998, Wania et al 2010). The carbon conversion ratio used for this study to estimate methane emissions is directly taken from Spahni et al (2011, discussion paper) who have directly adjusted it for this latitudinal belt without any parameter fitting and hence the results obtained should be interpreted with caution.

5.4 Comparison between modelled and estimated emissions

In LPJ-GUESS WHyMe, in tropical wetland sites, following Wania et al (2010), the slowly decomposing carbon under inundated conditions is mainly converted to carbon dioxide but a portion of it is allocated to a potential carbon pool for methanogens, following a methane to carbon dioxide ratio. A higher value of this parameter causes greater methane emissions since large amount of carbon gets released as methane. Wania et al (2010) have regarded it as a flexible parameter. This parameter was optimised for northern peatlands in LPJ-GUESS WHyMe to be 0.25 (Paul Miller, private communication), the value used in the present study. Another approach used in this present study of estimating emissions from modelled heterotrophic respiration output of LPJ-GUESS v2.1 gave resonable emissions which were much lower than the emissions given by simulating LPJ-GUESS WHyMe for tropical wetlands. A carbon conversion factor was much lower (0.0415) in this approach. This indicates that reducing the methane to carbon dioxide ratio (CH_4/CO_2 parameter) in LPJ-GUESS WHyMe from 0.25 might bring down the emissions to a reasonable range. New parameter adjustments might give a new lower value by carrying out testing for the tropical sites.

6.0 Conclusions and possible application of the findings

6.1 Conclusions

In this study methane emissions from tropical wetlands of natural origin were first estimated by upscaling of fluxes using site based observations. Emissions from LPJ-GUESS WHyMe simulations were also investigated, as well as a simpler approach of using modelled heterotrophic respiration values from LPJ-GUESS v2.1. The findings can be summarized as follows:

- Extrapolation of fluxes using site-based observations can introduce a lot of uncertainty due to the exceptional values at a few sites.
- Excluding exceptionally high site-based emissions from the upscaling gives total tropical methane emissions close to results of the inverse studies carried out in recent years.
- LPJ-GUESS with a wetland and methane module developed for high latitudes (LPJ-GUESS WHyMe) will need specific tropical wetland vegetation and its associated parameters, better water table calculations, seasonal inundation inputs, and more analysis of the factors governing the CO_2 to CH_4 production ratio in tropical regions, to provide a reasonable estimate for methane emissions from tropical wetlands.

- The LPJ-GUESS WHyMe model captures the spatial emission pattern though the total emission values are highly overestimated.
- Estimated methane emissions from modelled heterotrophic respiration values of LPJ-GUESS v2.1 using a fixed carbon conversion factor is close to the results of inverse studies carried out in recent years.

6.2 Possible application of the findings

- This study will be useful for providing input to the upscaling studies for the tropics based on various wetland types.
- This study also provides useful inputs in terms of the behaviour and needs of LPJ-GUESS WHyMe in simulating methane emissions in tropical wetlands.

7.0 Limitations of the study

1. It was required for the WWF dataset to 'Define Projection' and a false projection was defined as WGS-84 for the purpose of this study.
2. Upscaling for the Coastal wetland category used three study sites from India, which could have biased the upscaled values of the category towards India in the entire tropical belt.
3. Though efforts have been taken to include only those sites which are not affected by anthropogenic activities, methane emissions might have been impacted in Sundarban Mangrove forest site, India by the eco-restoration programme carried out in the area which includes artificial regeneration of mangrove forests (Mukhopadhay et al 2002). The emissions of methane gas could also have been influenced by the fishing activities in the Pulicat Lake, South India (Shalini et al 2006). Both the above mentioned research studies were used for the emission values for these sites in the upscaling approach and do not mention any such impact on methane emissions.
4. Lehner and Doll (2004) in their wetland classification have given various wetland classes. Wetland class 6 (Coastal Wetland) and wetland class 7 (Pan, Brackish/Saline Wetland) might occassionally ovelap in nature. However, the present study follows the wetland classification of Lehner and Doll (2004).

