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FIRE IN AFRICAN SAVANNA: TESTING THE IMPACT OF INCOMPLETE COMBUSTION ON PYROGENIC EMISSIONS ESTIMATES

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Abstract. African savannah fires are key sources of trace gases and aerosols, yet their true magnitude remains relatively poorly constrained. Here we present a detailed investigation of the amount of unburned material remaining in the ash produced by such fires, and examine whether this quantity needs to be considered when calculating atmospheric emissions. Emissions estimates for individual fires are usually based upon a calculation of the amount of fuel biomass combusted, usually estimated via a ''simple subtraction'' of the pre- and post-fire fuel loads. However, certain studies have concluded that this approach leads to gross overestimation of emissions, by perhaps 100%, due to the fact that a proportion of unburned fuel normally remains in the ''charred'' ash and that the simple subtraction method fails to take this fully into account. Whilst this latter point is true, we show that the mathematical relationship used previously to calculate the implications of this for emissions calculation is flawed. We demonstrate a new first-principles derivation of the quantity of mass combusted, taking into account any fuel remaining in the ash via measurement of ash mass loss on ignition (LOI). Using data from dry-season experimental fires in Botswana, we compared estimates of biomass combusted calculated via our LOI-based method to those obtained via the simple subtraction approach. We found a mean difference of $<10\%$, far less than the factor of 2 difference obtained when using the previous erroneous formula. Similar results are obtained for carbon and nitrogen emissions, and the findings are further supported by reassessment of previous data from early-to-mid-dry season savanna fires in Tanzania. These results indicate that the simple subtraction method overestimates emissions by far less than previously suggested, and that the method is likely to provide sufficient accuracy in most situations where emissions calculations are required. For fires where very substantial amounts of unburned material are expected to remain within the ash, and where an LOI-based approach to emissions calculation may therefore be particularly warranted, it is important that the correct formula derived herein is used, since errors inherent in the previous formula increase with increasing ash LOI.

Key words: biomass burning and global climate change; Botswana; combustion in natural fires; global emission budgets; loss on ignition (LOI); N and C emissions.

INTRODUCTION

The emission of gaseous compounds of carbon and nitrogen from wildfires has a significant impact on Earth's atmospheric chemistry, biogeochemical cycles, and radiative budget, as well as on local and regional air quality (Crutzen and Andreae 1990, Andreae and Merlet 2001). The importance of these effects is particularly pronounced in southern Africa, where estimates suggest that between perhaps 1/15 and 1/5 of global biomass burning emissions originate (Andreae 1991, Scholes et al. 1996*b*).

Wildfire emissions estimates of an individual chemical compound (X) are usually calculated as follows (Seiler and Crutzen 1980):

$$\text{Amount of gas species emitted (kg)} = L \times \text{EF}_X \quad (1)$$

where L = fuel biomass lost (volatilized) on combustion (kilograms of dry matter) and EF_X = emission factor of gas species X (grams emitted per kilogram of dry fuel combusted).

At the regional scale, L is usually calculated as the following product:

$$L = A \times B \times b \quad (2)$$

where A = area burned (hectares), B = pre-fire fuel density (kilogram/hectare), b = combustion factor (the proportion of dry fuel biomass actually combusted).

Whilst the Seiler and Crutzen (1980) approach has proven extremely useful, there is an ongoing requirement to reduce uncertainties inherent in its use so that more precise measures of the source strength and distribution of gaseous biomass burning products can be obtained (Lindesay 1997). To this end, a considerable body of research has aimed to better quantify the key

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parameters, including (1) application of improved remote sensing techniques to measure burned areas over large geographical regions (e.g., Trigg and Flasse 2001, Smith et al. 2002, Zhang et al. 2003), (2) the assessment of spatial variations in pre-fire fuel load using primary production models based on monthly rainfall or other parameters (Scholes et al. 1996*a*), (3) the analysis of variables such as fuel moisture content that may significantly influence combustion factors (e.g., Chaldil and Nunex 1995, Alonso et al. 1996), and (4) the determination of improved emission factors for common combustion products (Andreae and Merlet 2001, Korontzi et al. 2003).

A significant source of potential uncertainty in the parameterization of the Seiler and Crutzen (1980) method arises from the combustion factor, since this varies widely under different environmental conditions (Kasischke and Bruhwiler 2003, French et al. 2004). In this context, McNaughton et al. (1998) have suggested that many calculations of wildfire trace gas emissions may be very significantly overestimated due to the inappropriate use of laboratory-derived combustion factors applied to parameterizations of Eqs. 1 and 2 for natural fires. The main reason stated for this is that in natural fires, unlike many laboratory situations, the combustion process is often far from complete and the post-fire ash therefore contains a significant amount of material still able to burn (Alexander 1982). In this situation, trace gas emissions are clearly lower than would be the case if combustion had continued to 100% completion, where all available fuel would have been volatilized, leaving only incombustible mineral ash.

