Carbon fluxes and greenhouse gas emissions from wetland wildland fires in the 2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands

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ABSTRACT

At its 33rd session, the Intergovernmental Panel on Climate Change (IPCC) decided to produce additional guidance, the "2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands", to cover both inland wetlands and coastal wetlands. The 2006 IPCC Guidelines themselves note that the guidance on wetlands is incomplete. Emissions inventory methodologies for prescribed and wildland fires were specifically identified as a knowledge gap. While the IPCC (2006) Guidelines cover CO_2 and non-CO_2 emissions from fires, there is only limited guidance for above-ground carbon stocks and no guidance on losses from organic soils. Compared to vegetation fires, the uncertainties of emission estimates of peat fires are high, because peat can burn repeatedly and to different depths. Furthermore, various compounds and gases can be emitted depending on the type and density of the peat. Thus not only the area, but also the depth of the fires and the type of emissions must be determined, which is only feasible in higher Tier levels. We discuss tasks which include literature search, evaluation of scientific appropriateness, development of decision trees for national methods for carbon fluxes and greenhouse gas emissions for international prescribed and wildland fires on wetlands.

INTRODUCTION

The Intergovernmental Panel on Climate Change (IPCC) is working towards its next major report, the Fifth Assessment Report. Working Group I will issue "The Physical Science Basis" in mid-September 2013, Working Group II will issue "Impacts, Adaptation and Vulnerability" in mid-March 2014, Working Group III will issue "Mitigation of Climate Change" in early April 2014, and the "IPCC Fifth Assessment Report (AR5)" will be issued in October 2014. The next round of IPCC assessment report will again provide world governments with the most current scientific understanding of the state-of-knowledge about global climate change, the potential impacts to nations, and adaptation and mitigation strategies. The IPCC reports are intended to be periodic assessments of the most recent scientific, technical, and socio-economic information. The IPCC describes these assessments as "policy-relevant, but not policy-prescriptive".

One of the noted deficiencies in the IPCC (2006) Guidelines cover CO_2 and non-CO_2 emissions from fires. Previous IPCC guidelines covered above-ground carbon stocks (biomass and dead organic material) and failed to address losses from combustion of peatlands. Compared to above-ground vegetation combustion during wildland fires, the uncertainties of emission estimates of below-ground peat combustion are high. Peatland soils can combust for extended periods of time, burn repeatedly over time in response to changing soil moisture and surface hydrology, and combust to different soil depths. Emissions from above- and below-ground can produce various

compounds and gases which are emitted depending on vegetation type, wildland fire behavior, meteorlogy, and type, density, and depth of the peat. Accurate emissions estimates are not only area burned and vegetation consumption dependent, but also the depth and density of peat soil compustion and the type of emissions must be determined, which is only feasible in higher Tier 3 and 3 levels.

The global contribution of biomass burning to carbon (C) emissions in the atmosphere was identified as an important source of radiatively and photochemically reactive trace gases in 1980 (Seiler and Crutzen 1980), however the direct and indirect contributions of wildland and prescribed fires, biomass combustion for domestic and industrial uses, and fossil-fuel combustion to total C emissions and the positive feedbacks on the climate system remain difficult to assess (Bowman et al. 2009). Crutzen et al. (1979) investigated the atmospheric budgets of trace gases in the atmosphere including carbon monoxide (CO), molecular hydrogen (H_2), nitrous oxide (N_2O), nitric oxide (NO), nitrogen dioxide (NO_2), and carbonyl sulfide (COS). Seiler and Crutzen (1980) showed that these trace gases were emitted into the atmosphere in large quantities by measuring emission rates of trace gases relative to carbon dioxide (CO_2) in the smoke plumes of forest and grassland wildland fires. Total global emission rates of trace gases were approximated from CO_2 released into the atmosphere during wildfires and prescribed burning across different ecosystems and land management practices. A general model was used to estimate the biomass burned annually in global biomes which consisted of total land area burned, the average organic matter per unit area, the average above-ground biomass relative to the total average biomass, and the burning efficiency of the above-ground biomass. Seiler and Crutzen (1980) calculated annual global C emissions from wildland fires of 2-4 Pg C. However, the emissions model did not include the contribution of soil C released during wildland fires which have the potential to be much higher than aboveground emissions on a per unit land area basis. Wong (1978) estimated wildfire soil C emissions at 400Tg C yr^{-1} and Seiler and Crutzen (1980) subsequently revised downward to 100 Tg C yr^{-1}. A recent study (van der Werf et al. 2010) excluded fuelwood burning from the C emissions estimate of Seiler and Crutzen (1980) and calculated annual global C emissions of 2.6 Pg (ranging from 1.7-3.5 Pg C). The fire C emissions budget was allocated to agricultural waste burning (33%), shifting agriculture characterized by deforestation, agricultural production, and subsequent reforestation (29%), savanna region wildfires (21%), deforestation characterized by permanent forest removal (12%), temperate region wildfires (4%), and boreal region wildfires (1%).

