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ORIGINAL ARTICLE

The Tropical Peatland Plantation-Carbon Assessment Tool: estimating CO_2 emissions from tropical peat soils under plantations

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Abstract Land use change on Indonesian peatlands contributes to global anthropogenic greenhouse gas (GHG) emissions. Accessible predictive tools are required to estimate likely soil carbon (C) losses and carbon dioxide (CO_2) emissions from peat soils under this land use change. Research and modelling efforts in tropical peatlands are limited, restricting the availability of data for complex soil model parameterisation and evaluation. The Tropical Peatland Plantation-Carbon Assessment Tool (TROPP-CAT) was developed to provide a user friendly tool to evaluate and predict soil C losses and CO_2 emissions from tropical peat soils. The tool requires simple input values to determine the rate of subsidence, of which the oxidising proportion results in CO_2 emissions. This paper describes the model structure and equations, and presents a number of evaluation and application runs. TROPP-CAT has been applied for both site specific and national level simulations, on existing oil palm and *Acacia* plantations, as well as on peat swamp forest sites to predict likely emissions from future land use change. Through an uncertainty and sensitivity analysis, literature reviews and comparison with other methods of estimating soil C losses, the paper identifies opportunities for future model development, bridging between different approaches to predicting CO_2 emissions from tropical peatlands under land use change. TROPP-CAT can be accessed online from www.redd-alert.eu in both English and Bahasa Indonesia.

Keywords CO_2 emissions · Model · Plantations · Soil carbon · Tropical peat

1 Introduction

Over 50 % of tropical peatlands are found in South East Asia, of which almost 50 % were drained and deforested by 2006 (Hooijer et al. 2010; Page et al. 2011a, b). 83 % of Southeastern Asian

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peatlands are in Indonesia, where oil palm plantation development is a key driver behind the conversion of peat swamp forests (Page et al. 2011a, b).

In their natural state, ombrotrophic peat swamp forests take on a dome shape, with the soil saturated under a high water level (Hooijer et al. 2010). The soils are highly organic, made up of forest debris that does not undergo decomposition due to the anaerobic conditions, and thus maintains a high carbon (C) content. Conversion of these systems to oil palm plantations involves the installation of drainage canals to lower the water table depth (WTD) followed by harvesting of high value timber. Land is often left for extended periods of time during which shrubland can develop, and then the final preparation of the land involves clearing and often burning of any vegetation, mechanical compaction of the peat, and finally planting of the young palms (Sheil et al. 2009). Once drainage has occurred, the soils are irreversibly affected; immediately subsiding and losing soil C to the atmosphere through oxidation as carbon dioxide (CO_2) (Kool et al. 2006). Research into the rates of these emissions is limited, although there is increasing interest and focus on the topic, particularly following the 2011 signing of a Moratorium on New Forest Concessions in natural forests and peatland areas of Indonesia, and the biofuel debate surrounding palm oil from plantations grown on peatlands (Austin et al. 2012; Danielsen et al. 2009).

There are a number of approaches that can be used to establish the peat C losses and CO_2 emissions from these systems. Hergoualc'h and Verchot (2011) review two approaches accepted by the United Nations Intergovernmental Panel on Climate Change (IPCC)—the stock difference method which estimates the change in C pools before and after conversion, and the input–output method which estimates rates of C change in specific pools through assessment of soil C fluxes. Both of these methods require sampling in the site prior to and after land use conversion. The stock difference method requires data on the pools of above ground biomass, necromass, soil and below ground biomass to calculate total phytomass C stocks. The input–output method requires data on litterfall and root mortality, heterotrophic respiration (respiration from peat), methanogenesis, leaching, runoff, erosion and fire. As Hergoualc'h and Verchot (2011) demonstrate, there is currently very little data in the literature to estimate the peat C losses using either of these methods.

A third method, measuring the rate of subsidence over time after drainage, offers an alternative, but indirect, way of estimating the soil C losses. This method requires installation of subsidence poles in sites prior to land use change, which are then monitored on a regular basis to record the rate at which the peat subsides. Subsidence is caused by three processes; consolidation, compaction and oxidation (Wosten et al. 1997; Jauhiainen et al. 2012). Primary consolidation occurs due to the increased pressure of the soil layer above the WTD causing a loss of buoyancy in the soil below the WTD in the first year after drainage (Hooijer et al. 2012). Compaction, which perpetuates from the initial time of drainage, is the volume reduction of the peat above the groundwater level as it dries out and results in an increase in the soil bulk density (BD). Oxidation (depending on site conditions), which continues throughout from the start, causes a volume reduction of the peat above the WTD due to the loss of organic matter through decomposition, fires and soluble and physical removal (Hergoualc'h and Verchot 2011). Of the three processes contributing to subsidence, only oxidation results in GHG emissions into the atmosphere. Subsidence measurements in tropical peats are very limited, largely due to the long-term requirement of the measurements (decadal). There are four studies which have recorded subsidence in tropical peats, although these have incomplete subsidence records over time (Stephens and Speir 1969; Wosten et al. 1997; Deverel and Leighton 2010; Hooijer et al. 2012). Only the work of Hooijer et al. (2012) is based on Indonesian peats.

The development of models to predict soil C losses from tropical peatlands has been limited, with most existing models focusing on attempting to define the link between WTD and emissions in Riau and Jambi provinces in Indonesia (Hooijer et al. 2006; Hooijer et al. 2010; Jauhiainen et al. 2008). To date no process-based soil model has been applied to these systems, predominantly due to the limited availability of data with which to accurately simulate soil scenarios (Farmer et al. 2011). However, it is important to be able to predict soil C losses under land use management scenarios to enable informed decision making. Thus there is the need for a tool which can be used by a variety of stakeholders to ascertain the emissions resulting from conversion of tropical peatlands to other land uses. There are some examples of simple-to-use tools developed for stakeholder use that maintain a high level of scientific accuracy and integrity, for example the Scottish Government Carbon Calculator for Wind Farms on Peatlands (Nayak et al. 2008) and the Cool Farm Tool for calculating farm based emissions (Hillier et al. 2011). Both run in Excel and are examples of an easy to use, transparent interface.

By creating a tool which uses the relationships of subsidence to give the net soil CO_2 flux, coupled with model evaluation using the flux outputs as approved by the IPCC, this work presents an option for rapid quantification of peat CO_2 losses.

2 Methods

2.1 Introduction and ethos

Our literature research yielded two published peat subsidence studies within SE Asia, that of Wosten et al. (1997) and that of Hooijer et al. (2012). Wosten et al. (1997) describe a rate of subsidence of 4.6 cm yr^{-1} from years 14 to 28 after drainage, and 2 cm yr^{-1} from years 28 to 40 for a site in Malaysia converted in 1974. They estimate that oxidation makes up 60 % of subsidence, based on the results of a peat oxidation model. More recently, Hooijer et al. (2012) provides a detailed assessment of subsidence rates on Sumatran peatlands after drainage and a comparison with the results of the three other tropical peatland subsidence studies. They present equations for rates of subsidence in both *Acacia* plantations and drained forest sites, applicable to oil palm plantations (Hooijer et al. 2012). As this is the most extensive dataset, the Hooijer et al. 2012 rates of subsidence form the basis of TROPP-CAT, which are then coupled with environmental modifiers and site specific characterisation from which soil C losses and CO_2 emissions are determined. Figure 1 describes the steps within the model for calculating emissions.