Although some studies of pyrogenic emissions have assumed a degree of incomplete combustion (e.g., Scholes et al. 1996*b*, Van der Werf et al. 2003), the studies of Stronach and McNaughton (1989), Stronach (1990), and McNaughton et al. (1998) are some of the few to consider it in a more detailed manner via measurements of the actual proportion of unburned fuel present in ash, coupled with equation-based estimates of the total amount of ash produced by the fire (including amounts unable to be measured due to their almost immediate removal by fire-induced convection or wind). Based on such work, McNaughton et al. (1998) conclude current global wildfire emissions estimates may be overestimated by as much as 100%, because the full effects of incomplete combustion are not fully considered. This contention has then been noted in subsequent studies (e.g., Pereira et al. 1999). However, whilst we fully agree with Stronach and McNaughton (1989) and Stronach (1990) that the significance of variations in post-fire ash characteristics requires investigation, most particularly with regard to the amount of potentially combustible material left within the ash, we demonstrate here that certain of the mathematical relationships presented within these works are flawed. This casts doubt on the conclusion of McNaughton et al. (1998) that existing pyrogenic emissions estimates may be major overestimations, since the erroneous equations contributed to this finding. Corrected equations are derived herein and applied to both the original data from Stronach (1990) and to new data collected by ourselves during experimental savannah fires in Botswana. We use these new relationships and data to re-evaluate the importance of post-fire ash characteristics and combustion completeness for wildfire emissions estimates.

Background

Parameterization of the Seiler and Crutzen (1980) method at the country or regional-scale has generally been informed by smaller-scale studies of experimental fires that allow more direct measurement of the parameters of Eqs. 1 and 2, which can then be up-scaled to the larger setting. It is the study of incomplete combustion in a series of such small-scale experimental fires that led McNaughton et al. (1998) to question the validity of current biomass burning emissions estimates. When estimating emissions in small-scale fires, estimates of the fuel mass lost on combustion (L) for input into Eq. 1 are commonly derived by subtracting the mass of post-fire materials from the mass of pre-fire fuel (C; e.g., Shea et al. 1996, Trollope et al. 1996, Ward et al. 1996). The post-fire material can be considered as being composed of residual unburned fuel (R) and ash (A), though in many cases researchers would not separate these two and would provide a single value encompassing both materials:

$$L = C - R - A. \tag{3}$$

Stronach and McNaughton (1989), Stronach (1990), and McNaughton et al. (1998) inherently questioned the validity of Eq. 3, which we term the ''simple subtraction'' method. Specifically, Eq. 3 fails to (1) fully account for the fact that pre-fire fuel contains a proportion of incombustible material, and that the post-fire ash contains this material along with a variable proportion of potentially still-combustible material that was not fully burnt, and (2) that an unknown amount of this ash may have been removed from the immediate area by fire-induced convection and wind, making the mass (A) deduced by post-fire sampling less than the true amount produced. Stronach and McNaughton (1989) and Stronach (1990) suggested that these assumptions can be avoided by (1) measuring the proportion of combustible material left within the ash, and (2) by developing a new equation to calculate L without requiring knowledge of the actual mass of ash (A) produced. We agree with these suggestions, and with the introduction of the new requirement that aimed to meet them, namely that the mass loss on ignition of the pre-fire fuel (I_C) and the post-fire ash (I_A) be measured. These loss on ignition values were then input into an equation presented by Stronach and McNaughton (1989) and Stronach (1990) to calculate L:

$$L = (I_C - I_A)(C - R) \quad (4)$$

where I_C and I_A are the mass loss on ignition (LOI) of the pre-fire dry fuel and post-fire ash, respectively, calculated via sustained heating in a furnace until combustion is 100% complete, for example,

$$I_A = \frac{\text{Mass}_{\text{Pre-furnace}} - \text{Mass}_{\text{Post-furnace}}}{\text{Mass}_{\text{Pre-furnace}}}. \quad (5)$$

I_A can be expressed as a proportion (0–1) or as a percentage (0–100%). Full details of the approach are provided by Stronach (1990), and we hereafter refer to Eq. 4 as the Stronach and McNaughton method.

