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CO emissions from degrading plant matter

(II). Estimate of a global source strength

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ABSTRACT

From relationships between integrated daily CO emissions and received solar radiation obtained for different standing dead grasses in field experiments in a savanna region in South Africa, and making use of ecosystem and solar irradiation databases, we derive estimates on global CO production and seasonality from photochemical decay of dry grasses and litter. The photochemical CO source strength from standing dead plant material and litter in various grassland ecosystems and deciduous forests ranges from 20 to 65 Tg CO per year ($1\ \mathrm{Tg} = 10^{12}$ g). Accounting for potentially CO emitting ecosystems not included in the data set, we estimate that 60 ± 30 Tg of CO are annually emitted by photochemical degradation of decaying plant matter, mostly in the tropics. We further estimate thermal CO production from the global topsoil non-woody litter pool on the basis of global climate data and measured Arrhenius parameters to add another 40 Tg CO per year, much depending on the chosen parameters, and probably uncertain by a factor of 2. The total global source of CO by these mechanisms may thus be in the range 100^{+70}_{-50} Tg CO per year. Although the estimated CO source strength is a relatively small contribution to the global CO budget (2–8%), CO emissions may significantly compensate for CO deposition on soils in the tropics during certain times of the year. Currently, modeling studies mostly impose a constant CO deposition velocity from the atmosphere to the soil surface, based generally on measurements on bare soil. Future modeling efforts may need to include geographical and photochemical factors which play a role in CO exchange in tropical ecosystems.

1. Introduction

With carbon monoxide (CO) being the predominant reaction partner of the OH radical in the background troposphere knowledge of terrestrial sources and sinks of CO as well as their diurnal, seasonal and interannual variation is essential to understand the distribution of OH radicals, which, in turn, determine the abundance of numerous other trace gases in the atmosphere (Levy, 1971; Thompson and Cicerone, 1986; Bakwin et al., 1994; Dlugokencky et al., 1996; Crutzen, 1996). At the same time, reaction of CO with the OH radical is the dominant sink of atmospheric CO of $2–3 \times 10^{15}$ g per year. An earlier study by Conrad and Seiler (1985) estimated the relatively smaller soil sink to be 300 to 400 Tg CO each year. A number of recent studies have readdressed the soil sink strength issue (Scharffe et al., 1990; Sanhueza et al., 1994a, 1994b; Zepp et al., 1996; Zepp et al., 1997; Moxley and Smith, 1998; Sanhueza et al., 1998). It was found that soils are sinks in general, the direction of flux being mostly dependent on soil temperature. Still, the soil–atmosphere CO flux also depends on factors such as soil moisture (Moxley and Smith, 1998), soil management, like plowing

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(Sanhueza et al., 1994a, 1994b; Moxley and Smith, 1998) or burning (Zepp et al., 1997), vegetation cover and litter on the surface (Scharffe et al., 1990; Sanhueza et al., 1994a, Zepp et al., 1996; Sanhueza et al., 1998), and environmental parameters, such as solar irradiation conditions on the soil surface (Zepp et al., 1997). A dark production (Sanhueza et al., 1994a, Zepp et al., 1996; Sanhueza et al., 1998) as well as photochemical production of CO (Tarr et al., 1995; Zepp et al., 1997) was found from dead plant material, which had not been previously taken into account in estimating CO uptake at the surface. In this paper we will give estimates of the CO release from dead grass and forest litter and we show that they need to be considered in model calculations of the global CO concentrations.

Tarr et al. (1995) have shown that dead plant matter shows substantially higher CO emissions than living green plant material when irradiated. On the basis of their laboratory measurements at a single light intensity, Tarr et al. (1995) estimated a potential global CO source from dead plant matter of 60 to 90 Tg CO per year, primarily from tropical grasslands during the dry season. No other estimate on global CO production from plant litter currently exists.