Recent advances in satellite-derived fire products using MODerate resolution Imaging Spectroradiometer (MODIS) data from the Terra and Aqua satellites, the Advanced Very High Resolution Radiometer (AVHRR) sensor on the National Oceanic and Atmospheric Administration (NOAA) Polar Operational Environmental Satellite (POES), and the Geostationary Operational Environmental Satellite (GOES) to quantify burned areas in near-real-time have enhanced the ability to estimate regional and global wildland fire emissions (Gregoire et al. 2003; Simon et al. 2004; Giglio et al. 2006). Remotely sensed data and their products have been used in combination with biogeochemical and terrestrial ecosystem models to estimate emissions (Hoelzemann et al. 2004; Ito and Penner 2004; Jain et al. 2006; van der Werf et al., 2003, 2004, 2006). These studies estimated annual global wildland fire C emissions that ranged between 1 and 3 Pg C, with large interannual variability associated with global fire activity and ~20% uncertainty in C emissions (Field and Shen 2008; van der Werf et al. 2010). The spatial

and temporal uncertainty in wildland fire C emissions were highest in boreal, temperate, and equatorial Asian ecosystems due to the lack of accurate field measurements and remotely sensed satellite observations in estimating fuel consumption during long-duration organic soil wildfires. Uncertainties in the estimation of deforestation and burned area, fuel loading, and combustion efficiency were likely sources of underestimating global C emissions (van der Werf et al. 2010).

Quantifying the magnitude and spatial extent of C storage in peatlands is an important first step towards predicting C emissions during wildland fires and the changes in regional C balance in response to land use and land cover change. Peatlands are wetlands with an organic soil layer of at least 30 cm, which may extend to 15-20 m depth (Turunen et al. 2002), store more C than any other terrestrial ecosystem per square meter, and exert a net cooling effect on the global radiation balance (Dise 2009). Peatlands comprise less than 3% of the Earth's land area or 400 Mha and store an estimated 15-30% of the global soil C stocks (Limpens et al. 2008; Solomon et al. 2007) (Figure 1.). Boreal and subarctic peatlands cover 346 Mha and comprise a C pool that ranges from 273 Pg (Turunen et al. 2002) to 455 Pg (Gorham 1991) to 473–621 Pg (Yu et al. 2010), temperate peatlands cover an estimated 350 Mha and store 455 Pg of C (Moore 2002), tropical-subtropical peatlands in Southeast Asia cover 27.1 Mha and store 42–55 Pg C (Hooijer et al. 2010, Yu et al. 2010) and South American peatlands cover 4.5 Mha and have accumulated 13–18 Pg C (Yu et al. 2010). The spatial heterogeneity of peatland soils and vegetation poses challenges to quantifying C storage and wildland fire emissions, and estimating interannual variability and uncertainty. Global organic C is estimated to be 684–724 Pg of C in the upper 30 cm of soil, 1,462–1,548 Pg of C in the upper 100 cm, and 2,376–2,456 Pg of C in the upper 200 cm (Batjes 1996).

Figure 1. Peat distribution of the world
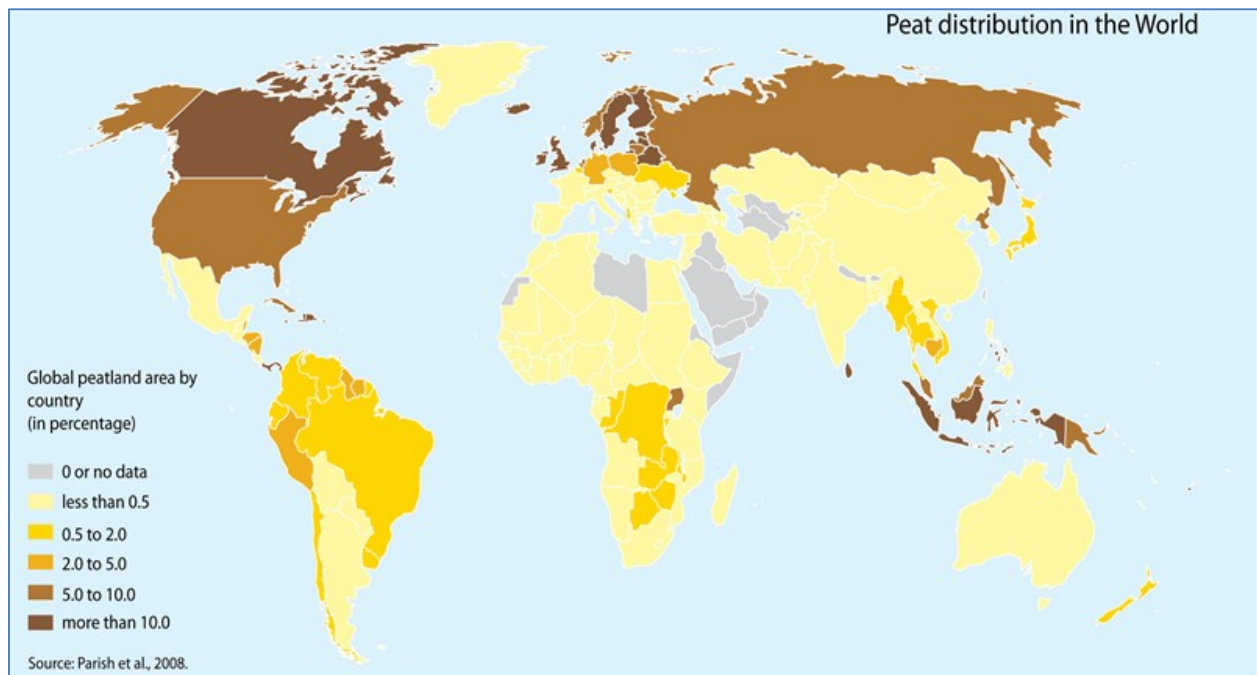
(Figure UNEP GRID-Arendal; http://www.grida.no/graphicslib/detail/peat-distribution-in-the-world_8660#)