2.2 Inputs; step 1

TROPP-CAT is written in Microsoft Excel with the specific aim of being widely accessible. The model is initialised using input data from a specific point in time; either prior to conversion (i.e. still peat swamp forest) or once a site has already been converted (i.e. a plantation of a certain age). All of the required inputs are easily obtainable without the need for complex laboratory analysis; the details of the input parameters are given in Table 1. Default values are based on average literature values for Indonesia and Malaysia.

2.3 Calculations; steps 2–7

The following calculations explain how TROPP-CAT calculates the rate of subsidence according to the WTD and then apportions this into consolidation, compaction, and C losses through oxidation (Table 2 gives definitions and units used). A temperature modifier is

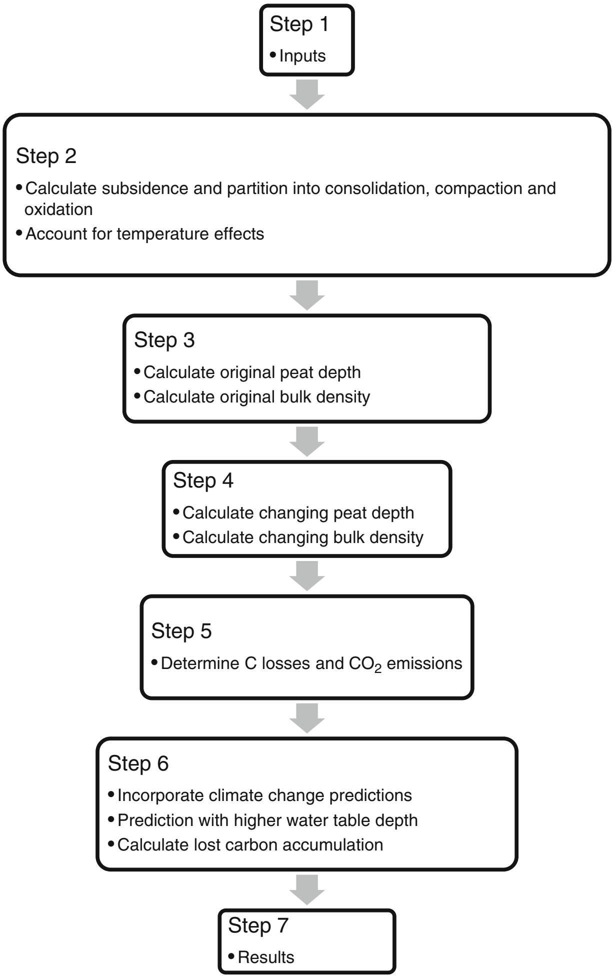

Fig. 1 Breakdown of model steps taken to calculate C losses

applied to the rate of oxidation, and from this the original BD and peat depth are calculated along with annual CO_2 fluxes. Emissions are also calculated under likely climate change scenarios and raised WTDs.

2.3.1 Step 2a; Calculating subsidence, Sub_{yrn}

Yearly subsidence is dependent primarily on the specified WTD (Hooijer et al. 2010; Stephens and Stewart 1976). Over the first 5 years from the time of conversion, t=0, subsidence occurs at a rapid rate due to the immediate loss of buoyancy and the sudden exposure of the peat to air as a result of drainage. This then stabilises to a more steady state (Wosten et al. 1997). The rate of subsidence for Years 1–5 needs to be calculated individually per year and partitioned into contributions from consolidation, compaction and oxidation to establish the CO_2 emissions resulting from the latter.

Table 1 Description of inputs, sources of data and default options

Input	Required information	Data collection	Default value	Unit
In.1	Was the site drained specifically for this plantation development? • If "yes", how long ago? • If "no", when was it drained, and how old is the plantation?	From plantation records, satellite imagery, personal accounts.	"Yes", "6" years ago. If the site is currently undrained, insert "yes" and then "0" as the time since drainage.	
In.2	Annual average water table depth of the plantation	Measured in the site, often by installing perforated PVC pipes into the soil which are monitored on a regular basis. Give consideration to the sampling scheme used.	−0.7 (Hooijer et al. 2012)	m
In.3	Is the bulk density (BD) of the soil surface prior to drainage known? • If "yes" then insert the value. • If "no" then insert the average BD below the water table depth of the current site	Soil sampling methods (Agus et al. 2011). Either the surface BD in an intact site or the average BD value of the soil from below the water table depth to a depth one meter before the lowest peat depth (i.e. avoiding any potential mineral soil interaction).	0.09 (Page et al. 2011a, b)	g cm^{-3}
In.4	Average peat depth of the plantation	Sampled either using an augur or a pole with a scooped end (Agus et al. 2011)	5.5 (Page et al. 2011a, b)	m
In.5	Average carbon content of the soil	Obtained using a number of methods; Loss-on-Ignition, elemental analysis, or modified equation based on that presented in Warren et al. 2012, $\%C = 100 \times \left(\frac{(BD \times 468.76) + 582}{BD \times 1000}\right)$ (Warren et al. 2012)	56 (Page et al. 2011a, b)	% C
In.6	*6a)* Average annual soil temperature of the site *6b)* Average annual air temperature of the site	In situ field measurements using a thermometer. Air temperature can also be obtained from local/national weather stations or online at www.ncdc.noaa.gov	30 (for both)	°C
In.7	Total area of the plantation	From plantation records, or if the site is yet to be converted then the predicted plantation size.	1,000 (to give the user an idea of the scale of emissions over an area)	ha
In.8	Was the site burnt prior to planting? • If "yes" then to what depth? If depth is unknown then insert 0.	Plantation history, personal accounts, or based on examination of the surface soil, in particular for evidence of charcoal.	"No" (as there will likely be evidence of burning on the soil surface if it had been burnt) and "0" (unknown)	m