We have carried out an extensive study on CO emissions from degrading plant matter (Schade et al., this issue), evaluating its dependencies on environmental parameters such as sunlight intensity, wavelength, temperature, and moisture, as well as leaf litter properties (Schade, 1997). In this second part of our presentation, we extrapolate our field and laboratory data on CO emissions globally to estimate gross CO production from degrading plant matter. A global CO source strength is derived for photochemically as well as thermally-induced CO emissions from dead plant matter based on global data sets on ecosystem distribution, solar irradiation at the ground, climatic factors, and amounts of litter on the soil surface. Implications for regional and seasonal net CO surface fluxes, and for the global CO budget are discussed.

2. Global extrapolation of CO emissions to the atmosphere

2.1. Photoinduced CO emissions

To estimate global, photochemically induced CO emissions we derive response factors (Subsection 2.1.1) to extrapolate from measured correlations between specific emissions, biomass, and insolation. This response factor is then used with global data sets on grass dominated ecosystem distribution and solar surface irradiance to calculate global CO emissions from grasslands. Field and laboratory data from Mainz and environs are next used to estimate response factors for temperate and tropical deciduous forests. Presumptions on the range of possible response factors are made to account for the grass height (short grassland versus tall grassland) or shadowing of the overstory in forests. A uniform seasonal climatology ignoring continental effects is applied to extract those months when CO emission from litter predominantly occurs (Subsection 2.1.2).

2.1.1. Response factors, R_f^{CO}. Tarr et al. (1995) used an average CO emission factor retrieved from laboratory measurements at a single light intensity together with a number of hours of midday solar irradiation equivalent to 1 day, and multiplied that with the potentially emitting area on the globe and its respective range of leaf area indices. Their approach assumes a linear increase of CO emissions with incident solar irradiation and an effective CO emitting area bigger than the respective ground area. Our approach is more based on the field results from South Africa: We integrated temperature- and soil-exchange corrected CO emissions (Q_{CO}^{hv}) over the course of the day and divided them by the respective insolation. Thereby, we chose ground area instead of leaf area as a reference quantity for the emissions because the measured CO emissions from the grass chamber integrate over all wavelengths and light directions, thus do not distinguish between direct and diffuse irradiance. The latter factor is important, as the UV radiation is more effective in CO production and mostly diffuse instead of direct. Furthermore, it can also be shown that sunlit leaf area of standing dead grass material is approximately equal to the respective ground area for the zenith angles encountered (Schade, 1997), so that our choice of reference quantity also applies for visible wavelengths which contain a much larger direct component of the radiation.

Response factors for cloud-free days were 7.3×10^{12} molec. CO J^{-1} for *Tristachya* and 13×10^{12} molec. CO J^{-1} for *Schizachyrium*,

Table 1. *Estimated response factors R_f^{CO} of CO emission in 10^{12} molecules CO J^{-1} daily insolation in various grassland ecosystems, and in potentially CO emitting other ecosystems*

	Short grassland	Wooded grassland (savanna)	Tall grassland	Deciduous forests		Cultivated land
				temperate[a)]	tropical[b)]	
high	3	10	15	70	50	15
average	2	5	10	50	30	10
low	1	2	5	30	10	5

[a)] Estimated from field measurements on beech leaf litter in Mainz (data not shown).
[b)] Estimated from laboratory results relative to temperate deciduous leaf litter (data not shown).

respectively. These numbers include the hysteresis effect and continuing CO emissions after sunset. They are less on cloudy or on partly cloudy days because of the smaller hysteresis as revealed by a response factor of 6×10^{12} molec. CO J^{-1} for *Schizachyrium* on 25 July (Schade et al., this issue). If the evaluated grasses are representative concerning their different appearances (colour and architecture) they may also be representative for the range of CO emissions exhibited by similar grass species in tropical as well as temperate environments.