In the continental United States, temperate peatlands are found primarily in the Great Lakes region in hardwood forest and non-forested ecosystems and in the coastal plain of the Southeastern and Gulf states. The total area of organic soils for the contiguous United States is estimated at 6.08 Mha and the amount of organic C held in organic soils is estimated at 1,714.7 Tg at 0-30 cm depth, 5,088.4 Tg at the 1-100 cm depth, and 7,590.0 Tg at the 0-150cm depth (Johnson and Kern 2003). The reported total C stored in temperate peatlands in one field study in the northern state of Minnesota was 1,286 ±125 Mg C ha-1, with 90–99% of that C found in peat soils that ranged from 1 to 5 m in depth (Weishampel et al. 2009). In the southeastern state of North Carolina, the estimated total area of peatland soils is 0.27 Mha with a total C pool of 327 Tg (Ingram and Otte 1981).

Wildland fire emissions in the continuous United States vary considerably year to year, with average annual C releases estimated at 58 Tg (Wiedinmyer and Neff 2007). Examinations of surface fires have attributed approximately two-thirds of the fire extent and emissions in the southeastern United States to prescribed fires (Wiedinmyer and Neff 2007; NIFC 2010). However, wildfires that ignite organic peat soils in this geographic area are frequent phenomena when drought conditions prevail. Despite their potential for large positive feedbacks to the climate system through sequestration and emission of greenhouse gases, peatland fires and their C emissions are not explicitly included in global climate models and therefore in predictions of future climate. In North America, modeling efforts in boreal regions have begun to address ground fire contributions to C emissions but temperate peat fires have received much less attention (Poulter et al. 2006; de Groot et al. 2007; de Groot et al. 2009). This information gap is in part due to uncertainties in soil depth, composition, and physical properties of region's peat soils.

METHODS
The IPCC was created in 1988 in order to evaluate the causes and effects of climate change and to collect scientific peer reviewed and published scientific and technical literature. The IPCC does not conduct its own research. Science panels collect and summarize the literature and review panel validate the findings resulting in published IPCC Assessment Reports which began in 1990, and have been subsequently updated in 1995, 2001, 2007, and the upcoming IPCC Fifth Assessment report in 2014. In its Forth Assessment Report in 2007 the IPCC projected a global sea level rise increase of 18 to 59 centimeters from 1990 to the 2090s, plus an unspecified additional rise as a result of accelerated melting of the large ice sheets covering Greenland and Antarctica. Best estimates and likely ranges for global average temperture increases for the six Special Report on Emissions Scenarios (SRES) emissions marker scenarios were presented in the IPCC Forth Assessment Report (AR4) and shown in Figure 2. The best estimate for the low scenario (B1) is a global increase in temperature of 1.8°C (likely range is 1.1°C to 2.9°C), and the best estimate for the high scenario (A1FI) is a global increase in temperature of 4.0°C (likely range is 2.4°C to 6.4°C).