Table 2 Definitions and units of terms

Symbol	Definition	Unit
Sub_{yrn}	Depth of subsidence in year n or the year specified	m yr^{-1}
$Sub_{COxCyr1}$	Depth of subsidence due to consolidation, oxidation and compaction	m yr^{-1}
BSD	Burn scar depth	m
WT	Water table depth, as inputted by the user (***In. 2*** in Table 2)	m
$MSub_{yrn}$	Depth of the measured subsidence in year n or the specified year	m
MWT_{yrn}	Average water table depth at which the measured subsidence was recorded	m
Con	Depth of subsidence due to consolidation in year 1 only	m
Ox_{yrn}	Depth of subsidence due to oxidation in year n or the specified year	m
Com_{yrn}	Depth of subsidence due to compaction in year n or the specified year	m
$Sub_{tempyrn}$	Depth of subsidence taking into account the effect of temperature on oxidation in year n or the specified year	m
$temp_{\%}$	Temperature percentage change, based on a Q_{10} of 2 between the measured soil temperature (***In. 8*** in Table 2) and 30.5 °C	%
PD_{yr0}	Original peat depth in year 0	m
PD_{yrn}	Peat depth in year n	m
$CSub_{yrn}$	Cumulative subsidence depth up to year n	m
BD_{yr0}	Original bulk density in year 0	g cm^{-3}
BD_{-WT}	Bulk density below the water table (***In. 5*** in Table 2)	g cm^{-3}
BD_C	Change in bulk density due to consolidation	g cm^{-3}
BD_{yrn}	Bulk density in year n	g cm^{-3}
$BD_{yrn\text{-}1}$	Bulk density in the year prior to year n	g cm^{-3}
$Sub_{CompOxyrn+1}$	Depth of subsidence due to compaction and oxidation in year n plus 1	M
PD_{yrn+1}	Peat depth in year n plus 1	M
$Cl_{ox\ yrn}$	Peat carbon losses	t C ha^{-1} yr^{-1}
$S_{\%C}$	Soil carbon content	% carbon
Cl_F	Carbon losses from fire	t C ha^{-1} yr^{-1}
$CO_{2emissions}$	Peat CO_2 emissions	t CO_2 ha^{-1}
C_{acmin}	Minimum rate of carbon accumulation	t C ha^{-1} yr^{-1}
C_{acmax}	Maximum rate of carbon accumulation	t C ha^{-1} yr^{-1}

Consolidation typically occurs in Year 1 as a result of the initial drop in the WTD in the fibrous peat (Hooijer et al. 2012), along with a smaller contribution to the subsidence from oxidation and compaction. Fire used for clearing plantations also occurs in this early stage. Sites are usually drained in a major drainage event due to the installation of drainage canals, so the consolidation effect primarily occurs in the first year of drainage only (Couwenberg 2009). Therefore, Year 1 subsidence is calculated as:

$$Sub_{yr1} = Sub_{COxCyr1} + BSD \tag{1}$$

where Sub_{yr1} is the amount of subsidence (m) in Year 1, $Sub_{COxCyr1}$ is the amount of subsidence due to consolidation, oxidation and compaction (m), and *BSD* is the burn scar depth (the loss of profile depth due to burning, m).

The method used to obtain the burn scar depth *BSD*, (m), depends on whether the site was burnt and the depth (m) of the burn (***In.8***, Table 1).

If the site was not burnt;

$$BSD = 0 \tag{2}$$

If the site was burnt and the depth is known;

$$BSD = In.8 \tag{3}$$

If the site was burnt and the depth is unknown, then likely minimum (0.30 m) and maximum (0.51 m) values for the burn depth (m) are used, based on the range of values in the literature (Page et al. 2002; Siegert et al. 2004; Ballhorn et al. 2009).

$Sub_{COxCyr1}$ is calculated from the amount of subsidence and the depth of the WTD during subsidence:

$$Sub_{COxCyr1} = -WT \times \left(\frac{MSub_{yr1}}{MWT_{yr1} - MWT_{yr0}} \right) \tag{4}$$

where *WT* is the site specific WTD (m) in Year 1 (***In.2*** in Table 1), $MSub_{yr1}$ is the measured subsidence (m, default of 0.75) in Year 1, MWT_{yr1} is the measured average WTD (m, default of 0.7) that $MSub_{yr1}$ was recorded at, and MWT_{yr0} is the initial average WTD (m, default of 0). Figure 2 illustrates this relationship, a similarly linear relationship has previously been presented for tropical peats (Hooijer et al. 2010). The default for measured subsidence is taken from Hooijer et al. (2012), where Year 1 subsidence was observed to average 0.75 m at a WTD of 0.7 m. This was derived from two transects through newly drained areas with observations prior to and after drainage, where Year 1 subsidence was between 0.6 and 0.9 m in deep fibric peats of Sumatra (Hooijer et al. 2012). In more or less decomposed peats this relationship may differ, but because this is the best available data the proportional relationship from this site can be applied to others, with site specific WTDs.

Subsidence in Years 2–5 is again calculated based on a proportion of subsidence and the WTD from Hooijer et al. 2012, see Fig. 2.

$$Sub_{yr2} = -WT \times \left(\frac{MSub_{yr2}}{(MWT_{yr2} - MWT_{yr0})} \right) \tag{5}$$

with default values of *MSub* for Years 2 and 3 set at 0.19 m, and for Years 4 and 5 to 0.145 m, based on measurements from Hooijer et al. 2012.

The annual subsidence from Year 6 onwards is calculated using the ‘intermediate’ equation presented in Hooijer et al. 2012 for *Acacia* and drained forest sites, as a function of WTD (***In.2*** in Table 1), and is generally much lower than the initial 5 years, as shown in Fig. 2.

$$Sub_{yr6+} = 0.69 - 5.98 \times WT \quad (r^2 = 0.43) \tag{6}$$

where Sub_{yr6+} is the subsidence for Year 6 and onwards (m) (Hooijer et al. 2012). Using the default options Sub_{yr6+} is equal to 0.05 m annually. Literature values for the rate of subsidence after the initial years of high subsidence have been recorded to be between 0.02 and 0.054 m yr^{-1} in SE Asian peats (Wosten et al. 1997; Hooijer et al. 2012). TROPP-CAT uses this equation that is based on results from both *Acacia* and drained forest sites, assuming it can also be applied to oil palm plantations as there is currently insufficient data to establish a relationship in oil palm sites.

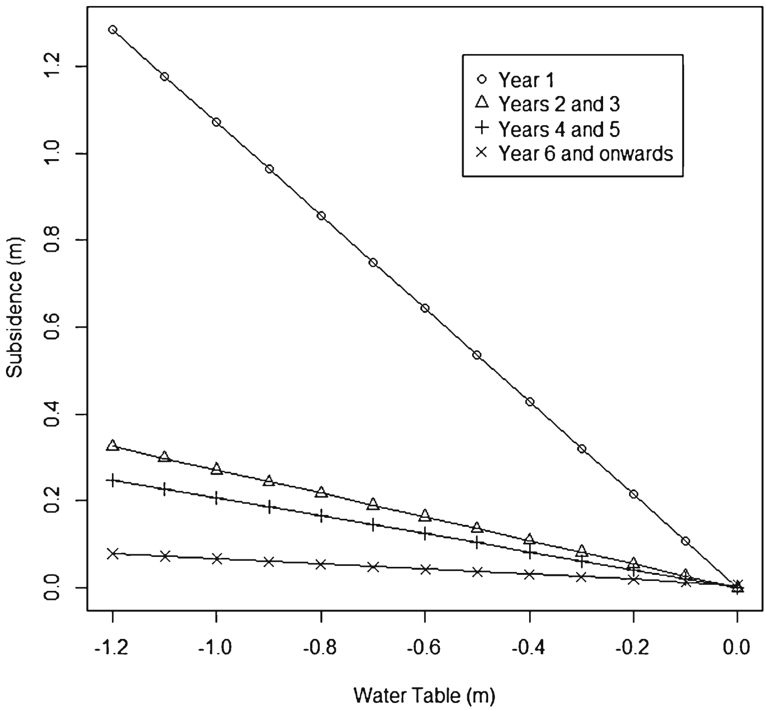

Fig. 2 Graph showing the relationship between subsidence and varying water table depths calculated for each year based on equations from Hooijer et al. 2012 as presented in Eqs. 4, 5 and 6 in this paper

