

Fire emissions from C₃ and C₄ vegetation and their influence on interannual variability of atmospheric CO₂ and δ¹³CO₂

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[1] Measurements of atmospheric trace gases provide evidence that fire emissions increased during the 1997/1998 El Niño event and these emissions contributed substantially to global CO₂, CO, CH₄, and δ¹³CO₂ anomalies. Interpretation and effective use of these atmospheric observations to assess changes in the global carbon cycle requires an understanding of the amount of biomass consumed during fires, the molar ratios of emitted trace gases, and the carbon isotope ratio of emissions. Here we used satellite data of burned area, a map of C₄ canopy cover, and a global biogeochemical model to quantitatively estimate contributions of C₃ and C₄ vegetation to fire emissions during 1997–2001. We found that although C₄ grasses contributed to 31% of global mean emissions over this period, they accounted for only 24% of the interannual emissions anomalies. Much of the drought and increase in fire emissions during the 1997/1998 El Niño occurred in tropical regions dominated by C₃ vegetation. As a result, the δ¹³CO₂ of the global fire emissions anomaly was depleted (–23.9‰), and explained approximately 27% of the observed atmospheric decrease in δ¹³CO₂ between mid-1997 and the end of 1998 (and 61% of the observed variance in δ¹³CO₂ during 1997–2001). Using fire emissions that were optimized in an atmospheric CO inversion, fires explained approximately 57% of the observed atmospheric δ¹³CO₂ decrease between mid-1997 and the end of 1998 (and 72% of the variance in δ¹³CO₂ during 1997–2001). The severe drought in tropical forests during the 1997/1998 El Niño appeared to allow humans to ignite fires in forested areas that were normally too moist to burn. Adjacent C₄ grasses (in woodlands and moist savannas) also burned, but emissions were limited, in part, by aboveground biomass levels that were 2 orders of magnitude smaller than C₃ biomass levels. Reduced fuel availability in some C₄ ecosystems may have led to a negative feedback on emissions.

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1. Introduction

[2] For the most part, grasses and trees in tropical ecosystems have different photosynthetic pathways (C₄ and C₃) that lead to distinct differences in their carbon isotope ratios [Sage and Monson, 1999]. These relatively large isotopic differences allow for partitioning of respiration and photosynthesis fluxes between these two plant functional types in ecosystems that have a mixed C₃ and C₄ canopy [Ometto *et al.*, 2002; Still *et al.*, 2003b] and for the estimation of soil carbon residence times in ecosystems that have undergone a shift from one pathway type to the other [Martin *et al.*, 1990; Veldkamp, 1994; Townsend *et al.*, 1995]. Globally, shifts in carbon fluxes from C₃ and C₄ ecosystems on interannual and decadal timescales influence

the δ¹³C of atmospheric CO₂ and consequently the ways that this tracer is used for partitioning land and ocean carbon sources and sinks [Ciais *et al.*, 1999; Townsend *et al.*, 2002; Still *et al.*, 2003a].

[3] Recent analysis of trace gas measurements by Langenfels *et al.* [2002] provide evidence that much of the global interannual variability of CO₂, CO, CH₄, and H₂ during the middle and late 1990s was caused by fires. Concurrent δ¹³CO₂ measurements from Langenfels *et al.* [2002] suggest that origin of the emissions anomalies was burning in forests. This “C₃” isotopic signature is qualitatively consistent with reports of increased burning activity during the 1997/1998 El Niño event in closed canopy forests in South America [Cochrane *et al.*, 1999; Nepstad *et al.*, 1999], and tropical forests and peatlands in Southeast

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Asia [Levine, 1999; Siegert et al., 2001; Page et al., 2002]. However, it is likely that other processes contributed to the atmospheric $\delta^{13}\text{CO}_2$ anomalies during this period, including different sensitivities of net primary production (NPP) and heterotrophic respiration (R_h) to drought and temperature [e.g., Jones and Cox, 2001], the effect of El Niño-induced drought stress on the ratio of stomatal conductance to photosynthesis in tropical ecosystems [Keeling et al., 2001; Langenfelds et al., 2002; Randerson et al., 2002a; Scholze et al., 2003], and ocean exchange [Feely et al., 1999]. As a result, some uncertainty remains as to whether fire emissions from C₄ grasslands increased in parallel to that observed in C₃ tropical forests during the 1997/1998 El Niño event, or if differences in regional climate or ecosystem processes led to a divergent emissions response between the two vegetation types.

[4] The availability of new satellite data products has made it possible to investigate patterns of C₃ and C₄ fire emissions at continental to global scales. Records of fire activity in the tropics extend from 1998 to the present from the Tropical Rainfall Measuring Mission (TRMM) Visible and InfraRed Spectrometer (VIRS) [Giglio et al., 2000], and globally from mid-1996 to the present from the Along Track Scanning Radiometer (ATSR) [Arino et al., 1999]. More recent satellite observations from the Moderate Resolution Imaging Spectroradiometer (MODIS) provide a means for converting these records of fire activity into time series of burned area [Justice et al., 2002]. In addition, a contemporary global map of fractional C₄ canopy cover [Still et al., 2003a] derived from other satellite and land cover sources [e.g., DeFries et al., 2000] allows for a partitioning of NPP and burned area between C₃ and C₄ vegetation types.