Nylsvley is located in the dry, cool end of the savanna climate zones in Africa (Scholes and Walker, 1993). Net primary productivity and aboveground biomass in the grass community is low compared to those in other grassland ecosystems. At our site the grass height was approximately 1 m on average, and more than half of the ground was covered by grass tufts. Therefore, we expect the CO emissions in other grasslands, with higher aboveground biomass and leaf area index than measured at *Nylsvley* (Coupland, 1979; Scholes and Walker, 1993), to emit up to 3× as much CO per ground area. However, the two grass species investigated had higher aboveground biomass ($\geqslant$800 gdw m^{-2}) and leaf area indices (4 to 7) than the dominant grass species, *Eragrostis pallens*, at the *Nylsvley* site. Furthermore, these data are on the high end of aboveground biomass and leaf area index for grasslands. Therefore, we presume an average CO emission factor for savanna grasslands of 5×10^{12} molec. CO J^{-1} daily insolation. Tall grasslands, as mentioned above, may have as high as 3× that value, whereas short grasslands, where much of net primary productivity takes place below ground and which are mostly found in northern hemisphere temperate continental climates, will exhibit a much lower CO emission. We have summarized estimated response factors for various grasslands in Table 1. We adopted CO emissions from *Eragrostis* (data not shown), which was still partially green during our measurements campaign in the dry season, therefore emitting less CO than dead grasses, to represent the minimum of possible CO emissions from dead grasses.

Besides grassland ecosystems several other ecosystems are potential CO emitters from degrading plant matter at the ground. Deciduous forests, either temperate or tropical, accumulate litter on the ground. This litter layer usually exists all year round but is mostly protected from direct sunlight by the overstory. In temperate deciduous forests, on average, only 10% of incident solar irradiation reaches the ground during the foliated period while up to 30% can reach the ground during the leafless, but darker, part of the year. Values are approximately the same in tropical deciduous forests due to similar leaf area indices (Reichle, 1981). Additionally, we expect cultivated land, occupying approximately 14% of the earth's land surface (DeFries and Townshend, 1994), to emit CO from dry plant matter, e.g., grain fields at times of harvest. We summarized estimated response factors for CO emission from forest and agricultural systems in Table 1, too. Cultivated land was treated as tall grassland because we considered mainly cropland with dry grain harvest (see below). Numbers for deciduous leaves may be overestimates because they were evaluated under "cloud-free" conditions (data not shown). A response factor calculated from data presented by Zepp et al. (1997, Fig. 5) is approximately 3× as high as our average value and, instead, suggests a possible underestimate by our chosen value.

Table 2. *Litter occurrence factor, f_{eco}^{month} for the months during which CO emission can occur (denoted by a 1) and months during which CO emission is scaled to account for light penetration (classes 3 and 11) or for a reduced area coverage (class 10, see text)*

	Latitude	Month of the year											
ecosystem	SH	7	8	9	10	11	12	1	2	3	4	5	6
class[a)]	NH	1	2	3	4	5	6	7	8	9	10	11	12
6 and 7	0°–30°	1	1	0	0	0	0	0	0	0	(1)[b)]	(1)[c)]	1
	>30°	0	0	0	0	0	0	0	1	1	1	1	0
3 and 11	>30°	0	0	0.3	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.3	0
	0°–30°	0.3	0.3	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.3	0.3
10	0°–30°	0	0	0	0	0	0	0	0	0	0.5	0.5	0.5
	>30°	0	0	0	0	0	0	0.5	0.5	0	0	0	0

[a)] Ecosystem classes were taken from DeFries and Townshend (1994): 6 = wooded grassland (savannas), 7 = grassland; 3 = high latitude deciduous forest; 11 = broadleaved deciduous forest; 10 = cultivated land.
[b)] Only for latitudes higher than 20°.
[c)] Only for latitudes higher than 10°.

2.1.2. Litter occurrence factor, f_{eco}^{month}. This correction factor is introduced to account for the influence on CO emissions by monthly litter availability and light attenuation in the ecosystems.