Figure 2. IPCC Forth Assessment Report Global Temperature Projections to 2100 (Figure SPM-5 from the AR4).
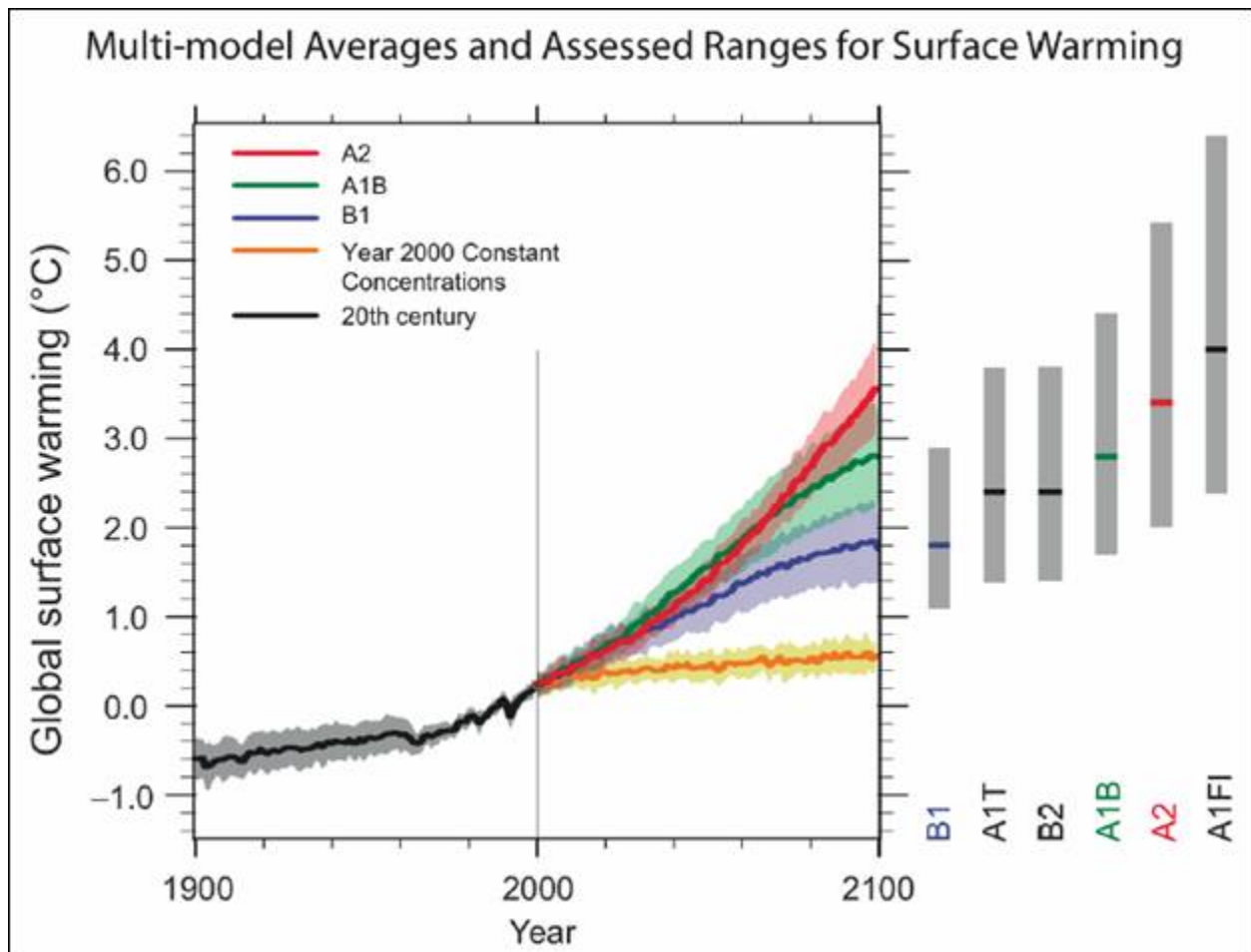
Climate warming associated with elevated greenhouse-gas concentrations is likely to create atmospheric conditions and wildland fire fuels that are conducive to large-scale severe fires. The consensus view of the IPCC is that projected higher summer temperatures will likely increase the annual wildland fire window of high fire risk by 10-30%. Areas such as Canada could see a potential increase in area burned 74-118% by the year 2100. General circulation model studies suggest that fire occurrence or area burned could increase across North America under a doubled CO_2 environment because of increases in lightning activity, the frequency of surface pressure and associated circulation patterns conducive to surface drying, and fire-weather conditions in general that are conducive to extreme wildland fire behavior.

Both uncontrolled (wildfires) and managed (prescribed) fires can have a major impact on the non-CO_2 greenhouse gas emissions from wetland biomass burning, smoldering combustion of soil organic C stocks, and spontaneous ignition of peat in stockpiles. Determining the spatial extent and temporal variability of C storage in boreal, temperate, and tropical peatlands is an

important first step towards predicting C emissions during uncontrolled and managed fires and the changes in regional carbon balance in response land use and land cover, and climate change.