Testing the Equations

The Stronach and McNaughton method

Via the Stronach and McNaughton method (Eq. 4), Stronach (1990) calculated that the amount of biomass combusted (L) in experimental woodland fires in Serengeti National Park, Tanzania, was, in general, only ~50% of that estimated using the simple subtraction method (Eq. 3). This led McNaughton et al. (1998) to conclude that emissions estimates from such fires at both the local and regional scale may currently be grossly overestimated, in this case by a factor of two. However, we believe Eq. 4 to contain a flaw that generates significant error, casting doubt on the reliability of any conclusion reached via its use.

We now demonstrate the error in Eq. 4, and go on to derive a corrected equation that can be used to assess the true effect of incomplete combustion on pyrogenic emissions estimates, through measurement of the fuel and ash LOI parameters.

Taking the Stronach and McNaughton method, Eq. 3, and expanding gives

$$\begin{aligned} L &= I_C(C - R) - I_A(C - R) \\ &= CI_C - RI_C - (C - R)I_A. \end{aligned} \quad (6)$$

Considering the terms on the right-hand side of Eq. 6 in comparison to those of the simple subtraction method (Eq. 3), the first term ($C \cdot I_C$) represents the theoretical maximum value of L, i.e., the mass lost in the case that the original fuel is completely burnt and thus totally reduced to incombustible mineral ash and gaseous emissions products. The second term ($-R \cdot I_C$) represents the amount of fuel that actually remains completely unburned after the fire (i.e., the residual fuel mass, assuming that this is the same material as the pre-fire fuel and has not been altered by the fire). The third term ($-(C-R)I_A$) should therefore represent the amount of potentially combustible material that actually remains in the partly combusted ash, but which could theoretically have been volatilized to gas (if the fire were intense or long-lived enough to lead to 100% combustion completeness). This third term is where the error is found. One would actually expect the amount of potentially combustible material remaining in the ash to be equal to the mass of ash multiplied by its mass loss on ignition, i.e., ($-I_A A$), which would provide the full LOI-based equation as

$$L = CI_C - RI_C - AI_A. \quad (7)$$

Eqs. 6 and 7 are only identical if the difference between the pre- and post-fire fuel loads ($C-R$) is equal to the mass of ash (A) produced. This is clearly not the case, since the difference between the pre- and post-fire fuel loads is a function of both the mass of ash *and* the mass of gas produced by the fire, the latter being, in general, a more significant quantity. The flaw in the Stronach and McNaughton method (Eq. 4) therefore lies in this assumption, that the mass of ash (A) resulting from the fire is equal only to the difference between the pre- and post-fire fuel masses ($C-R$). Having established this error, there is a need to derive a corrected form of this equation from which the parameter L can be estimated without requiring an actual measurement of the mass of ash (A). This is necessary since, as already pointed out, an unknown quantity of ash is lost prior to any sampling via fire-induced convection and wind.

Derivation of new LOI-based equations

Taking first an example where all available fuel (C) is directly volatilized, i.e., 100% combustion completeness. In this case, R (residual *uncombusted* fuel) is zero and C is totally converted to gaseous emissions and a quantity of (incombustible) mineral ash (C_K) given by

$$C_K = C(1 - I_C). \quad (8)$$

Consider then a second, more standard case, in which combustion is incomplete and the post-fire materials consist of both residual uncombusted fuel (R) and incompletely combusted ash (A). These post-fire components can be subject to further heating, and if this were done until all combustible material was completely volatilized, an amount of mineral ash (R_K) from the residual fuel and (A_K) from the previously incompletely combusted ash would ultimately remain. By definition, mineral ash is incombustible and, since all the initially available fuel has now undergone complete combustion, the quantity of mineral ash (R_K and A_K) generated by this latter two-stage route is identical to the quantity (C_K) generated by the former route where 100% combustion completeness was reached directly, i.e.,

$$C_K = A_K + R_K \quad (9)$$

where, in the form of Eq. 8, $R_K = R(1 - I_R)$ and $A_K = A(1 - I_A)$.

Eq. 9 can therefore be expressed as

$$C(1 - I_C) = A(1 - I_A) + R(1 - I_R). \quad (10)$$

Since the residual uncombusted fuel (R) is assumed to be an identical material to the original fuel (C), the

assumption can be made that $I_R = I_C$, and this can be substituted into Eq. 10, which can then be rearranged to provide the total mass of ash (A) produced:

$$A = (C - R)\left(\frac{1 - I_C}{1 - I_A}\right). \quad (11)$$

This measure of A is then substituted into Eq. 3 to give Eq. 12, a relationship that properly takes into account the amount of potentially combustible material remaining in the ash, but without requiring knowledge of the actual mass of ash produced (see Appendix for full derivation):