(a) Grasslands: The occurrence of standing dead grasses and litter is not uniformly distributed throughout the year, or across the globe. We assumed a simple climatology, rather independent of regional differences in the tropics (between 30°S and 30°N) with a length of the dry season varying from 3 to 5 months in the latitude bands 0°–10°, 10°–20°, and 20°–30°, respectively. Outside the tropics the last 2 months of the growing season, during which standing dead plant material and litter starts to accumulate, and the first two autumn months were considered, that is August to November in the NH. Seasonality of litter occurrence is assumed to be symmetrical around the equator and in duration; continental aspects are ignored.

(b) Deciduous forests: Litter is available in deciduous forests year round. For temperate deciduous forests we infer an average of 10% of incident radiation on the ground litter from April to September (NH) and 30% incident radiation in March, October and November. The winter months were ignored. Similarly, for the tropical deciduous forests we assume 10% of the light to reach ground litter during the wet season (March to October in the NH) and 30% during the dry season (November to February in the NH).

(c) Cultivated land: Cultivated cropland where dry grain is harvested amounts to approximately one half of total cultivated land (7 out of 14 million km^2; FAO, 1992). In the temperate zone crops may emit CO during the main months of harvest, that is during July and August in the NH. In the tropics these months are at the end of the wet season and we account for emissions during October to December on the NH and April to June in the SH, respectively.

Typical values for $f_{\mathrm{eco}}^{\mathrm{month}}$ are shown in Table 2.

2.1.3. Extrapolation. To calculate photochemical CO emissions from standing dead and litter biomass in an ecosystem the area and distribution of different ecosytems was taken from the vegetation data set of DeFries and Townshend (1994, Table 3). It consists of 11 ecosystem classes, which have been derived from remote sensing. Data sets of monthly mean solar global irradiance at the ground, including clouds, were taken from Bishop and Rossow (1991), and uniformly distributed over the smaller vegetation grid. Total CO emissions for a specific month summed over all latitudes and longitudes as well as the ecosystems considered are calculated by the expression

$$S_{\mathrm{CO}} = \sum_{\mathrm{eco}} \sum_{\mathrm{lon}} \sum_{\mathrm{lat}} f_{\mathrm{eco}}^{\mathrm{month}} \times A_{\mathrm{cell}}^{\mathrm{eco}} \times J_{\mathrm{e}} \times R_{\mathrm{f}}^{\mathrm{CO}} \times 3600 \times 24 \times d_{\mathrm{m}} \times 28 \times R_{\mathrm{A}}^{-1} \quad [\mathrm{g\ CO\ month}^{-1}], \tag{1}$$

where $A_{\mathrm{cell}}^{\mathrm{eco}}$ denotes the ground area of the grid

cell of the respective ecosystem, J_e is the respective solar irradiation ($W\,m^{-2}$) from the Bishop and Rossow (1991) data set, d_m is the number of days in the month, and R_A is the Avogadro constant. For J_e, the year 1990 has been used. However, year-to-year variations did not effect the results presented here significantly. Within the ecosystem database we treated tropical grasslands as tall grassland and temperate grasslands as short grasslands (Table 3). However, the data set of Mellilo et al. (1993) shows short and tall grasslands to be nearly equally distributed between tropical and temperate latitudes. Therefore, our assumption is a simplification in favour of tropical latitudes.

Total degrading plant matter CO emissions calculated from eq. (1), not considering soil CO fluxes, ranged from 20 to 65 Tg CO per year with an average of 42 Tg CO per year, and were annually distributed as shown in Fig. 1a. The highest contribution of CO emissions stemmed from savannas and grasslands making up 60% of the total. 85% of these occurred in the tropics, which may be an overestimate as stated above. Deciduous forests accounted for 28% of emissions, cultivated crops for the rest. The latitudinal distribution of CO emissions shown in Fig. 1b also depicts the dominance of savannas and grasslands, which are responsible for the main peaks at 20°S and 10°N of the equator.