Non-CO$_2$ greenhouse gas emissions from biomass burning

Both uncontrolled (wildfires) and managed (prescribed) fires can have a major impact on the non-CO$_2$ greenhouse gas emissions from wetlands. Wetlands (i.e. marshes, swamps, bogs, and fens located within Marine, Estuarine, Riverine, Lacustrine, and Palustrine systems) include any land that is covered or saturated by water for all or part of the year, and that does not fall into the IPCC Forest Land, Cropland, or Grassland categories. IPCC guidance on estimating and reporting greenhouse gas (GHG) emissions from wetlands is confined to managed wetlands. Managed wetlands are defined as wetlands where the water table is artificially changed (e.g., drained or raised) or those created through human activity (e.g., damming a river). Emissions from unmanaged wetlands are not reported. In wetlands, emissions of CO$_2$ from biomass burning also need to be accounted for because they are generally not synchronous with rates of CO$_2$ uptake. This is especially important after shrub and forest stand replacing wildfires, and shifting cultivation. Where the type of wetland changes (e.g., conversion of shrub and forested wetlands to herbaceous vegetation and open water), there may be net emissions of CO$_2$ from biomass burning during the initial years, in particular if significant fine and coarse woody debris and shrub and forest biomass is burnt during the conversion. Over time, however, the impacts are not as great as those that result from Wetlands converted to forest land or grassland. Fire emissions during land-use conversion are reported in the new land-use category unless restricted Approach 1 land area representation is being used without supplementary data to enable land use conversions to be identified explicitly, in which case fire emissions from wetlands remain in the wetland category.

Non-CO$_2$ emissions (particularly carbon monoxide (CO), methane (CH$_4$), non-methane volatile organic compounds (NMVOC) and nitrogen (e.g., N$_2$O, NO$_x$) species) that result from incomplete combustion of biomass in managed wetland are reported, regardless of their nature (natural or anthropogenic fire). The amount of biomass burnt in any one fire may change from region to region, as well as vary seasonally. The efficiency of combustion and the corresponding fraction of the biomass converted into non-CO$_2$ greenhouse gases may also vary. Countries report non-CO$_2$ emissions from biomass burning in *Wetlands Remaining Wetlands* using annual data, instead of an average of activity data for a given period. This allows the reporting to capture interannual fluctuations due to climatic events (such as El Niño), or natural climatic variability (unusually dry years, when disturbances from fire may be more frequent). Generally, the estimates are highly uncertain due to the lack of reliable and accurate data on the area burned, mass of fuel available for combustion, above- and below-ground fuel consumption, and emission factors. The general method for estimating greenhouse gas emissions in *Wetlands Remaining Wetlands is* described in Equation 2.27 in the 2006 IPCC Guidelines for Natural Greenhouse Gas Inventories, Chapter 2.

Equation 2.27
Estimation of greenhouse gas emissions from fire

$$L_{fire} = A \cdot M_B \cdot C_f \cdot G_{ef} \cdot 10^{-3}$$

Where:

> L_{fire} = amount of greenhouse gas emissions from fire, tonnes of each GHG e.g., CH_4,
> N_2O, etc.
> A = area burnt, ha
> M_B = mass of fuel available for combustion, tonnes ha-1. This includes biomass, ground
> litter and dead wood. When Tier 1 methods are used then litter and dead wood
> pools are assumed zero, except where there is a land-use change
> C_f = combustion factor, dimensionless
> G_{ef} = emission factor, g kg-1 dry matter burnt

Note: Where data for M_B and C_f are not available, a default value for the amount of fuel actually burnt (the product of M_B and C_f) can be used under Tier 1 methodology.

Emissions from biomass burning are estimated from the above-ground biomass, and DOM pools. With burning, below-ground biomass is assumed to remain constant after disturbance, or transferred to the soil pool. Default values for Tier 1 method or components of a Tier 2 method are provided in Section 2.4 of Chapter 2.

Choice of method
Figure 3 presents a general decision tree that guides the selection of the appropriate Tier level to report non-CO_2 emissions from biomass burning. A proposed decision tree for appropriate Tier level for reporting non-CO_2 emissions from biomass burning in wetlands is presented in Figure 4. If biomass burning in wetlands is not a key category, countries may choose to report non-CO_2 emissions using Tier 1 method, which is based on highly aggregated data and default combustion and emission factors. However, if biomass burning in wetlands is a key category, countries should report inventory and reporting approaches by applying the highest Tier possible, given national circumstances. For prescribed fires, country-specific data are required to generate reliable estimates of emissions. In wetlands, both the CO_2 emissions due to biomass burning and the CO_2 removals resulting from vegetation regrowth are accounted for when estimating the net carbon flux.

Tier 1
Equation 2.27 in the 2006 IPCC Guidelines for Natural Greenhouse Gas Inventories, Chapter 2 is applied when choosing to report under a Tier 1 method. Tier 1 is based on highly aggregated data and default combustion and emission factors. If data on Mass of Fuel Available for Combustion (MB) are not available, countries are asked to use the default data in Table 2.4 in the 2006 IPCC Guidelines for Natural Greenhouse Gas Inventories, Chapter 2 for the mass of fuel consumed. However, since the data in this table is provided by vegetation types and sub-categories, countries applying these default data should stratify the area of wetlands in their territory before choosing the appropriate default value (or values) to be applied.