$$L = (C - R)\left(\frac{I_C - I_A}{1 - I_A}\right). \quad (12)$$

For the purposes of this paper, we refer to Eq. 12 as the Smith et al. method, and comparison of this with the Stronach and McNaughton method (Eq. 4) illustrates that the latter fails to include the denominator of $(1 - I_A)$. This means that for fires where some potentially combustible material remains in the ash (i.e., those having $I_A > 0$), use of the Stronach and McNaughton method underestimates emissions to the atmosphere, and the degree of underestimation increases with ash LOI. Thus, maximum underestimation will occur in situations of low combustion completeness. These errors do not affect the Smith et al. method (Eq. 12), which can also be rearranged to produce the correct form of Eq. 7 (see Appendix for full derivation):

$$L = I_C(C - R) - I_A A. \quad (13)$$

We tested the significance of these findings using data from both the original 1987 experimental fires of Stronach (1990), carried out in Serengeti National Park, Tanzania, and data from a new set of experimental fires in Botswana conducted in 2001 using a similar experimental design.

Materials and Methods

Study area

To evaluate the significance of the newly derived Smith et al. method, in comparison to the Stronach and McNaughton and simple subtraction approaches, eight experimental fires were conducted within Chobe National Park, Botswana (Fig. 1), at the end of the 2001 dry season (14–23 October). Chobe National Park is located in a region subject to annual biomass burning (Scholes et al. 1996*a*) and comprises a diverse range of ecosystems, being situated in the transition zone between the arid/nutrient-rich savannas of the central Kalahari and the moist/nutrient-poor savannas of northern Zambia (Huntley and Walker 1982, Kamuhuza et al. 1997). Experimental procedures were largely based on those of Stronach and McNaughton (1989), with fires conducted in areas of light–moderate woodland savanna, interdispersed with pockets of open grassland. The tree species *Baikiaea plurijuga* Fabaceae-Caesalpinioideae (nutrient-poor/deciduous), *Combretum* spp., and *Colophospermum mopane* Fabaceae (nutrient-rich/broad-leaf) and the grass species (all Poaceae) *Dactyloctenium giganteum*, *Eragrostis* spp., *Brachiaria negropedata*, *Panicum maximum*, and *Aristida stipitata* were present near and within the experimental fire plots. At the time of the experiment, the grass swards contained only senesced biomass and litter, though some nearby trees retained green foliage. Grass had a maximum height of ~0.5 m, but lay predominantly horizontally due to trampling by large mammals (primarily elephants).

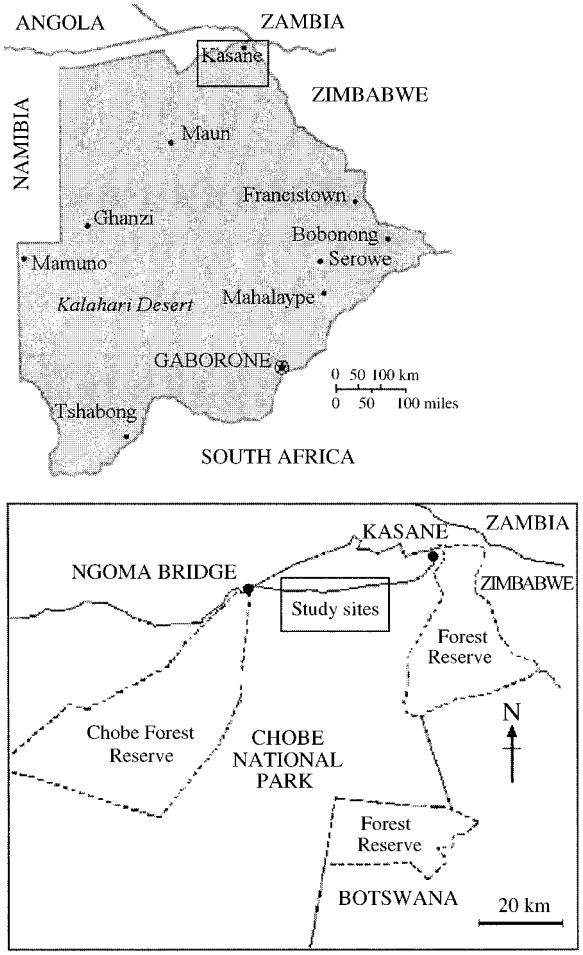

FIG. 1. The location of the study sites in Chobe National Park, located in northern Botswana, southern Africa.