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Website

http://library.elkhornslough.org/twp/ESTWP/ESTWP_PLAN_glossary.pdf

Appendix

A.

Delta- "A wetland-river-upland complex located where a river forms distributaries as it merges with the sea; there are also examples of inland deltas such as the Peace-Athabasca Delta in Canada and the Okavango Delta in Botswana." (Mitsch & Gosselink 2007)

Mangrove- Mangrove implies to tropical and subtropical ecosystems that possess various collection of salt loving vegetation (able to endure salty conditions) established by the covered shores and estuaries. (EJF 2006)

Tidal Freshwater marsh- "Marsh along rivers and estuaries close enough to the coastline to experience significant tides by nonsaline water. Vegetation is often similar to nontidal freshwater marshes" (Mitsch & Gosselink 2007).

Salt Marsh- "A halophytic wetland on alluvial sediments bordering saline water bodies where water level fluctuates either tidally or nontidally"(Mitsch & Gosselink 2007).

Tidal Wetland- Regions by the shore side as well as in estuary where the land is containing water during the period when the tides are high and is removed (drained) during the times when there is a small tide.

Estuary- "A coastal embayment consisting of deepwater subtidal habitats and adjacent intertidal wetlands that are usually semi-enclosed by land but have open access to ocean waters that enter with the tides and are usually diluted by freshwater."

Coastal Lagoon- Coastal lagoon is characterized as a low body of water along the shore having an obstruction which disconnects it from the ocean but is joined irregularly for minimum by single or more than that, inlets to the ocean, and is generally located parallel to the shore. (Kjerfve B 1994)

B.