2.3.2 Step 2b; partitioning subsidence due to consolidation, compaction and oxidation; Con, Com_{yrn}, Ox_{yrn}

Consolidation in Year 1 *Con* (m) can be calculated as:

$$Con = \left(Sub_{yr1} - BSD\right) - Sub_{yr2} \tag{7}$$

The amount of subsidence due to oxidation and compaction in Year 1 is assumed (based on data presented in Hooijer et al. 2012) to be the same as that in Year 2, which again is derived as a function of the subsidence (with the default based on rates in Hooijer et al. 2012);

$$Ox_{yr1} + Com_{yr1} = Ox_{yr2} + Com_{yr2} = Sub_{yr2} \tag{8}$$

where $Ox_{yr\ldots}$ is the subsidence depth from oxidation in the specified year (m), $Com_{yr\ldots}$ is the subsidence depth from compaction in the specified year (m) and Sub_{yr2} is the subsidence in year 2 (m).

The default proportions of subsidence due to oxidation and compaction for Years 1–5 are based on the proportional quantities found in Hooijer et al. 2012. Where site specific proportions are available then these can be used instead to improve accuracy.

$$Ox_{yr1} = 0.75 \times Sub_{yr2} \tag{9}$$

$$Com_{yr1} = 0.25 \times Sub_{yr2} \tag{10}$$

where Ox_{yr1} is subsidence due to the oxidation and Com_{yr1} is subsidence due to compaction in Year 1 respectively, and where Sub_{yr2} is defined in Eq. 8. From Year 6 onwards, the proportion of oxidation of total annual subsidence is set between 60 and 92 % depending on the BD values, using a polynomial relationship to define the oxidation (Wosten et al. 1997; Hooijer et al. 2012). Similar to the effect observed in Neilson (1988) where a reduction in respiration was observed with an increase in BD due to loss of aeration, we apply a factor to limit the oxidation, although this is an estimate as this remains currently un-quantified for tropical peats compared to other soils (Murayama and Bakar 1996; Smith et al. 2000).

With the inputs set to the default options the total subsidence over the first 5 years is equal to 1.40 m, of which 0.63 m was due to oxidation, 0.22 m to compaction and 0.56 m due to consolidation (as shown in Fig. 3).

2.3.3 Step 2c; Accounting for temperature effects, $Sub_{tempyrn}$, Ox_{temp}

The rate of decomposition in peats increases positively with an increase in soil temperature (Silvola et al. 1996). Although there are limited studies on tropical peat that have specifically looked at the effect of temperature on decomposition, a doubling of decomposition rate with a 10 °C increase in temperature has been observed (Brady 2002; Hirano et al. 2008; Stephens and Stewart 1976). Areas with lower temperatures have a higher sensitivity to temperature (Kirschbaum 1995), but because this tool has been developed for sites in the tropics, the temperature is never expected to fall below 20 °C and thus a Q_{10} of 2 (the temperature coefficient of the rate of change in decomposition due to a 10 °C temperature change) can be assumed at all sites (the 2007–2011 recorded air temperatures in Indonesia ranged between 26.8 and 27.2 °C with daily values over that time period between 23 and 31 °C (NOAA Satellite and Information Service, Jambi Sultan Thaha airport weather station)). Jauhiainen et al. (2012) indeed apply a Q_{10} of 2 to their study to account for diurnal variability on emissions in their site, where diurnal air temperatures averaging 26.7± 2.9 °C (mean ± S.D.) and 26.9±4.2 °C were recorded from two sites. In sites with higher temperatures the relationship between temperature and microbial decomposition may change, although this is un-quantified in tropical peats and thus a Q10 of 2 is assumed to be most applicable (average annual temperatures along Indonesia's coastal plains are typically 28 °C (UNFCCC 1999)).

The reference temperature for the model calculations is assumed to be 30.5 °C (the average soil temperature recorded at the study site used to calibrate the model). The following equation is used to modify the rates of subsidence based on the temperature modifier:

$$Sub_{tempyrn} = Sub_{yrn} + \left(m_t \times \left({}^{Ox_{yrn}}/100\right)\right) \tag{11}$$

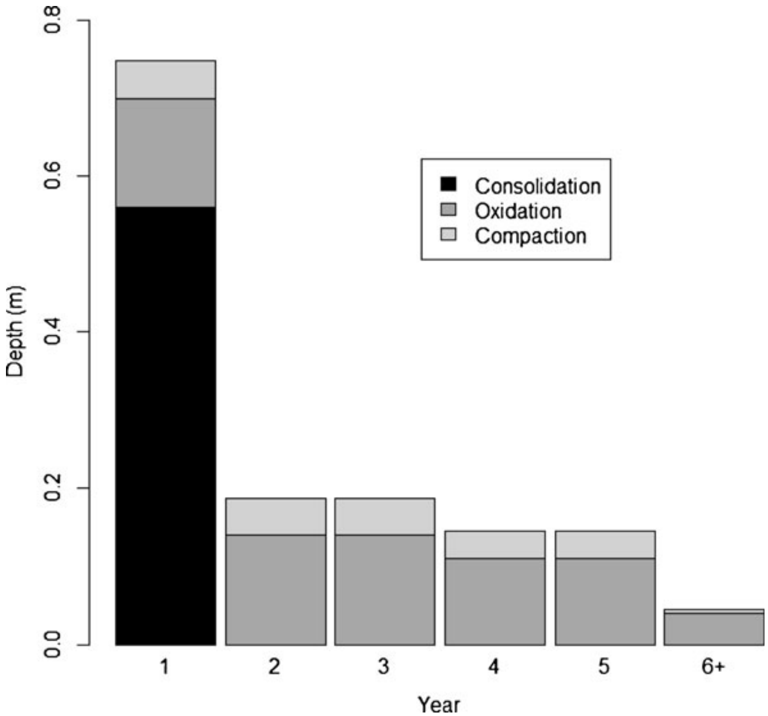

Fig. 3 Graph showing the contribution of consolidation, oxidation and compaction to subsidence as calculated for each year in a site with a WTD of −0.7 m and peat depth of 5.5 m

where $Sub_{tempyrn}$ is the subsidence (m) calculated taking into account the temperature for each year, Sub_{yrn} is the value of subsidence (m) calculated at 30.5 °C for each year, Ox_{yrn} is the depth of soil (m) lost due to oxidation in Year n and m_t is the temperature modifier, based on the difference between the actual soil temperature (***In.6*** in Table 1) and the reference temperature 30.5 °C, with a Q_{10} of 2, equal to;

$$m_t = (t{-}30.5) \times f \tag{12}$$

where t is the site soil temperature (***In.6*** in Table 1), 30.5 is the reference temperature on which the model is based and f is the percentage value used to calculate the temperature modifier by, equal to 10 if t>30.5 and 5 if t<30.5.