Experimental details

Fire plots were 5 × 5 m in area, with the fuel available for combustion at each plot being defined as the total quantity of non-tree aboveground biomass <1 m height. Available fuel was classified into the components of grass (which was the dominant fuel) and litter, which itself was subdivided into leaf litter and woody debris. Fuel loads for each plot were determined by clipping and collecting all biomass to the soil level

within five 25 × 25 cm quadrats. Locations of the pre-fire quadrats were randomly selected from within the 2 m wide firebreak that surrounded each experimental fire plot, prior to construction of the firebreak. Natural fuel loads within the plots varied between 2000 kg/ha and 9930 kg/ha, but we loaded three plots with additional grass biomass (up to 21 000 kg/ha) to cover the full range of fuel loads found within the Park. Additional biomass was added in a way that simulated the natural geometry of the grass swards. Fires on all eight plots were lit at the upwind edge and left to burn until extinguished naturally. Fires with the largest fuel loads burned for longer periods, and maximum time to fire extinction, as indicated by a complete absence of smoldering or flaming combustion, was 25 minutes and 43 seconds.

Post-fire materials were sampled at five fixed locations within each plot and separated into the component classes of unburned fuel (*R*), consisting of grass, leaf litter, and woody debris, and ash (*A*). The latter generally appeared as dark, incompletely combusted material, rather than mineral ash. Analysis of the carbon (C) and nitrogen (N) content of each of the pre- and post-fire components was carried out using a NCS 2500 CHNS analyzer (Carlo Erba, Milan, Italy). Since the ''emission factor'' of a species typically describes the emission of a particular chemical compound, rather than the overall emission of an element contained within many emitted compounds, in this paper we refer to the ''effective emission factor'' of carbon and nitrogen, respectively, expressed in grams per kilogram of dry fuel combusted.

Calculation of the loss on ignition of each of the pre-fire and post-fire samples was performed following the procedure of Stronach and McNaughton (1989). Firstly, all samples were individually weighed and placed in a muffle furnace for 12 h at 100°C and then re-weighed, in order to obtain a dry fuel mass measurement that ensured the vast majority of water was removed prior to further analysis. Samples were then heated to 500°C in the same furnace for a further 18 h to reduce them to incombustible mineral ash. Following this ashing process, the samples were removed from the furnace and rapidly re-weighed (to avoid them absorbing atmospheric moisture). The LOI of each sample was then calculated from these latter two measurements using Eq. 5.

In addition to the data collected in Chobe National Park experiment, we also used the experimental results from Stronach (1990), which include data on fuel combusted and pre- and post-fire fuel and ash LOI from experimental woodland savanna fires carried out in Serengeti National Park, Tanzania, as described in Stronach and McNaughton (1989). The Serengeti fires were conducted mainly in the early (May–July) to mid- (August to the first week of October) dry season, and Stronach (1990) calculated the fuel mass lost (*L*) in each of these fires using both the simple subtraction (Eq. 3) and Stronach and McNaughton (Eq. 4) methods. Via application of the $(1 - I_A)$ denominator to the results from the Stronach and McNaughton method, we were able to also calculate the value of *L* based on the Smith et al. method (i.e., that which would have been calculated via Eq. 12).

TABLE 1. Proportional mass loss on ignition (LOI; mean ± SD) of pre- and post-fire components, calculated using Eq. 5.

Component	Pre-fire LOI	Post-fire LOI
Grass	0.92 ± 0.07	0.92 ± 0.13
Leaf litter	0.93 ± 0.03	0.90 ± 0.09
Woody debris	0.88 ± 0.10	0.92 ± 0.16
Ash		0.58 ± 0.22

RESULTS

Biomass volatilized

For the fires in Chobe National Park, the mean LOI values of the post-fire grass, leaf litter, and woody debris components were each within one standard deviation of their mean pre-fire values (Table 1), supporting the assumption inherent in Eqs. 11 and 12 that I_R is insignificantly different to I_C. The post-fire residual unburned fuel can therefore correctly be assumed to be the same material as pre-fire.

The total fuel mass lost (*L*) within each Chobe fire was estimated using Eqs. 3, 4, and 12, and the results are compared in Fig. 2. The Stronach and McNaughton LOI-based method (Eq. 4) results in a mean estimate of total fuel mass lost equivalent to 49% of that calculated by the simple subtraction method (Eq. 3), a significant difference that is in broad agreement with the findings of McNaughton et al. (1998). In contrast, application of the Smith et al. LOI-based method (Eq. 12) to the same data results in a mean estimate of *L* equivalent to 91% of that estimated using the simple subtraction method. Therefore, calculations of the fuel mass combusted made via the Smith et al. and simple subtraction methods agree to within 10%, even though the latter fails to account for variations in the amount of potentially combustible material left within the ash. Calculation of (*b*), the combustion factor used within Eq. 2 and given by the proportion of dry fuel actually combusted (i.e., *L*/*C*), produced values of 0.65 ± 0.0.21 (mean ± 1 SD) using the simple subtraction method, 0.56 ± 0.22 using the Smith et al. method, but 0.28 ± 0.23 using the Stronach and McNaughton method. This indicates how the latter approach could lead to very significant underestimation of regional or global emissions if used to inform parameterization of the Seiler and Crutzen (1980) method (Eqs. 1 and 2).