C++ code used for getting the output for wetland areas in the tropics

```
// Reads in and processes high-resolution tropical wetland data (Lehner-Döll dataset extracted and preprocessed by

// Shubhangi Lamba into the ras_upscale_all.txt file) and creates a 0.5 degree gridlist file with the same tropical

// wetland information as area fractions.

// Can also be used for wetland information in other regions.

// Paul Miller, Lund, 2011

#include <stdio.h>

#include <string.h>

#include <time.h>

#include <gutil.h>

#include <iostream>

#include <math.h>

using namespace std;

// DATA IN

xtring file_gridlist = "E://TropicalWetlands//tropicalordered_full.txt";

// Stream pointer to file_gridlist

FILE *in_grid;

xtring file_ras = "E://TropicalWetlands//ras_upscale_all.txt";

// ... and streams

FILE *in_ras;
```

```
// DATA OUT

// Output file name ...

xtring file_out = "E://TropicalWetlands//gridlist_tropicalwetlands.txt";

// ... and streams

FILE *out_tropwet;

// Output file name for latitudinal wetland area totals

xtring file_zonal_out = "E://TropicalWetlands//zonal_areas.txt";

// ... and streams

FILE *out_zonal2;

long lo = 0;

// LIMITS (from IGBP-DIS)

const double MINBK = 0.0;

bool openrasfile() {

	in_ras=fopen((char*)file_ras,"r");

	if (!in_ras)

		return false;

	printf("Opened RAS file successfully\n");

	return true;

}

int getmean(int loncolnum, double& mean, double limit, int& limitexceeded, double data[6][4320]) {

	int landpts = 0;

	mean = 0.0;

	limitexceeded = 0;
```

```
	for (int col = loncolnum-1; col < loncolnum+5; col++) {
			for (int row = 0; row < 6; row++) {
			if (data[row][col] != -2) {
				landpts++;
				mean += data[row][col];
				if (data[row][col] > limit)
					limitexceeded++;
			}
		}
	}
	if (landpts != 0)
		mean /= landpts;
	else
		mean = -999.0;
	return landpts;
}
//
double pixelsize(double longpos,double latpos,double longsize,double latsize,int postype) {
//c	(Ben Smith, 15/5/97)
//
//c	Returns area in square km of a pixel of a given size at a given point
//c	on the world.  The formula applied is the surface area of a segment of
//c	a hemisphere of radius r from the equator to a parallel (circular)
//c	plane h vertical units towards the pole: S=2*pi*r*h
```

```
//
//c     longpos   longitude position (see postype)
//c     latpos    latitude position (see postype)
//c     longsize  longitude range in degrees
//c     latsize   latitude range in degrees
//c     postype   declares which part of the pixel longpos and latpos
//c               refer to:
//c               0 = centre
//c               1 = NW corner
//c               2 = NE corner
//c               3 = SW corner
//c               4 = SE corner
        double pi,r,h1,h2,lattop,latbot,s;
        pi=3.1415926536;
        r=6367.425;   //mean radius of the earth
        lattop=latpos;
        if (postype==0) lattop=latpos+latsize*0.5;
        if (postype==3 || postype==4) lattop=latpos+latsize;
        if (lattop<0.0) lattop=-lattop+latsize;
        latbot=lattop-latsize;
        h1=r*sin(lattop*pi/180.0);
        h2=r*sin(latbot*pi/180.0);
        s=2.0*pi*r*(h1-h2);  //for this latitude band
        return s*longsize/360.0;  //for this pixel
```

```
}
// Is this 30' cell in the CRU cell?
bool isincrucell(double dlon, double dlat, double raslon, double raslat) {
        if (raslat >= dlat && raslat < dlat + 0.5) {
                        // Latitude OK, how about longitude?
                        if (raslon >= dlon && raslon < dlon + 0.5) {
                                return true;
                        }
        }
        return false;
}
int main(int argc,char* argv[]) {
   try {
        double dlon,dlat;
        bool eof=false;
        // Open output file
        out_tropwet=fopen(file_out,"w");
        if (!out_tropwet) throw("out file error\n");
        // Open output file
        //out_zonal2=fopen(file_zonal_out,"w");
        //if (!out_zonal2) throw("out zonal file error\n");
        // Open list of grid coordinates
        in_grid=fopen((char*)file_gridlist,"r");
        if (!in_grid) throw("grid list error\n");
```

```
// Open ras files
in_ras = fopen((char *)file_ras,"r");
if (!in_ras) throw("ras file error\n");
printf("Opened new gridlist, existing grid list and ras files successfully\n");
bool firstgrid = true; // whether simulating first grid cell in linked list
xtring descrip;
// class index, 0-11
int cl = 0;
long in_ras_safe = 0;
long ngridcell = 0;
fpos_t prev_pos = NULL;
fpos_t pos = NULL;
fpos_t new_pos = NULL;
bool oncecellfound = false;
double lastlat = -99;