The calculated CO emission is definitely an underestimate because we considered only the core months of emissions during which dead grass, crop or deciduous leaf litter is present, as shown in Table 2. We also did not account for possible emissions from arid shrublands ($\sim 12 \times 10^6\,km^2$), temperate coniferous and mixed forests ($\sim 22 \times 10^6\,km^2$). Grass litter is present in tropical and temperate grasslands and savannas also during the wet season of the year. Accounting for additional months of CO emissions from these ecosystems would add 0.5 to 2 Tg CO per month per ecosystem class, and we thus estimate another 10 Tg CO to be emitted during those times of the year. In addition, assuming a low response factor of 1×10^{12} molec. CO J^{-1} for arid shrublands we estimate another 5 Tg CO from such areas occurring all year round.

In summary, we estimate that 60 ± 30 Tg CO per year are emitted from the photochemical degradation of standing dead plant matter, grass and leaf litter, dominated by dry season standing dead and grass litter in tropical savannas and grasslands. A similar estimate was given by Tarr et al. (1995).

Table 3. *Ecosystem database on estimated yearly average non-woody top soil litter quantities, as well as calculated yearly amounts of non-woody litter fall (1 g carbon equals 2.1 g dry matter), together with estimated Arrhenius parameters used for the global extrapolation of thermally-induced CO emissions*

Ecosystem class (DeFries and Townshend, 1994)	Total land area (km^2)	Non-woody litter fall (Pg dw yr^{-1})[a)]	Non-woody litter pool (g dw m^{-2})[b)]	Arrhenius parameters[c)]	
				E_A (kJ mol^{-1})	ln A
1. broadleaf evergreen forest	1.53E + 07	25	1000	75	57.5
2. coniferous evergreen forest and woodland	1.36E + 07	3.0	7000	85	62
3. high latitude deciduous forest and woodland	5.89E + 06	2.5	3500	85	62
4. tundra	8.68E + 06	1.3	5000	85	62
5. mixed coniferous forest and woodland	7.51E + 06	3.6	3000	85	62
6. wooded grassland	2.41E + 07	13.2	500	65	52.5
7. grassland	2.19E + 07	3.9	400	65	52.5
8. bare ground	1.74E + 07	0.7	100	65	52.5
9. shrubs and bare ground	1.14E + 07	1.0	200	65	52.5
10. cultivated crops	1.44E + 07	6.4	50	65	52.5
11. broadleaf deciduous forest and woodland	3.62E + 06	0.7	1200	90	63.5
sum	1.44E + 08	61.3	226.6		

[a)] Litter fall = NPP (Pg C) × (aboveground part) × (1 − loss) × (non-woody part) × 2.1.
[b)] 10^{15} grams dry weight per year; grams dry weight per square meter (the sum corresponds to the total dry weight of aboveground non-woody litter in Pg, calculated via use of the surface area of the respective ecosystem class).
[c)] Estimates based on Schade et al. (*Tellus*, this issue).