For comparison to the Chobe Park findings, Fig. 3 shows the equivalent results for the Serengeti National Park data reported in Stronach (1990). Use of the Stronach and McNaughton method (Eq. 4) again results in an estimate of the total fuel mass lost (*L*) around half

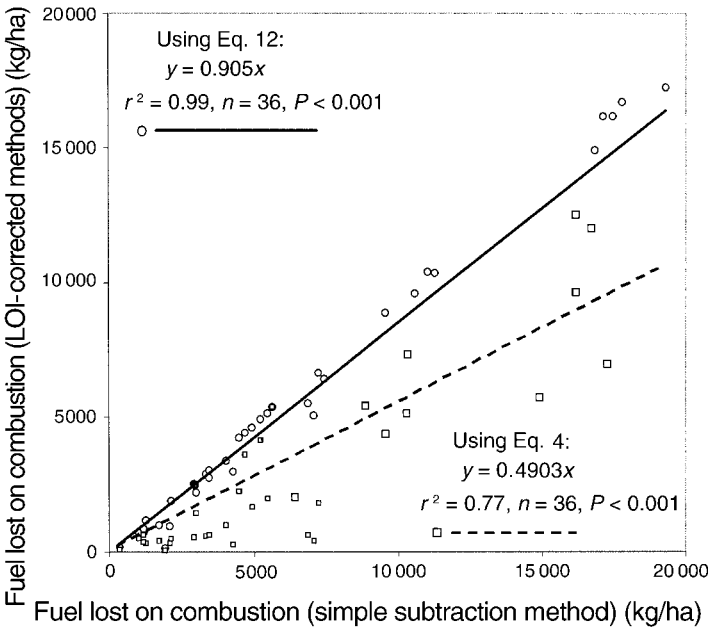

FIG. 2. Estimates of fuel biomass lost on combustion (L) from experimental fires carried out within Chobe National Park, calculated via the Stronach and McNaughton method (Eq. 4) and Smith et al. method (Eq. 12), both of which take into account the loss on ignition (LOI) of the pre- and post-fire materials at each sample point, and the simple subtraction method (Eq. 3), which does not. The least-squares linear best-fit (with zero intercept) relationships are also shown.

that of that calculated via the simple subtraction method (Eq. 3), again in agreement with the findings of McNaughton et al. (1998). In contrast, the estimates of fuel mass lost calculated using the Smith et al. LOI-based method (Eq. 12) are, on average, within 20% of those calculated by the simple subtraction method.

Nitrogen and carbon emissions

For the Chobe National Park fires, the quantities of nitrogen and carbon emitted via volatilization of the fuel biomass combusted in each fire were calculated. The percentage of nitrogen and carbon content of the pre-fire fuel components (Table 2) were used with the masses (C) and (R) to calculate the quantity of nitrogen and carbon contained in, respectively, the pre-fire fuel and the post-fire residual biomass. Since combustion was incomplete in all fires, some nitrogen and carbon also remained within the ash. However, we could not directly measure the total mass of ash (A) produced during each fire, since, as already stated, an unknown amount was convected away or removed by wind, particularly during the more intense, higher fuel load fires. Instead, Eq. 11 of the Smith et al. method was used to calculate A and, by combining this with the measured