double zonalwetarea = 0.0; // km2
double lastraslat = -99.0;
bool newcrulat = false;
long linectr = 0;
while (!eof) {
// Read next record in file
        eof=!readfor(in_grid,"f,f",&dlon,&dlat);
        ngridcell++;
```

```
if (fabs(lastlat - dlat) > 0.001) {
//if (true) {
        newcrulat = true;
        // Open output file
        FILE* out_zonal2=fopen(file_zonal_out,"a");
        if (!out_zonal2) throw("out zonal file error\n");
        if
      (ngridcell!=1) fprintf(out_zonal2,"%6.1f%15.3f\n",lastlat,zonalwetarea);
        fclose(out_zonal2);
        //cout << test << endl;
        zonalwetarea = 0.0;
        lastlat = dlat;
}
// if (true) fprintf(out_zonal2,"%6.1f%15.3f\n",lastlat,zonalwetarea);
// get area of CRU cell
double crupixelsize = pixelsize(dlon,dlat,0.5,0.5,3);
// Print a simple progress counter to screen & file
int rem = (int)ngridcell%100;
if (rem == 0) {
        cout << ngridcell << "  " << crupixelsize << endl;
}
// summed areas (km2) of the Lehner-Döll classes IN THIS CRU CELL
double classareas[12];
```

```
if (!eof && !(dlon==0.0 && dlat==0.0)) { // ignore blank lines at end (if any)
	// *** New CRU cell - initialise
	// set class areas to 0;
	for (cl = 0; cl < 12; cl++) classareas[cl] = 0.0;
	// Rewind ras file first, then jump to the last position to save time
	if (lastlat == 30.0) /*|| newcrulat)*/ {
		rewind(in_ras);
		linectr = 0;
	} else if (newcrulat && lastlat < 29.5) {
		fsetpos(in_ras, &prev_pos);
	}
	else
		fsetpos(in_ras, &pos);
	// *** Determine class areas ***
	bool allfound = false;
	while (!allfound) {
		// Ras file format:
		// ,0,1.000000,-95.139999,30.000000
		double id, pid,code,raslon, raslat;
		//bool ras_eof=!readfor(in_ras,"1X");
		if (newcrulat)
			fgetpos( in_ras, &new_pos );
		bool
ras_eof=!readfor(in_ras,",f,f,f,f",&pid,&code,&raslon,&raslat);
		linectr++;
```

```
				// Update the file postition pointer the FIRST time we find a ras latitude that is
				// within 0.5 degrees of the CRU latitude
				if ((raslat < dlat + 0.5) && newcrulat) {
					cout << "New position at line: " << linectr << endl;
					newcrulat = false;
					//fgetpos( in_ras, &pos );
					prev_pos = pos;
					pos = new_pos;
				}
				if (!ras_eof) {

					int icode = (int)code-1; // classareas array index, 0-11
					// Don't even consider this cell if we're not near enough
					if (fabs(dlat-raslat) < 1.0 && fabs(dlon-raslon) < 1.0) {
						// Is this 30' cell in this CRU cell?
						if (isincrucell(dlon,dlat,raslon,raslat)) {
						// Yes, then calculated the area ...
						// Area in km2 of the 30' cell, assuming coords in SW corner
							double thirtysecs = 1.0/120.0;
							double raspixelsize = pixelsize(raslon,raslat,thirtysecs,thirtysecs,3);
							//cout << "CRU pixel: " << crupixelsize << endl;
```

```
//cout << raslon << " " << raslat << "  " <<
raspixelsize << endl;

// ... and add the area to the class array
classareas[icode] += raspixelsize;
// Add to the zonal sum
zonalwetarea += raspixelsize;
/*
// Record this file position as the last
if( fgetpos( in_ras, &pos ) != 0 ) {
    cout << "fgetpos error" << endl;
    throw;
} else
    oncecellfound = true;
*/
}
}
// No need to search anymore if we've gone South of the
CRU cell
if (raslat < dlat)
    allfound = true;
    } else {
    allfound = true;
        }       // ras_eof?
} // while !allfound
// *** End of - Determine class areas ***
```

```
// Print the CRU cell plus the class percentages
// sum class areas and fractions
double totalfrac = 0.0;
for (cl = 0; cl < 12; cl++) {
        classareas[cl] /= crupixelsize;
        totalfrac += classareas[cl];
}
// Fractions OK?
if (totalfrac < 0 || totalfrac > 1.2) {
                cout << "bad totalfrac: " << totalfrac << endl;
                throw;
}
// Ensure that the sum of the fractions never exceeds 1!
if (totalfrac > 1.0000) {
        for (cl = 0; cl < 12; cl++) {
                classareas[cl] /= totalfrac;
                totalfrac = 1.0;
        }
}
// Write data for this cell

fprintf(out_tropwet,"%6.1f%6.1f%9.5f%9.5f%9.5f%9.5f%9.5f%9.5f%9.5f%9.5f%9.5f%
9.5f%9.5f%9.5f%9.5f%15.5f\n",dlon,dlat,

classareas[0],classareas[1],classareas[2],classareas[3],classareas[4],classareas[5],
```

```
classareas[6],classareas[7],classareas[8],classareas[9],classareas[10],classareas[11],totalfrac,crupixelsize);
		} // if valid CRU cell
	} // while loop through CRU cells
	cout << ngridcell << " cells processed" << endl;
	int test;
	cin >> test;
	}
	catch(...) {}
	fclose(in_grid);
	fclose(in_ras);
	fclose(out_tropwet);
	//fclose(out_zonal2);
	return 0;
}
```