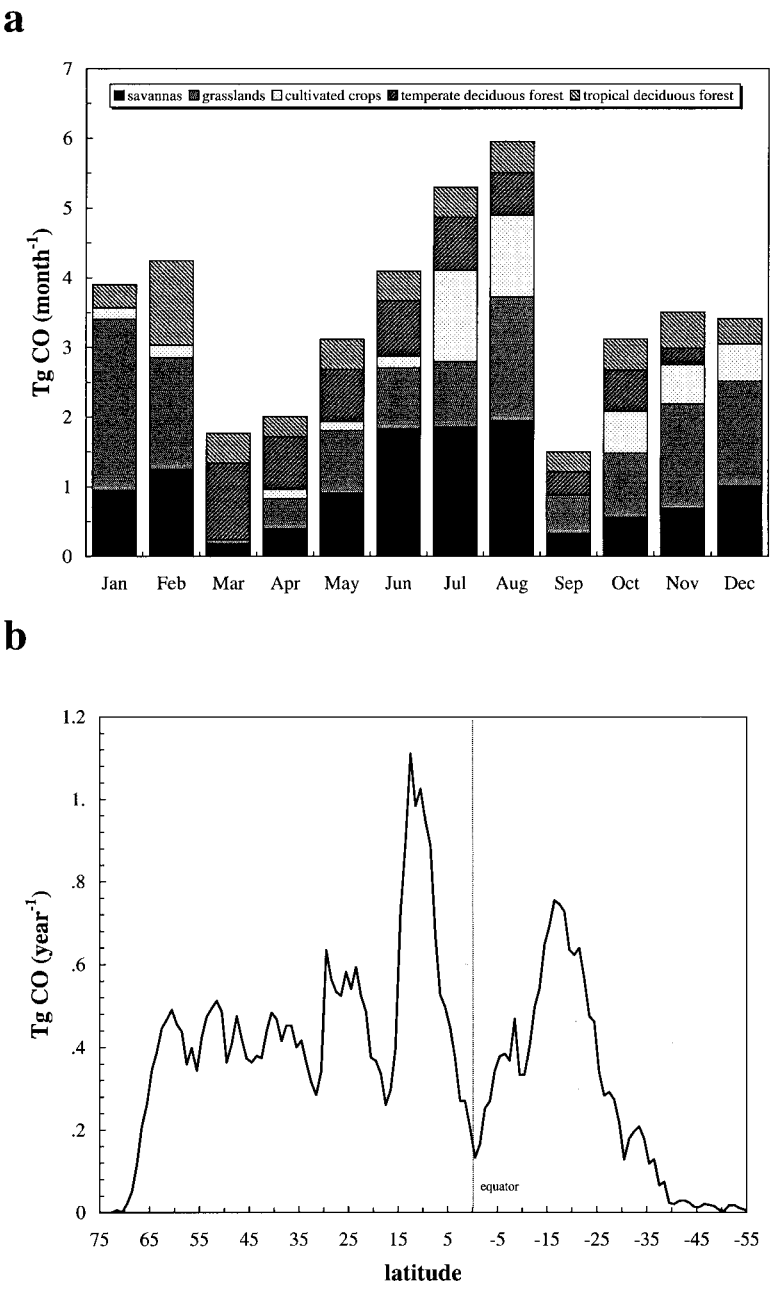

Fig. 1. Annual (a) and geographical (b) distribution of modeled global photochemical CO emissions.

2.2. Thermally-induced CO emissions

Leaf and grass litter showed substantial CO emissions when heated (Schade, 1997), and this CO emission is promoted by moisture. As the emission can generally be described by an Arrhenius-type equation, we used the calculated activation energies, and pre-exponential factors together with data on the global pool of organic carbon in degrading plant litter to estimate possible global CO emissions from thermal CO production from non-woody litter. Average top soil, non-woody litter quantities, which are the average amounts of litter in mature ecosystems on top of the mineral soil surface and in equilibrium with litter fall carbon input and respiration on a year by year basis were estimated. As the global ecosystem database we again chose the data set of DeFries and Townshend (1994). Top soil litter data for these ecosystem classes were collected from different sources (Ajtay et al., 1979; Coupland, 1979; Reichle et al, 1981; Vogt et al., 1986; Melillo et al, 1993), and our litter estimates are summarized in Table 3. Average climate data for the years 1930 to 1960 were taken from the Leemans and Cramer (1990) data set. We assumed air temperature to be equal to top soil temperature, which may overestimate actual temperatures in temperate and may underestimate actual temperatures in tropical latitudes. Daily temperature variation was modeled by a sinusodial curve based on min–max variations from the mean. It could be shown that this treatment reproduced daily integrated CO emissions calculated from actual temperature data to within 5% (Schade, 1997). The variation around the average temperature from the Leemans and Cramer (1990) data set was individually estimated from actual station data around the globe.