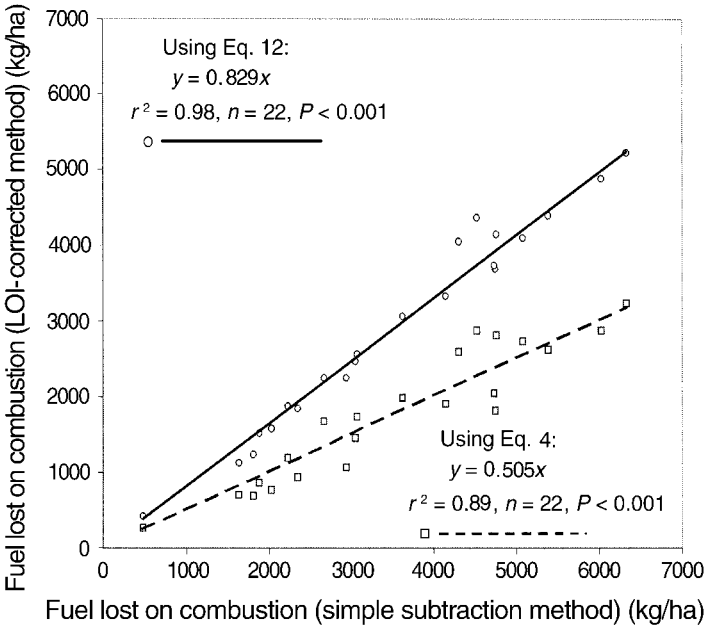

FIG. 3. Estimates of fuel biomass lost on combustion (L) for woodland savanna fires carried out within Serengeti National Park, Tanzania, and reported in Stronach (1989), calculated here via the Stronach and McNaughton method (Eq. 4) and Smith et al. method (Eq. 12), both of which take into account the loss on ignition (LOI) of the pre- and post-fire samples at each sample point, and the simple subtraction method (Eq. 3) which does not. The least-squares linear best-fit (with zero intercept) relationships are also shown.

TABLE 2. Percentage by mass of nitrogen and carbon contents (mean ± SD) of pre- and post-fire components.

Component	Carbon content (%)				Nitrogen content (%)			
	Grass	Leaf	Wood	Ash	Grass	Leaf	Wood	Ash
Pre-fire	43.79 ± 2.62	49.19 ± 1.34	47.03 ± 1.34		0.76 ± 0.25	1.22 ± 0.11	0.90 ± 0.20	
Post-fire	44.76 ± 2.19	51.84 ± 2.23	51.30 ± 8.53	24.06 ± 9.16	0.93 ± 0.26	1.68 ± 0.28	1.03 ± 0.61	0.89 ± 0.38

percentage of nitrogen and carbon contents of the ash, the total mass of these species present within the ash was calculated. Subtraction of the nitrogen and carbon contained within the residual biomass and ash from that of the pre-fire fuel then provided an estimate of the amounts volatilized based on the Smith et al. method. This was then compared to the values estimated using the simple subtraction method, calculated using Eq. 3 and the percentage of nitrogen and carbon contents of each component.

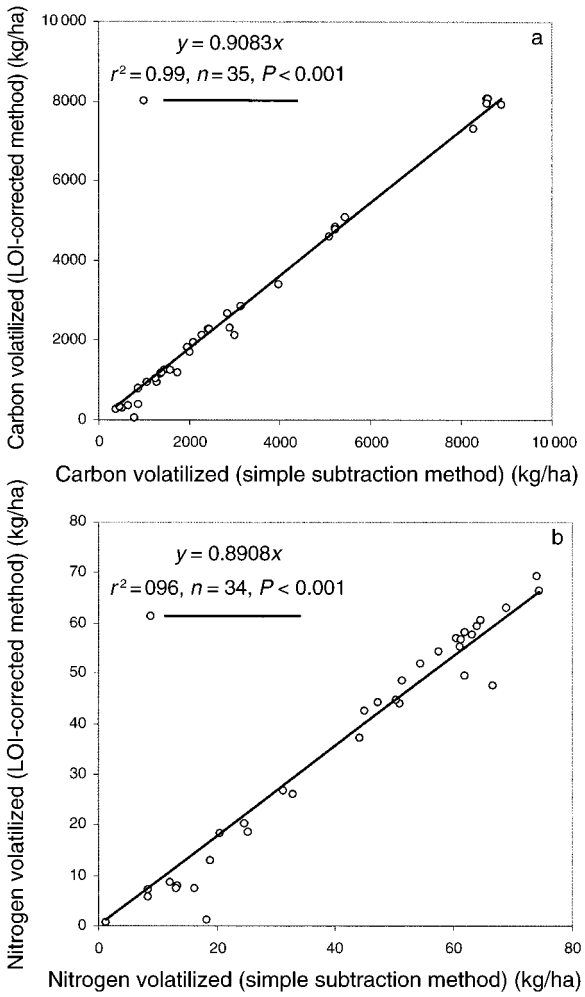

FIG. 4. Comparison of (a) carbon and (b) nitrogen volatilized in experimental fires in Chobe National Park, as derived using fuel biomass combustion estimates (L) calculated via the Smith et al. method (which takes into account the loss on ignition (LOI) of the pre- and post-fire samples) and the simple subtraction method (which does not). The least-squares linear best-fit (with zero intercept) relationships are also shown.

The small variation in the percentage of carbon content of the pre-fire fuel samples (Table 2) results in emissions of carbon being linearly proportional to the mass of fuel combusted, i.e., the effective emission factor of carbon is approximately constant (EF_C = 491 g/kg, r^2 = 0.99, n = 36, $P < 0.001$). Hence, as with the original biomass combustion estimates (Fig. 2), the estimate of carbon volatilized calculated using the Smith et al. method is, on average, within 10% of that calculated using the simple subtraction method (Fig. 4a).