2.3.4 Step 3; Calculating the original peat depth, PD_{yr0}

Knowing the original peat depth enables calculations of annual future change to peat depth, which is then used to calculate annual BD changes. The original peat depth is calculated based on the subsidence that has occurred between time 0 and the current year, including any subsidence from fire.

Taking either the time since drainage or the age of the oil palm (***In.1*** in Table 1) and the current peat depth PD_{yrn} (m, ***In.4*** in Table 1), the original peat depth is calculated as:

$$PD_{yr0} = PD_{yrn} + CSub_{yrn} \tag{13}$$

Using the default values of PD_{yrn}=5.5 m and WT=−0.7 m and where $CSub_{yrn}$ (m) is equal to:

$$CSub_{yrn} = Sub_{yr1} + Sub_{yr2\ldots} + Sub_{yrn} \tag{14}$$

and taking into account the temperature effect, TROPP-CAT calculates PD_{yr0}=6.95 m.

2.3.5 Step 3b; Calculating the original bulk density prior to drainage and consolidation, BD_{yr0}

The original BD is required to calculate annual soil C losses. If the original BD is known, then this is used as an input. If the original surface BD is unknown, then it is assumed that the BD at a depth of 1 m below the average WTD (***In.3*** in Table 1) is an indication of the pre-drainage BD with a consolidation effect, and thus it is possible to determine what the original BD value would have been pre-drainage if the consolidation effect is removed (Hooijer et al. 2012):

$$BD_{yr0} = BD_{-WT} - \left(BD_{-WT} \times \frac{Con}{PD_{yro}} \right) \tag{15}$$

where BD_{-WT} is BD below the WTD (g cm^{-3}, ***In.3*** in Table 1), Con is the amount of consolidation, and PD_{yro} is the original peat depth.

2.3.6 Step 4a; Calculating peat depth, PD_{yrn}

For each year a new peat depth is calculated based on the previous year's rate of subsidence:

$$PD_{yrn} = PD_{yrn-1} - Sub_{yrn} \tag{16}$$

where $PD_{yrn\text{-}1}$ is the peat depth in the year previous to year n (m) and Sub_{yrn} is the subsidence in year n (m), all values take into account the temperature effect. The peat depth values are then used to calculate the BD in the current year.

2.3.7 Step 4b; Calculating bulk density, BD_{yrn+1}

The BD is set to increase only during the first 5 years, when the higher levels of consolidation and compaction occur. Although there is continued compaction in all years, the higher level of oxidation is assumed to balance out any increase to BD that would occur from this (Hooijer et al. 2012).

For years 1–5, the BD is calculated by:

$$BD_{yrn} = BD_{yrn-1} + \left(BD_{\ yrn-1} \times \left(\frac{Com_{yrn}}{\left(Sub_{CompOx\ yrn} \Big/ \left(PD_{yrn} \Big/ 100 \right) \right)} \right) \right) \tag{17}$$

where $BD_{yrn\text{-}1}$ is the BD in the year previous to year n (g cm^{-3}), BD_{yrn} is the BD in the year n (g cm^{3}), Com_{yrn} is the depth of subsidence due to compaction in year n (m, Eq. 10), $Sub_{CompOxyrn}$ is the subsidence due to oxidation and compaction in year n, and PD_{yrn} is the peat depth in year n.

2.3.8 Step 5; Carbon losses and CO_2 emissions, $Cl_{ox\ yrn}$, CO_2

In all years, with the exception of Year 1, peat C losses ($Cl_{ox\ yrn}$, t C ha^{-1} yr^{-1}) as a result of subsidence due to oxidation, are calculated as:

$$Cl_{ox\ yrn} = \left(BD_{yrn} \middle/ 100\right) \times S_{\%C} \times Ox_{yrn} \tag{18}$$

In Year 1, emissions from fire are included:

$$Cl_{yr1} = Cl_{ox\ yrn} + Cl_F \tag{19}$$

where

$$Cl_F = BD_{yr0} \times S_{\%C} \times BSD \tag{20}$$

where Cl_F are the C losses from fire (t C ha^{-1}), BD_{yr0} is the original BD as calculated by Eq. 15, *BSD* is the burn scar depth (cm, ***In.8*** in Table 1) and $S_{\%C}$ is the soil C content (% C, ***In.5*** in Table 1). C losses are then converted into CO_2. Using the default options, over the first 5 years the cumulative CO_2 emissions total 1,114 t CO_2 ha^{-1}, a loss of 9 % of the total original soil C ha^{-1}. From Year 6 onwards the net CO_2 emissions settle to a steady annual emissions value of 72 t CO_2 ha^{-1} (see Table 3 for an annual breakdown of C loss when using default values).

In sites where the BD is higher than 0.1 g cm^{-3}, the second component of the BD modifier is applied, limiting the C losses. A 3rd order polynomial curve is used to adjust the actual BD to account for the reduction in soil aeration effect, with the maximum input value that the model works with set to 0.4 g cm^{-3} (set as the model upper limit as it is an unlikely BD value in these soils, not observed in Indonesian peats e.g. Page et al. 2002; Melling et al. 2005a, b; Kool et al. 2006).

2.3.9 Step 6a; Incorporating climate change predictions, $temp_{original}$, $temp_{yrn}$, Sub_{cc}

Based on the work of the IPCC, predicted temperature increases for SE Asia are likely to range between 0.15 and 0.37 °C per decade (IPCC 2007). TROPP-CAT takes this into account by applying temperature changes to the rate of oxidation, using a Q_{10} of 2 (Eq. 11), for both the best and worst case climate change scenarios.

Table 3 Annual results using default values

Year	Annual average CO_2 emissions from oxidation, loss of accumulation and fire (t CO_2 ha^{-1} yr^{-1})	Cumulative average CO_2 emissions from oxidation, loss of accumulation and fire (t CO_2 ha^{-1} yr^{-1})	Average annual heterotrophic emissions (t CO_2 ha^{-1} yr^{-1})
1	228	227	224
2	230	457	224
3	232	690	226
4	180	869	174
5	181	1,051	175
6+	70	1,121	64

Fire losses are zero under the default scenario

2.3.10 Step 6b; Higher water table depth, $Sub_{COxCyrnWT}$

Raised WTDs have been shown to reduce subsidence and are suggested as one mechanism for peat soil conservation (Stephens and Speir 1969). To demonstrate one option for emissions reductions under alternative plantation management practices, a second set of results are calculated based on a 0.20 m higher WTD. These workings are exactly the same as the original subsidence calculations (Eqs. 1, 4, 5 and 6) except that the subsidence linked to the inputted WTD is modified. Using the default inputs, the average annual CO_2 emissions that would result from a 0.2 m higher WTD would drop from 102 to 76 t CO_2 ha^{-1} yr^{-1}. Across a plantation of 1,000 ha, this is equivalent to a reduction of 0.65 Mt CO_2 over a 25 year oil palm cycle, 26 % of emissions from a plantation with the original 0.7 m WTD.