Figure 3. Generic decision tree for identification of appropriate tier to estimate
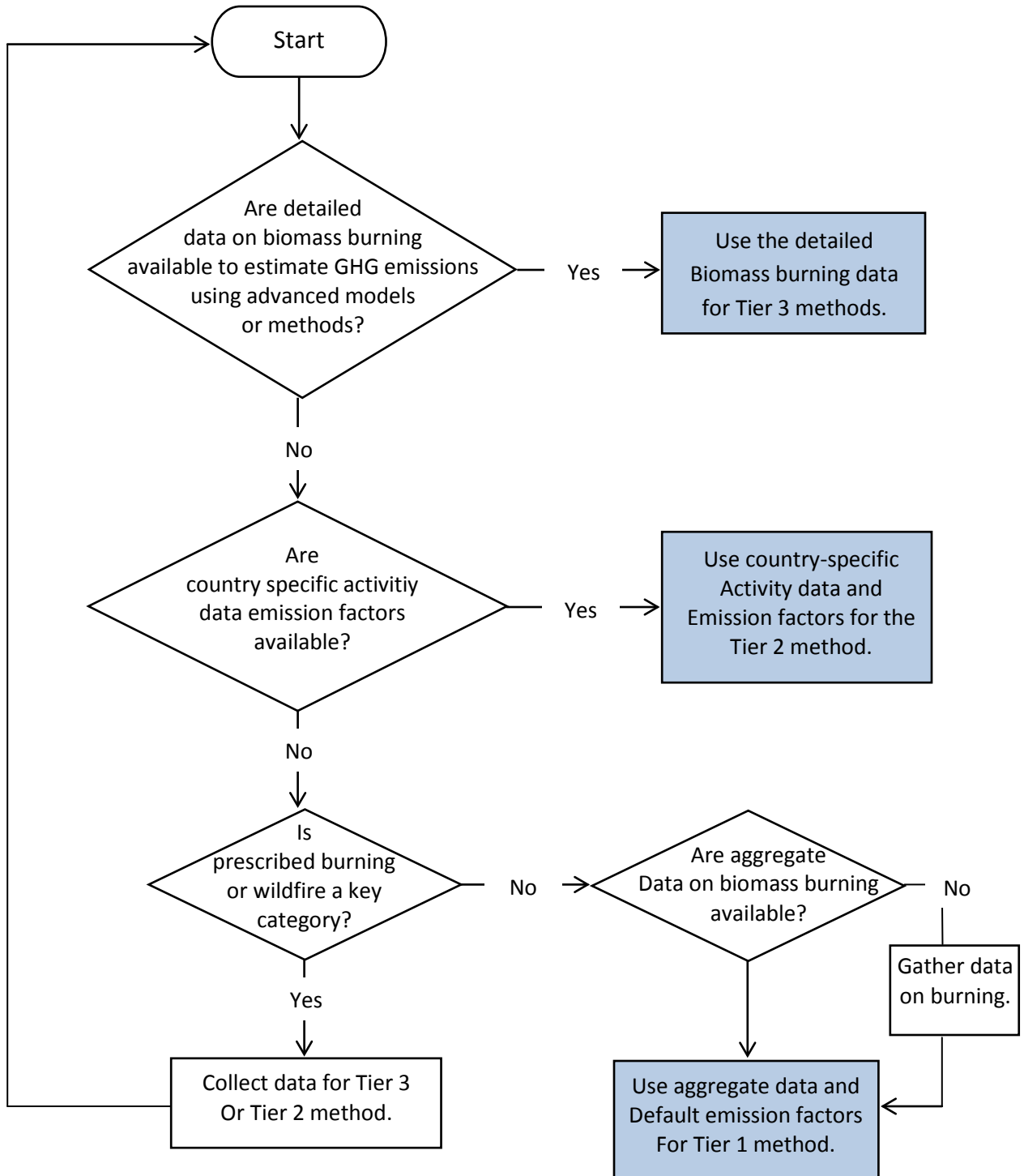greenhouse gas emissions form fire in a land-use

Table 2. Table 2.4 in the 2006 IPCC Guidelines for Natural Greenhouse Gas Inventories, Chapter 2

TABLE 2.4
FUEL (DEAD ORGANIC MATTER PLUS LIVE BIOMASS) BIOMASS CONSUMPTION VALUES (TONNES DRY MATTER HA^{-1}) FOR FIRES IN A RANGE OF VEGETATION TYPES
(To be used in Equation 2.27 , to estimate the product of quantities ' $M_B \cdot C_f$ ' , i.e., an absolute amount)