[5] When combined, these satellite products allow us to explore hypotheses regarding the processes regulating fire emissions. In low productivity grasslands, for example, the effect of drought may have the opposite effect on fire activity from that in highly productive forest ecosystems. Justice et al. [1996] and Barbosa et al. [1999] provide evidence that drought in southern Africa decreases the extent of burned areas in xeric vegetation during the following dry season because anomalously low NPP limits fuel density, and thus the spread of fires. This negative feedback has also been recognized by the need for minimum net primary production (NPP) and aboveground biomass thresholds for fire activity in global prognostic fire models [Thonicke et al., 2001]. It remains unknown what kind of effect this feedback may have on global CO₂ and $\delta^{13}\text{CO}_2$ levels or their interannual variability.

[6] Within savannas, fires play an important role in regulating the abundance of grasses and trees, along with other controls such as nutrient and water availability, and other forms of disturbance such as herbivory and grazing [Medina and Silva, 1990; Scholes and Archer, 1997]. Many studies have documented rapid, substantial increases in the population size and productivity of woody species over a period of years to decades following fire suppression [e.g., Moreira, 2000]. This rapid response may be partly attributed to decreases in the mortality rate of young saplings and woody shrubs growing within the grass layer [Hoffmann and Moreira, 2002]. Typically mortality rates for young trees are high because of the vulnerability of living tissue (leaves and woody stems) to ground fires, particularly during the dry season when the aboveground tissues of many grasses are senescent. In addition, frequent fires decrease litter and shading within the herbaceous layer, thus increasing the susceptibility of seedlings to

mortality from drought stress [Hoffmann, 1996]. With increasing stature and age class, fire-induced tree mortality declines as a result of some combination of (1) the development of protective bark [Gill, 1981; Gignoux et al., 1997], (2) greater belowground carbohydrate storage [Gignoux et al., 1997], and (3) a decrease in fire damage to the canopy because of its increased height (thus separation from fuels in the surface layer) [Shea et al., 1996]. This dynamic equilibrium between tree and grass plant functional types makes savanna carbon fluxes and their isotopic composition sensitive to shifts in the fire regime that occur in response to drought stress on ENSO (El Niño–Southern Oscillation) timescales, and in response to human pressures such as fuel wood collection and agriculture on decadal and century timescales [Hao and Liu, 1994; Ramankutty and Foley, 1999; Ludwig et al., 2003; Yevich and Logan, 2003].

[7] The complexity of the ecological and socio-economic processes described above makes it challenging to isolate tree and grass contributions to fire emissions in savannas and at savanna-forest boundaries. Nevertheless, new modeling frameworks to achieve this partitioning are needed for an improved understanding of ecosystem functioning in response to multiple elements of global change, and more immediately, for the interpretation of variability in atmospheric trace gases, including CO₂, CO, and CH₄, and their isotopic variations. Here we present a first attempt, at a global scale, to estimate fire emissions from C₃ and C₄ vegetation using satellite data [Arino et al., 1999; Giglio et al., 2000], a global map of C₄ vegetation cover [Still et al., 2003a], and a biogeochemical model [Van der Werf et al., 2003, 2004]. Our objectives were to assess differences in climate and ecosystem controls on fire in C₃ and C₄ vegetation at interannual timescales and to improve our understanding and use of atmospheric $\delta^{13}\text{CO}_2$ as a tracer in atmospheric inversion studies of regional carbon sources and sinks. As a part of our analysis, we estimate the contribution of fires to variability in global atmospheric $\delta^{13}\text{CO}_2$ during 1997–2001.

5. Conclusions

[46] C₄ ecosystems account for ~4% of contemporary global plant biomass [Still et al., 2003a] and 20% to 27% of global primary production [Lloyd and Farquhar, 1994; Fung et al., 1997; Still et al., 2003a]. Building on these studies, we estimate that 31% of global fire emissions have a C₄ origin and that approximately one fifth of C₄ aboveground biomass returns to the atmosphere each year by fire. These satellite-derived estimates of global C₄ emissions highlight the importance of fire as a major biogeochemical and evolutionary force in savanna ecosystems.

[47] Most of the interannual variation in global fire emissions during the 1997 to 2001 period occurred in areas dominated by C₃ vegetation. For this reason, the $\delta^{13}\text{C}$ of global fire emissions anomalies was highly depleted, with a mean of -23.9% . During the 1997/1998 El Niño, the first anomalously high emissions event in August through November of 1997 was almost entirely C₃ in origin, while the second emissions event in the middle of 1998 had a large C₃ and small C₄ component. As a consequence of the depleted $\delta^{13}\text{C}$ signature of emissions (and the large increase in total emissions), fires contributed substantially to the decrease in atmospheric $\delta^{13}\text{CO}_2$ observed between mid-1997 and the end of 1998.