Based on a total top soil non-woody litter quantity of approximately 230 Pg dry matter (Table 3), which is in the high range of pool data as compiled by Matthews (1997), we calculate that 40 Tg CO could be emitted from the thermal decay of organic carbon in the global litter pool. This estimate does, however, not take into account, that the CO produced might actually not reach the atmosphere when simultaneous CO consumption takes place in the soil–litter interphase (Sanhueza et al., 1998). More than 30% of the calculated emissions would take place in coniferous forests and woodlands. However, our estimate on the Arrhenius parameters of the litter in these ecosystems (Table 3) is based on deciduous leaf litter, and may thus not be applicable. Fig. 2 shows the latitudinal distribution of the calculated potential CO emissions. The model emissions predominantly occurred in mid to high latitude forest, where high amounts of litter accumulate, and in the tropics, an effect of higher temperatures and continuous litter input near the equator. Tropical rain forests were calculated to emit 40% of the global source while other tropical ecosystems add another 20%.

Modeled gross CO emissions were found to be very sensitive to the adopted Arrhenius parameters. An *e*-fold increase of the *A*-factor taking into account higher leaf moisture (Table 1 in Schade et al., this issue) leads to a proportional increase in global CO emissions. Lowering the computed activation energy by only 5 kJ mol^{-1} for all ecosystem classes, without lowering the *A*-factor, led to approximately 7× global CO emissions, showing how important it is to improve the databases on critical environmental and especially emission factors.

We also note that thermal CO production from the litter pool could increase due to climate warming and we calculated a relative increase of 15% from model runs with elevated temperatures, i.e., +1°C between 40°S and 40°N, +2°C between 40° and 70° on both hemispheres, and +3°C in higher latitudes (average increase: 1.5°C, expected for a doubling of the concentration of equivalent CO_2 in the atmosphere).

Summarizing, we estimate that our calculated value of 40 Tg CO per year may be in doubt by a factor of 2, mostly due to uncertainties in Arrhenius factors, the influence of moisture, missing data on coniferous leaf litter, and the assumption that air temperature is similar to litter temperature.

Note that a similar estimate, the global CO source from soil organic matter of 17 ± 15 Tg CO yr^{-1}, has been presented by Seiler and Conrad (1987). Another approach, recently presented by Potter et al. (1996) and based on a "nominal CO production factor" (mg CO d^{-1} (g C)$^{-1}$ in soil organic matter) for the upper 30 cm of soil, led to the result that only 10 Tg CO yr^{-1} might be emitted by soils. The scenario of Potter et al. (1996) is based on a modeled $1^\circ \times 1^\circ$ spatial

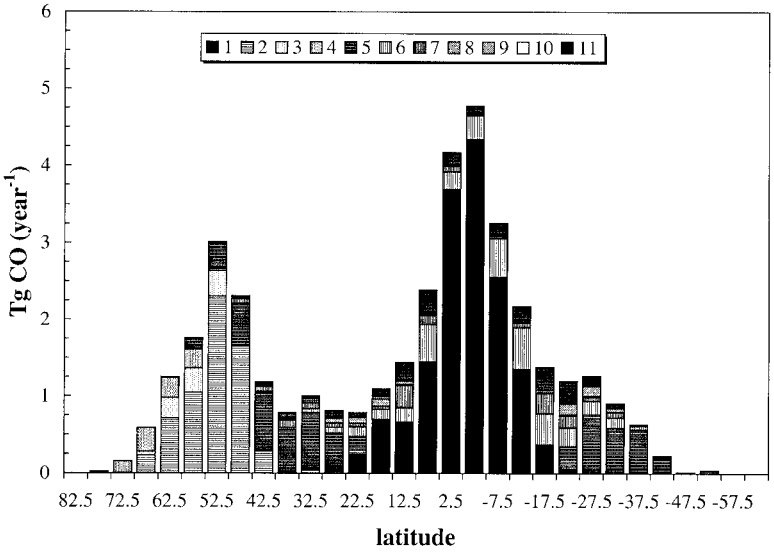

Fig. 2. Latitudinal distribution of calculated thermally-induced CO emissions per ecosystem class.

resolution data set of the amount of carbon in the soil surface layer (Potter and Klooster, 1997).