2.3.11 Step 6c; Carbon accumulation, C_{accum}

Peat swamp forests typically accumulate C in the soil, due to the anaerobic conditions and therefore the slow decomposition of organic matter. Sorensen (1993) summarises a selection of peat accumulation predictions, ranging from less than 0.5 to 3 mm yr^{-1}, and Brady (2002) comments that conditions in intact peat swamp forests will be between steady state or accumulating peat. Based on this evidence, the minimum rate of peat accumulation is set to 0 (i.e. steady state) and the maximum to 3 mm yr^{-1}. This is expressed as minimum (C_{acmin}) and maximum (C_{acmax}) C accumulation (t C ha^{-1} yr^{-1}) by:

$$C_{acmin} = 0 \tag{21}$$

$$C_{acmax} = \left(3 \times BD_{yr0} \times S_{\%C} \times 10\right) \Big/ 100 \tag{22}$$

the 10 in Eq. 22 being a residual of the conversion of units. The average of these two values is added to the annual soil C losses.

Using the default values, the annual losses of accumulation are between 0 and 1.51 t C ha^{-1} yr^{-1}, equivalent to an average of 2.8 t CO_2 ha^{-1} yr^{-1}, assuming no accumulation under plantation conditions.

2.3.12 Step 7; Model output

TROPP-CAT summarises results for the average total and annual losses of soil C and net CO_2 emissions over a 25 year period (i.e. one oil palm cycle or five *Acacia* rotations) on a per hectare and site basis for a business as usual scenario and with a raised WTD. Climate change scenarios are used to predict future peat C stock losses. Maximum and minimum values are given for all results.

The model is set up to run from time of drainage rather than the age of the plantation, with the emissions presented on the results page of the spreadsheet as those due to plantation development only, ensuring that emissions not attributed to the plantation are excluded (i.e. if the site had originally been drained for other purposes).

Using the default inputs, the total soil C losses over a 25 year plantation cycle are between 678 and 716 t C ha^{-1}. This is equivalent to an average of 2,556 t CO_2 ha^{-1} over this time period, which at a 0.20 m higher WTD (of 0.5 m) would have been 1,902 t CO_2 ha^{-1}.

3 Analysis of model behaviour and model evaluation

3.1 Model sensitivity

A sensitivity analysis was carried out for the model using the default values for each input. The model was highly sensitive to time since drainage, but only between Years 1–5. The most sensitive input parameters on outputted emissions were WTD, BD, %C and soil temperature (Fig. 4). The model is particularly sensitive to soil temperature, due to the Q_{10} relationship used. The model responds similarly to BD and C content, due to the direct relationship with these variables within the emissions calculations. The model is not highly sensitive to peat depth, even when it is set to a 100 % increase above the original conditions (Fig. 4).

3.2 Model uncertainty

An uncertainty analysis was done to assess the relative importance of each input to the model result, holding default values for the model constant as individual inputs were altered within the likely range of input values as obtained from the literature (Table 4, Nayak et al. 2010). Peat depth, WTD and BD introduce the highest level of uncertainty in the input

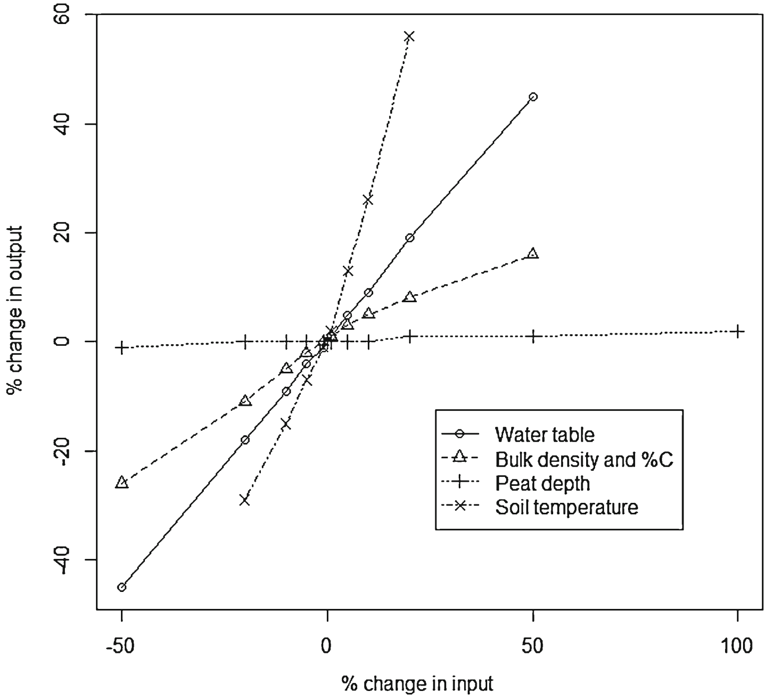

Fig. 4 Graph showing the sensitivity of inputs to change. The % change in input differs for each input based on the change that it imparts on the input and then the model e.g. for the default peat depth of 5.5 m, a 100 % increase in the input to 11 m depth is still a feasible peat depth, but the model cannot work with a 100 % decrease to 0 m. With the BD and %C, a 100 % change would set the input at unrealistic values e.g. a %C value of 56 % increasing by 50 % would give us 78 % which is an unreasonable value and one which the model is not designed to use. In the case of WTD an increase in the input relates to a deepening of the WTD

Table 4 Uncertainty test of model inputs

Input	Literature minimum	Default	Literature maximum	% change in inputs	Minimum emissions (t CO_2 ha yr^{-1})	Average emissions (t CO_2 ha yr^{-1})	Maximum emissions (t CO_2 ha yr^{-1})	% change in emissions	Relative contribution to emissions uncertainty[a]
Soil temperature (°C)	26.5[b]	30	33.3[b]	23	85	102	132	46	2
Carbon content (% C)	44.69[c]	56	57[d]	22	82	102	104	22	0.98
Water table depth (m)	−0.36[b]	−0.7	−1.08[b]	103	58	102	152	92	0.89
Bulk density (g cm^{-3})	0.076[e]	0.09	0.18[f]	116	94	102	127	32	0.28
Peat depth (m)	0.5[g]	3	20[g]	650	100	102	107	7	0.01

[a] The relative contribution to emissions uncertainty is calculated as % in emissions/% change in inputs (Nayak et al. 2010)

[b] Jauhiainen et al. 2012

[c] Melling et al. 2005a, b

[d] Shimada et al. 2001

[e] Page et al. 2004

[f] Farmer (unpublished)

[g] Hooijer et al. 2010

values, due to the large range of values presented in the literature. This high uncertainty in the peat depth (due to variability in literature values) did not lead to high uncertainty in modelled outputs due to the low model sensitivity to this input (relative contribution to emission uncertainty=0.01). The observed range of WTDs is high, which is perhaps surprising considering that plantation management needs to maintain a specific range of WTD for optimum plantation output. This causes high uncertainty in emissions and one of the highest relative contributions to uncertainty in the emissions results (relative contribution to emission uncertainty=0.89). C content and soil temperature also have high relative contribution to uncertainty in the emissions; in the case of the soil temperature this is due to a low uncertainty in input variables and a proportionally higher uncertainty in model output.