The quantity of nitrogen volatilized, calculated using the Smith et al. method is, on average, within 11% of that derived using the simple subtraction method (Fig. 4b), although there is more scatter than with the calculation of carbon volatilized (i.e., compared to Fig. 4a) because the percentage of nitrogen content of the different fuel components varied more than did the percentage of carbon content (Table 2). The effective emission factor of nitrogen (EF_N) is found to be relatively consistent (EF_N = 9.3 ± 3.1 g/kg) for plots where the natural fuel load was used, but diverged markedly on the three plots where additional senesced grass had been added to increase pre-fire fuel loading (Fig. 5). This is a direct result of the lower nitrogen content of the senesced grass fuel when compared to the other fuel types (Table 2), and indicates that constant effective emission factors can only be assumed in savanna environments if fuel type proportions are invariant over space and time.

DISCUSSION AND CONCLUSIONS

The equations we have derived to estimate total biomass lost during combustion in natural wildfires, which take into account the effect of incomplete combustion via measurement of the fuel and ash mass loss on ignition, differ from those of Stronach and McNaughton (1989). Comparison between the new equations presented here and those in Stronach and McNaughton (1989) demonstrates that the latter significantly overestimate the importance of the residual ash component because of an inherent but incorrect assumption that the difference between the pre- and post-fire fuel loads is equal to the mass of ash produced by the fire, rather than to the mass of ash *and* gaseous products as is actually the case.

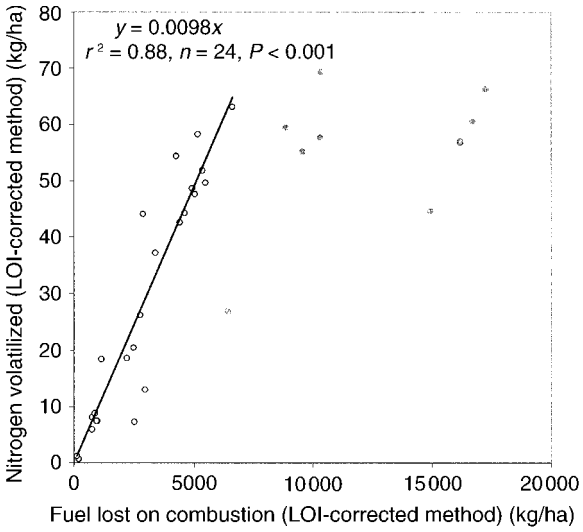

FIG. 5. Relationship between the amount of nitrogen volatilized and the quantity of fuel biomass lost on combustion (L), both calculated via the Smith et al. method (which takes into account the loss on ignition (LOI) of the pre- and post-fire samples). Solid circles represent data for experimental fire plots where additional grass biomass was added prior to ignition, and open circles represent plots where the natural pre-fire fuel loads were left unchanged. The least-squares linear best fit to data from the latter (naturally loaded) plots is also shown.

When used with field data from late dry-season experimental fires in southern African savanna, our new derivation suggests that the commonly applied simple subtraction method (Eq. 3) can be used to calculate the mass of fuel combusted to accuracies of ~10% of that calculated using the significantly more time-consuming methods derived herein, which consider variations in the combustion completeness of the ash through measurement of its mass loss on ignition (LOI). Furthermore, re-assessment of data from Stronach (1990) of early-to-mid-dry-season fires in Serengeti National Park, Tanzania, demonstrates that the simple subtraction method estimates biomass lost to within ~20% of that estimated via the more time-consuming LOI-based method. These variations are significantly less than the factor of 2 differences calculated via use of the flawed Stronach and McNaughton (1989) approach, and cast significant doubt on the conclusion of McNaughton et al. (1998) that global pyrogenic emissions maybe grossly overestimated due to the use of inappropriate combustion factors.

We conclude that, in the case of natural savanna wildfires occurring well into the dry season, the additional sampling effort required to collect LOI data of the pre- and post-fire components may be unnecessary for all but the most accurately required emissions calculations. For fires where the combustion factor might be expected to be much lower, for example, those occurring outside of the main dry periods, consideration of the component LOIs becomes more necessary. In such cases, it is most important that Eq. 12 derived in this paper is applied, rather than Eq. 4 provided by Stronach and McNaughton (1989), since the underestimation resulting from use of the latter equation increases with the proportion of potentially combustible material left in the ash. We recommend further experiments be conducted in the early dry season, when combustion factors would be expected to be at a minimum, to fully assess the applicability of the assumptions inherent in Eq. 3 under those conditions.

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APPENDIX

Loss on ignition: determining the total biomass lost (volatilized) on combustion (*L*) is available in ESA's Electronic Data Archive: *Ecological Archives* A015-029-A1.