3. Implications

The CO source derived in this study can be of local to regional significance. In the tropics, where plant cycles are governed by rainfall rather than temperature, the photochemical CO source is primarily active during the dry season. Additionally, it is only active during daylight hours, so that a seasonal as well as a diurnal cycle of CO emissions will occur. In remote grassland and savanna areas not influenced by biomass burning, photochemically induced CO emissions from standing dead grass and litter during the dry season may possibly influence the ambient CO mixing ratio, and thereby the local OH budget. As during our field study daytime degrading plant matter CO emissions were up to an order of magnitude higher than soil CO uptake, we conclude that during the dry season tropical savannas and grasslands will be a net CO source to the atmosphere.

The tropical rain forests, although not yet included in our estimate on the photochemical CO source strength, can also be a net CO source due to thermal CO production from top soil litter. This conclusion has recently also been presented by Potter et al. (1996). However, their theoretical study calculated a net CO emission of only 10^{10} molec. CO $cm^{-2} s^{-1}$ from the ground. Our own laboratory measurements on a leaf litter composite sampled from a tropical rain forest site in Costa Rica lead to an estimate of approximately 10^{12} molec. CO $gdw^{-1} s^{-1}$ at 25°C. Estimating a total amount of 1000 g m^{-2} dry matter on the ground this is equal to a gross emission of 1×10^{11} molec. CO $cm^{-2} s^{-1}$, which is 10× the value of Potter et al. (1996) but is still lower than that given by Kirchhoff and Marinho (1990). The latter calculated a net surface flux of 4×10^{11} molec. CO $cm^{-2} s^{-1}$ from their vertical CO measurements inside the Amazonian rain forest. The large disagreement between these different studies shows that work is still needed in this area of research. However, as leaf litter CO fluxes at temperatures higher than 25°C exceed literature data on soil CO deposition, we expect the tropical rain forest to be a net source of CO throughout most of the year.

4. Conclusions

Our estimate on the photochemical CO production from degrading plant matter of 60 to 90 Tg

CO per year agrees well with that of Tarr et al. (1995). It supports the notion that a relatively small CO source, previously not accounted for, has to be considered in the global CO budget. Although the estimated total CO emissions approaching 100 Tg per year are small compared to the total global CO budget, they cannot be ignored compared to normally assumed CO deposition on soils. Our results lead to the conclusion that tropical savannas, grasslands and rain forest soils can be net atmospheric CO sources because of CO production from standing dead material and top soil litter. Published measurements on soil CO uptake, mainly performed in temperate environments, are not conclusive on whether litter on the soil surface played a role (e.g., Liebl and Seiler, 1976; Moxley and Smith, 1998). Several recent studies addressed the effect of plant litter (Sanhueza et al., 1994a; Zepp et al., 1996; Sanhueza et al., 1998). Based on their and our results, older estimates on global net CO soil deposition are probably too high. The theoretical study of Potter et al. (1996) calculated global CO deposition on soils as low as 16 Tg per year, whereas the current measurement-based IPCC (1994) estimate is 350 Tg CO yr^{-1}. In the most recent publication (Sanhueza et al., 1998) the authors reduced the estimate to 115–230 Tg CO yr^{-1}. Including our own CO emission estimates, we conclude that global net CO soil fluxes are probably smaller than 200 Tg CO yr^{-1}, deposited to the ground.

Global models still mostly impose a uniform CO uptake on the soil surface. In the future, they should include geographical and seasonal factors, which reduce CO uptake in tropical ecosystems, or may even cause a net CO source at the ground during certain times of the year. More measurements on photochemically as well as thermally-induced CO emissions from degrading plant matter appear necessary.

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