3.3 Model evaluation

The model output soil C losses represent the net C loss from heterotrophic emissions, fire, CH_4 emissions and soluble and physical removal. Hergoualc'h and Verchot (2011) present estimates of the possible C losses in tropical peatlands, indicating that 1.0±0.5 t C ha^{-1} yr^{-1} is lost through soluble and physical removal, and CH_4 emissions in oil palm (*Elaeis guineensis*) plantations are often negligible. Therefore, in the absence of better data, the model can be evaluated by directly comparing the model estimates of losses due to oxidation and fire (with an assumed value for emissions due to soluble and physical removal), to field measurements of soil C losses.

The model functionality was tested for the *Acacia* site of Hooijer et al. 2012, which was not independent of the data used to develop the model. The model simulated emissions to within 4 % of the measured emissions. Independent evaluations were also done to quantify the expected uncertainty in the model estimates at a number of sites in Riau and Jambi provinces in Indonesia and one site in Malaysia for *Acacia* and oil palm plantations of different ages. The model was also used to quantify heterotrophic emissions in sites where only the total soil efflux (from both heterotrophic and autotrophic sources) was measured. However, further evaluation of the model is limited by availability of data and thus as more results become available in the literature the model can be further evaluated and improved upon (Table 5).

3.3.1 Independent evaluations

All site inputs and evaluation results can be found in Table 5. In the 14 year oil palm the model overestimated the average measured value, but the modelled value was within the experimental error introduced by the uncertainty in the measured heterotrophic emissions. This uncertainty was due to the high variability in the CO_2 efflux measured, which ranged from less than 10 to over 150 t CO_2 ha yr^{-1} (Marwanto et al. in prep). In the Malaysia site, the literature reported heterotrophic emissions between a possible range due to uncertainty in the measured and modelled emissions for the site (Melling et al. 2005a, b), TROPP-CAT modelled emissions 4 % above the range of measured emissions (Table 5).

The model was also applied to sites with unknown heterotrophic emissions and used to interpret the measured results that were available on the total efflux (heterotrophic and autotrophic emissions). In three of the Jambi oil palm sites the measured emissions for this site ranged between a minimum heterotrophic emissions value and a maximum efflux value for the site. The minimum possible heterotrophic value was based on an average rate obtained from respiration collars with zero root density below them (i.e. only heterotrophic

Table 5 Table showing inputs used for each evaluation and measured and modelled emissions for each site. Blank cells are where no measured data is available

Site	Site drainage and history	Water table depth (m)	Bulk Density (g cm^{-3})	Peat depth (m)	Soil C (%)	Soil and air temperature (°C)	Plantation area (ha)	Burn history	Measured heterotrophic emissions (t CO_2 ha^{-1} yr^{-1}±SE)	Modelled heterotrophic emissions for that year (t CO_2 ha^{-1} yr^{-1})	Average total measured efflux (t CO_2 ha^{-1} yr^{-1}±SE)	Modelled heterotrophic emissions as a percentage of total efflux (%)
6 year average *Acacia*, (Jauhiainen et al. 2012)	Average 6 years	−0.7	0.073	8.89	54 (using BD and Warren et al. 2012)	30.5, 30	Default (1,000 ha)	no	80 (average emissions)	83 (average emissions		
Jambi 14 year oil palm, (Marwanto 2012)	14 years	−0.99	0.14	5.9	49.96	26.7, 28	Default	no	46±30	69		
Malaysia, (Melling et al. 2005a, b)	Drained 6 years, oil palm 4 years	−0.602	0.15	5.55	44.7	27.8, 30.5	Default	? no	34 to a possible maximum of 40	42		
Jambi 4 year commercial oil palm	Drained approx. 8 years, oil palm 4 years	−0.727	0.08	6	51.17	27.94, 26.9	1516.06	yes	31±2 to 97±17	51	97±17	53 %
Jambi 6 year commercial oil palm	Drained approx. 8 years, oil palm 6 years	−0.66	0.081	7	51.29	26.58, 27.98	1053.45	yes	24±1 to 75±10	44	75±10	59 %
Jambi 7 year commercial oil palm	Drained approx. 8 years, oil palm 7 years	−0.57	0.18	3.76	59.27	28.31, 26.9	802.96	yes	27±2 to 98±18	55	98±18	56 %
Jambi 1 year smallholder oil palm	Drained approx. 8 years, oil palm 1 year	−0.24	0.14	0.97	46.37	27.02, 27.05	Default	yes		18	33±3	55 %
Jambi 4 year smallholder oil palm	Drained approx. 8 years, oil palm 4 years	−0.59	0.15	1.5	46.47	27.02, 27.05	Default	yes		40	52±6	77 %

emissions, but likely missing some rhizosphere microbial respiration (Kelting et al. 1998)). The maximum value was the average overall total efflux from the site (Table 5).

3.3.2 Moratorium scenarios

Under the 2011 Moratorium on New Forest Concessions in primary natural forests and peatland areas in Indonesia, a total of 22.5 M ha of forest and peatlands were temporarily protected (Murdiyarso et al. 2011). Of this area, 11.2 M ha were previously unprotected peatland. However, 5.8 M ha of peatland in Indonesia remained unprotected outside of the Moratorium's boundaries and those of conservation areas (Murdiyarso et al. 2011). Table 6 shows the likely emissions that would result if permanent conservation legislation and national regulations on peatland management were implemented across these peatlands, as simulated by TROPP-CAT (RSPO 2007; ASEAN Secretariat 2003). However, this does not take into account other ecosystem services and benefits provided by the peatland forest systems, which must be given consideration. Apart from conservation across all 16 M ha, the combination of both national regulations and conservation legislation results in the highest emissions reductions (1.59±0.151 Gt CO_2 yr^{-1} (Table 6)).

4 Model limitations and improvements

The model uses a number of assumptions for parameterisation and evaluation, mainly due to limitations in the extent of available data. With further publication of new research, TROPP-CAT can be improved, whilst maintaining its core principal of user friendly access.

4.1 Subsidence and oxidation

Some error may be introduced by setting the default rate of subsidence based on the results of just one study on a certain peat type (Hooijer et al. 2012). Although the subsidence measurements from their work are extensive and comparable with other tropical peat studies, peat at sites across Indonesia at different stages of decomposition and depth may subside at different rates. However, there is currently no data available to quantify this.