Vegetation type	Subcategory	Mean	SE	References
Primary tropical forest (slash and burn)	Primary tropical forest	83.9	25.8	7, 15, 66, 3, 16, 17, 45
	Primary open tropical forest	163.6	52.1	21,
	Primary tropical moist forest	160.4	11.8	37, 73
	Primary tropical dry forest	-	-	66
All primary tropical forests		**119.6**	**50.7**	
Secondary tropical forest (slash and burn)	Young secondary tropical forest (3-5 yrs)	8.1	-	61
	Intermediate secondary tropical forest (6-10 yrs)	41.1	27.4	61, 35
	Advanced secondary tropical forest (14-17 yrs)	46.4	8.0	61, 73
All secondary tropical forests		**42.2**	**23.6**	66, 30
All Tertiary tropical forest		**54.1**	**-**	66, 30
Boreal forest	Wildfire (general)	52.8	48.4	2, 33, 66
	Crown fire	25.1	7.9	11, 43, 66, 41, 63, 64
	Surface fire	21.6	25.1	43, 69, 66, 63, 64, 1
	Post logging slash burn	69.6	44.8	49, 40, 66, 18
	Land clearing fire	87.5	35.0	10, 67
All boreal forest		**41.0**	**36.5**	43, 45, 69, 47
Eucalypt forests	Wildfire	53.0	53.6	66, 32, 9
	Prescribed fire – (surface)	16.0	13.7	66, 72, 54, 60, 9
	Post logging slash burn	168.4	168.8	25, 58, 46
	Felled, wood removed, and burned (land-clearing fire)	132.6	-	62, 9
All Eucalypt forests		**69.4**	**100.8**	
Other temperate forests	Wildfire	19.8	6.3	32, 66
	Post logging slash burn	77.5	65.0	55, 19, 14, 27, 66
	Felled and burned (land-clearing fire)	48.4	62.7	53, 24, 71
All "other" temperate forests		**50.4**	**53.7**	43, 56

Tier 2
Tier 2 extends Tier 1 by incorporating more disaggregated area estimates (per vegetation types, sub-categories) and country-specific estimates of combustion and emission factors for each stratum. The area burnt is estimated using remotely sensed data of adequate spatial and temporal resolutions analyzed according to a robust sampling design. The periodicity of data acquisition is crucial in areas where burning occurs during a specific period in the year, which can extend over several months. Countries are asked to report the area burnt, to capture the month-to-month variation of the area burnt.

Tier 3
The Tier 3 method is based on models with algorithms to generate regional scale maps of area burnt using satellite data of multiple sources and of moderate spatial resolution. The results should be validated using high spatial resolution data augmented by field observations, and refined based on the validation results and feedback from operational users. A sampling approach can be designed to generate estimates of area burnt. The Tier 3 method should provide estimates (fluxes) of the impact of biomass burning on all pools, including below-ground biomass.

Choice of emissions factors

The mass of fuel available for combustion (M_B of Equation 2.27) is critical for estimating the non-CO_2 emissions. Default data to support estimation of emissions under a Tier 1 approach are given in Tables 2.4 to 2.6 in the 2006 IPCC Guidelines for Natural Greenhouse Gas Inventories, Chapter 2. Countries are asked to judge how their vegetation types correspond with the broad vegetation categories described in the default tables. Guidance for this is provided in Chapter 3 Consistent Representation of Lands in the 2006 IPCC Guidelines for Natural Greenhouse Gas Inventories, Chapter 2. Countries using Tier 2 are likely to have national data at disaggregated level on M_B, according to forest types and management systems. Tier 3 estimation requires spatial estimates of M_B according to different forest types, regions and management systems. Tier 3 estimation methods can also distinguish fires burning at different intensities, resulting in different amounts of fuel consumption.

Choice of activity data
Estimates of area burnt in wetlands are needed. A global database exists that covers the area burnt annually by fires but this will not provide reliable data for the area burnt annually by prescribed fires in individual countries. It is *good practice* to develop national estimates of the area burnt and the nature of the fires especially how they affect forest carbon dynamics (e.g., effects on shrub and tree mortality) to improve the reliability of national inventories. Countries using Tier 2 are likely to have access to national estimates. Tier 3 estimation requires regional and forest type specific estimates of area subjected to fire and fire intensity.