C.

Parameter values and PFT definitions relevant to the Tropical Wetland runs

By Shubhangi Lamba and Paul Miller, Lund, 2011

! Parameters changed often

nyear 500 ! number of years to run simulation for

npatch 10 ! number of replicate patches to simulate

ifwhy 1

wetland_runon 0 ! mm/day

! >0: run ON, so WETTER, <0: run OFF, so DRIER, 0: - no effect

use_wania_decomposition 1 ! Whether to use Rita Wania's standard LPJ-WHyMe decomposition

! in wetlands (1), or a new scheme (0)

!///

!// PARAMETERS FOR PFTS

!// Run GUESS with -help option for list of keywords and their meanings

group "common" (

! Parameters common to all PFTs

lambda_max 0.8

emax 5

reprfrac 0.1

wscal_min 0.35

pathway "c3"

respcoeff 1.0

exud_frac 0.175 ! Rita's value

)

group "tree" (

! Parameters common to all trees

common

lifeform "tree"

ltor_max 1

crownarea_max 50.0 ! AW: 27.3

k_allom2 60 ! was (and AW has) 40. Ben has 60,which corresponds to obs (pfpparameters.doc)

k_allom3 0.67

k_rp 1.6

wooddens 200

rootdist 0.6 0.4 ! PM100203 - ensembles change - was 0.67 0.33, and AW had this too