One of the key assumptions within the calculator is the proportional contribution of oxidation to overall subsidence based on values from Hooijer et al. (2012) and Wosten et al. (1997). Although the methods used to obtain these values have limited description in Wosten

Table 6 Emissions scenarios for previously unprotected peatland areas included under the Moratorium (11.2 M ha) and excluded under the Moratorium (5.8 m ha)

Scenario	Emissions
11.2 M ha and 5.8 M ha of peatland left un-conserved under a business as usual scenario	2.1±0.167 Gt CO_2 yr^{-1}
11.2 M ha and 5.8 M ha left un-conserved but subject to ASEAN and RSPO standards of management	1.4±0.044 Gt CO_2 yr^{-1}
11.2 M ha conserved, 5.8 M ha business as usual	0.762±0.061 Gt CO_2 yr^{-1}
11.2 M ha conserved, 5.8 M ha subject to ASEAN and RSPO standards of management	0.51±0.016 Gt CO_2 yr^{-1}
11.2 M ha and 5.8 M ha all conserved	0 Gt CO_2 yr^{-1}

et al. (1997), and are based on assumed values of C content and BD from below WTD in Hooijer et al. 2012, they are the most comprehensive estimates to date for Indonesian peats and are comparable to other results from tropical peats.

4.2 Bulk density

Although the model allows for original BD data to be inputted, it is assumed that this information will not be available to most land use managers as change will have already occurred to the soil in question. Calculating the original BD using the BD value from below the WTD assumes that apart from consolidation (which TROPP-CAT accounts for), these BD values are representative of original surface BD (which from a peat core in a Kalimantan peat swamp forest showed no significant difference at 100 cm increments down the 9 m peat profile, Page et al. 2004). An alternative way to estimate the original BD would be to use the surface BD of the current site and back-calculate what the likely effect of compaction and oxidation would have been to get the original BD. However, the spatial and temporal variability that this soil layer is exposed to makes it difficult to accurately assess the range of effects. Alternatively the surface BD of an adjacent, un-drained site could be used. However it is almost impossible to find sites of similar original conditions due to differences in locations on the peat dome and the lack of a nearby intact peat swamp forest. Additionally, drainage in plantations could potentially have an effect over larger areas, possibly to areas beyond the plantation boundaries, so even neighbouring forest sites may have been affected by drainage.

In its current state, TROPP-CAT uses a very basic BD modifier that restricts the contribution from oxidation to overall subsidence, and calculates C losses to an adjusted BD value once the BD reaches 0.1 g cm^{-3}. This is based on the assumption that higher BDs will limit soil aeration (Kasimir-Klemedtsson et al. 1997), but there is no available data on this for these peats.

4.3 Fire

The effect of fire in the model is limited in its assumption that all the soil C in the burn scar depth is lost to the atmosphere. In reality, a proportion of this will become inert organic matter in the soil, remaining there for substantial periods of time (Gonzalez-Perez et al. 2004). Currently the default range of peat scar depth is based on limited values from the literature. As more research into the effects of burning in peatland is published, new defaults can be incorporated.

4.4 Soil C pools

TROPP-CAT does not partition soil C into pools, which may cause an over or under estimation of emissions. The model currently accounts for a likely increase in resistant organic matter in the soil surface, but this is limited to the subsidence observed in Wosten et al. (1997).

4.5 Inter-annual fluctuations over time

The model does not account for changes to the WTD over the duration of the plantation lifetime; but rather assumes that management maintains a steady WTD as most plantations have a target WTD. To maintain simplicity of use and application to large scale plantations, it is more practical to have an annual WTD as an input, rather than using monthly or daily data but this could be incorporated in a future version of the model. In addition, the model does not consider the effects of irreversible drying and other possible impacts to the peat due to changes in WTD.

4.6 Plantation management

Additional management operations, such as applying empty fruit bunches and palm oil mill effluent or fertiliser to the soil, are not accounted for in TROPP-CAT. Application of the palm by-products has been shown to add organic C to the soil, increasing soil C by about 0.3 t C ha^{-1} yr^{-1} (Melling et al. 2005a, b) which is equivalent to 1.3 % of annual average total soil C losses for the Hooijer et al. 2012 *Acacia* site and is therefore considered small enough to exclude. The CO_2 emissions resulting from the application of fertiliser to Indonesian peats is yet to be documented in detail. The use of the fertilised Hooijer et al. 2012 sites for model parameterisation means that on less fertilised sites measured emissions may be lower than those that may be predicted using TROPP-CAT.

4.7 soil pH

TROPP-CAT is parameterised for acidic soils. However, any effect of change in pH is not accounted for by the model, even though this is documented as having an impact on CO_2 emissions (Smith et al. 2010). Smith et al. (2010) apply a pH modifier in their ECOSSE model, whereby the rate of decomposition decreases once the pH falls below a critical threshold of 4.5. Although their model is applicable to tropical peats, the effect of change in pH is excluded from TROPP-CAT at this time due to lack of data in the literature from which to test and validate this modifier.

4.8 Further application

TROPP-CAT can be applied to *Acacia* and oil palm plantations, and in theory could be applied to other types of tree based and annual crop systems on peat as well, although it is yet to be validated against these land use types. Although TROPP-CAT has been developed for application in Indonesia, it could be applied to other SE Asian peatlands, particularly in Malaysia, as shown in the evaluation section. Default values for other countries may vary slightly, but the basic functions of the calculator could be expected to be applicable across peatlands of SE Asia due to the similar climatic conditions, if the original vegetation and soil conditions (i.e. peat swamp forest) were comparable. The model is currently limited to drainage depths between −0.5 and −1.2 m, peat depth of a minimum of 0.5 m and use for peat soils only.

5 Conclusions

A functional tool is presented that predicts emissions from tropical peats under plantation management using only readily available input data. Sensitivity of key inputs, in particular the soil temperature, BD and %C highlight the value of site specific data, although running the model with default values does give acceptable results. Although the calculator is based on a number of assumptions and includes some limitations, evaluation of outputs across sites has shown that it simulates net CO_2 fluxes from the soil to within 6 % of measured emissions and, in the case of a site with highly variable results, within the range of measured error. It has also been used to estimate heterotrophic emissions in situations where only the total efflux is known. As further research into rates of subsidence, proportions of this due to C loss processes, effects of BD on emissions and other specific conditions to tropical peats becomes available, this work can be used to further improve model outputs and applicability across tropical peats.

Calculations provided by TROPP-CAT demonstrate the potential emissions reductions that could be achieved through changes to plantation management, even by as little as a 20 cm rise to the WTD. Considering that WTD is a key driver of subsidence and oxidative losses of soil C, the outputs of this model highlight the importance of WTD management. The model offers the opportunity for site specific, regional and even national simulations within Indonesia, and with caution can be applied to other countries in SE Asia.

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