Uncertainty assessment
There are several sources of uncertainty related to estimates of non-CO2 emissions from biomass burning in wetlands. Fire behavior varies greatly among wetland types and hence, disaggregation of vegetative formations will lead to greater precision. The fraction of fuel that is actually combusted during biomass burning (combustion factor) varies greatly, not only between

ecosystems, but also between fires, between years, above- and below-ground biomass, and as a function of cultural practices. Measurements from a given fire, year, and/or cultural setting cannot be extrapolated with confidence to other regions or years, or to biome scale. A major cause of uncertainty in estimating the contribution of biomass burning to emissions of trace gases is the extent of area burnt, intensity of the fire, and the rate of spread, especially in long-duration deep organic soil combustion and in tropical ecosystems. Precision estimates vary widely and depend essentially on the accuracy of the estimates of area burnt, proportion of the available fuel oxidized, and the biomass fuel available. Uncertainties of estimates of areas burnt can vary markedly depending on the methodology employed – for example, where very high resolution remote-sensing is used it may be of the order of 20%, whereas the use of global fire maps may result in uncertainties of up to two-fold. Uncertainties in estimates of greenhouse gas emissions over large regions from fire are likely to be at least 50%, even with good country-specific data, and at least two-fold where only default data are used.

Figure 4. Proposed decision tree for identification of appropriate tier to estimate carbon stocks and non-CO$_2$ greenhouse gas emissions for uncontrolled and managed fires in managed wetlands.
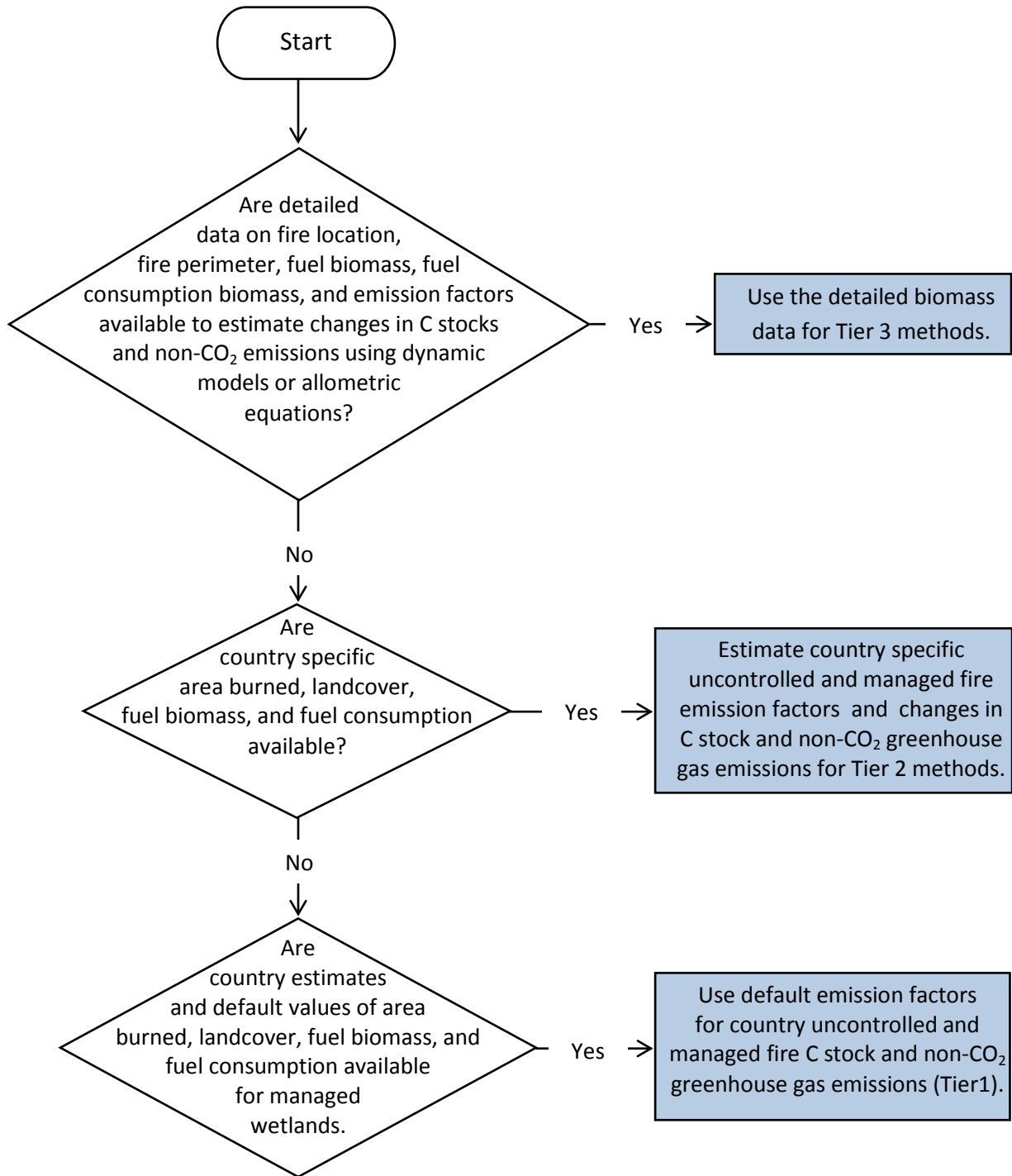
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