turnover_root 0.7 ! PM100203 - ensembles change - added

cton_leaf 29

cton_root 29

cton_sap 330

kest_repr 200

kest_bg 0.1

kest_pres 1

litterme 0.3

k_chilla 0

k_chillb 100

k_chillk 0.05

min_snow 0.0 ! AW parameter

```
	zero_max 100000 ! AW parameter
	! PM100203 - Checked agains ENSEMBLES .ins file
)
group "grass" (
	! Parameters common to all grasses
	common
	lifeform "grass"
	litterme 0.2
	cton_leaf 29 ! PM
	cton_root 29 ! PM
	parff_min 1000000 ! ensembles change - was 1250000
	intc 0.01
	fireresist 0.5
	sla 32.4
	gmin 0.5
	min_snow 0.0
	! PM100203 - ensembles - added these:
	ltor_max 0.5
	rootdist 0.9 0.1  ! Fraction of fine roots in the upper and lower soil layers.
	phenology "any"
	phengdd5ramp 100			! C3 har 50 hos Thomas
	leaflong 1				! Leaf longevity (years)
	turnover_leaf 1
	turnover_root 0.7			! 0.5 hos guess2008
```

```
)
group "broadleaf" (
! Parameters common to broadleaved trees
	gmin 0.5
	sla 24.3
	phenology "summergreen"
	leaflong 0.5
	turnover_leaf 1
	phengdd5ramp 200 ! PM, unless otherwise specified
	intc 0.02
	k_allom1 250 ! AW: 200
	k_latosa 6000 ! AW: 4000
)
! PM100203 - ensembles - added:
group "evergreen" (
	! Parameters common to all evergreen trees
	phenology "evergreen"
	phengdd5ramp 0
)
! PM100203 - ensembles - added:
group "summergreen" (
	! Parameters common to all summergreen trees
	phenology "summergreen"
	phengdd5ramp 200
```

```
	leaflong 0.5
	turnover_leaf 1
)
! SL - taken from guess2008
group "tropical" (
	! Parameters common to all tropical trees
	tcmin_surv 15.5
	tcmin_est 15.5
	tcmax_est 1000   ! no limit
	twmin_est -1000  ! no limit
	gdd5min_est 0    ! no limit
	pstemp_min 2
	pstemp_low 25
	pstemp_high 30
	pstemp_max 55
	respcoeff 0.15
)
group "shadetol" (
	! Parameters common to shade-tolerant trees
	est_max 0.05
	parff_min 350000       ! 1250000
	alphar 3.0
	greff_min 0.04
	turnover_sap 0.05
```

```
)
group "shadeintol" (
	! Parameters common to light demanding trees
	est_max 0.05 ! SL, was 0.2
	parff_min 2500000
	alphar 10.0
	greff_min 0.08! 0.1
	turnover_sap 0.1	! 0.08
)
! ***
! Flood-tolerant tropical broadleaved evergreen trees. Include 1 or 0, depending on
! wetland type.
! ***
! SL - adapted TrBE from guess2008
pft "TrIBE" (
	! Moderately flood-tolerant tropical broadleaved evergreen tree
	include 1
	tree
	broadleaf
	shadeintol
	evergreen
	tropical
	leaflong 2
	turnover_leaf 0.5
```

```
	longevity 200
	fireresist 0.1
	! wetland values
	zero_min 0
	drought_tolerance 0.43
	wtp_max 100 ! -301
	inund_duration 31 ! days
	bulk_dens 20
	acro_root_frac 0.5
)
! SL - adapted TrBE from guess2008
pft "TrS_Man" (
	! Flood-tolerant Tropical broadleaved evergreen tree
	! "Shade tolerant Mangrove"
	include 0
	tree
	broadleaf
	shadetol
	evergreen
	tropical
	leaflong 2
	turnover_leaf 0.5
	longevity 200
	fireresist 0.1
```

```
	! wetland values
	zero_min 0
	drought_tolerance 0.43
	wtp_max 500 ! -301
	inund_duration 31 ! days
	bulk_dens 20
	acro_root_frac 0.5
)
! SL - adapted TrBE from guess2008
pft "TrI_Man" (
	! Flood-tolerant Tropical broadleaved evergreen tree
	! "Shade intolerant Mangrove"
	include 0
	tree
	broadleaf
	shadeintol
	est_max 0.1
	evergreen
	tropical
	leaflong 2
	turnover_leaf 0.5
	longevity 200
	fireresist 0.1
	! wetland values
```

```
	zero_min 0
	drought_tolerance 0.43
	wtp_max 500 ! -301
	inund_duration 31 ! days
	bulk_dens 20
	acro_root_frac 0.5
)
pft "GRS_C3" (
	! Flood-tolerant Tropical (C3) grass
	include 1
	grass
	pathway "c3"
	rootdist 0.9 0.1
	gmin 0.5
	phenology "any"
	leaflong 1
	cton_leaf 40 ! PM_moss
	cton_root 40 ! PM_moss
	ltor_max 0.4 ! PM_moss
	turnover_leaf 1
	turnover_root 0.5
	phengdd5ramp 100 ! PM_moss, was 50, but RW has 100
	! SL - tropical now
	tropical
```

```
	!pstemp_min -5
	!pstemp_low 5
	!pstemp_high 30
	!pstemp_max 45
	!tcmin_surv -1000
	!tcmin_est -1000
	!tcmax_est 1000
	!twmin_est -1000
	!gdd5min_est 0
	! guess2008 - DLE
	drought_tolerance 0.4 ! PaulM - guess
	! PM - taken from AW's GFT
	zero_min 0 ! SL
	! PM - zero_max 1000 restricts establishment in an Irish bog, for example
	! zero_max 1000
	wtp_max 500 ! SL 100 ! mm
	inund_duration 31 ! days
	bulk_dens 2
	acro_root_frac 0.75
)
pft "GRS_C4" (
	! Flood-tolerant Tropical (C4) grass
	include 1
	grass
```

pathway "c4"

rootdist 0.9 0.1

gmin 0.5

phenology "any"

leaflong 1

cton_leaf 40 ! PM_moss

cton_root 40 ! PM_moss

ltor_max 0.4 ! PM_moss

turnover_leaf 1

turnover_root 0.5

phengdd5ramp 100 ! PM_moss, was 50, but RW has 100

! SL - tropical now

tropical

!pstemp_min -5

!pstemp_low 5

!pstemp_high 30

!pstemp_max 45

!tcmin_surv -1000

!tcmin_est -1000

!tcmax_est 1000

!twmin_est -1000

!gdd5min_est 0

! guess2008 - DLE

drought_tolerance 0.4 ! PaulM - guess

```
        ! PM - taken from AW's GFT
        zero_min 0 ! SL
        ! PM - zero_max 1000 restricts establishment in an Irish bog, for example
        ! zero_max 1000
        wtp_max 500 ! SL 100 ! mm
        inund_duration 31 ! days
        bulk_dens 2
        acro_root_frac 0.75
)
```

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