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Incorrect interpretation of carbon mass balance biases global vegetation fire emission estimates

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Vegetation fires are a complex phenomenon in the Earth system with many global impacts, including influences on global climate. Estimating carbon emissions from vegetation fires relies on a carbon mass balance technique that has evolved with two different interpretations. Databases of global vegetation fire emissions use an approach based on 'consumed biomass', which is an approximation to the biogeochemically correct 'burnt carbon' approach. Here we show that applying the 'consumed biomass' approach to global emissions from vegetation fires leads to annual overestimates of carbon emitted to the atmosphere by 4.0% or 100 Tg compared with the 'burnt carbon' approach. The required correction is significant and represents ~9% of the net global forest carbon sink estimated annually. Vegetation fire emission studies should use the 'burnt carbon' approach to quantify and understand the role of this burnt carbon, which is not emitted to the atmosphere, as a sink enriched in carbon.

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Vegetation fires have existed in the Earth system since shortly after the appearance of terrestrial vegetation ~420 million years ago^{1,2} and are a necessary disturbance for maintaining some ecosystems³. They also have a range of anthropogenically deleterious consequences such as damage to assets and infrastructure, loss of life, as well as degrading ambient air quality leading to negative impacts on human health⁴. Vegetation fires also perturb global biogeochemical cycles, with impacts on climate^{4–6}. It is estimated that over the period 2001–2010, global vegetation fires emitted an average of 2.5 Pg per year (1 Pg = 1×10^{15} g) of carbon to the atmosphere⁷, equivalent to 30% of annual-averaged anthropogenic emissions from fossil fuel combustion over 2004–2013 (ref. 8). Changes in global vegetation fire regimes, such as an increased fire frequency, have been predicted from modelling studies undertaken in the northwest of the United States⁹, as well as Mediterranean-type ecosystems under a warmer and wetter future climate¹⁰. Furthermore, charcoal records from boreal forests suggest that current vegetation fire frequencies are at their highest level in the last 3,000 years¹¹ and predictions of a future increase in fire intensity have been made¹². Given the global impact of vegetation fires on ecosystems and climate, accurate accounting methods are required to estimate their greenhouse gas emissions, to characterize their climate forcing and to properly design carbon mitigation strategies involving the management of vegetation.

Using the Intergovernmental Panel on Climate Change (IPCC) methodology¹³, total emissions from fire are calculated using the product of activity and an emissions factor (EF). Activity refers to a process occurring in the environment that leads to emissions (for example, fire) and an EF is thus defined as emissions per unit activity.

When calculating an EF from fire, the principle of a carbon mass balance (CMB) is invoked, with the technique ultimately being attributed to either Ward *et al.*¹⁴ or Radke *et al.*¹⁵. While the partitioning of the chemical species of interest and total emitted carbon into reference-gas-normalized emission ratios is consistently applied in vegetation fire emission studies^{16–18}, there have been inconsistencies in the treatment of vegetation exposed to fire but not emitted to the atmosphere (that is, post-burn combustion residue).

In this article, we show that neglecting changes in the post-burn carbon content (CC_{post} , %) leads to an upward bias in emission estimates for the ‘consumed biomass’ CMB interpretation compared with the ‘burnt carbon’ approach. We therefore recommend that vegetation fire studies employ the ‘burnt carbon’ approach to more accurately estimate emissions, by taking into account the change in carbon content from post-fire residues.

Results

Definitional preliminaries. Following the definitions from Surawski *et al.*¹⁶, we define ‘burnt’ as fuel that has been thermally altered as a result of exposure to fire and either emitted to the atmosphere or left in the post-fire residue; and we define ‘consumed’ as that component of the fuel that is emitted to the atmosphere as a result of exposure to fire. We follow the definition of Keane *et al.*¹⁹ that ‘fuels are the dead and live biomass available for fire ignition and combustion’.

The basis of biased emission estimates. Since the publication of the CMB technique¹⁵, the method has been interpreted and applied in two different ways in the vegetation fire emission literature^{17,20}. The first is the ‘consumed biomass’ approach (Fig. 1, top pathway), which is based on the simplifying assumption that all burnt carbon is volatilized and emitted. We

demonstrate below that this assumption is incorrect and leads to biased results. The second method, the ‘burnt carbon’ approach, additionally takes into account changes between the pre- and post-fire carbon content of the fuel and is unbiased (Fig. 1, bottom pathway).

Both approaches have the same starting point, which is the amount of biomass fuel before burning (B_{pre} , t ha^{-1} on a dry matter basis) and its carbon content (CC_{pre} , %). In the absence of measurements of fuel carbon content, a carbon content of 50% is commonly assumed¹⁸, although a value of 45% has also been suggested²¹. The pre-burning carbon load (t ha^{-1} on a dry matter basis) can then be calculated from estimates of both B_{pre} and CC_{pre} ($C_{\text{pre}} = B_{\text{pre}} \times CC_{\text{pre}}$). Both interpretations of the CMB technique rely on estimates of biomass fuel after burning (B_{post}) to enable calculation of a combustion factor ($CF = (B_{\text{pre}} - B_{\text{post}})/B_{\text{pre}}$) (ref. 13). It is the subsequent analysis where the two interpretations of the CMB technique diverge and bias is introduced.

The ‘consumed biomass’ approach is more commonly applied^{21–25} (and references therein) and does not require any further measurements after B_{post} has been calculated. In this case, estimation of an EF is based on consumed biomass only and reports EFs as the mass of a chemical species emitted per kilogram of dry fuel consumed. The ‘burnt carbon’ approach is far less commonly applied^{16,17,26,27} and requires an estimate of the post-burning carbon content for burnt fuel that is not emitted to the atmosphere. Estimating CC_{post} enables the post-fire carbon load ($C_{\text{post}} = B_{\text{post}} \times CC_{\text{post}}$) to be calculated. This in turn enables burnt carbon to be partitioned between that emitted to the atmosphere ($\Sigma C_{\text{emit}} = C_{\text{pre}} - C_{\text{post}}$) and that remaining as post-burn combustion residue (C_{post} , for example, charred material enriched in carbon; Fig. 1). Consequently, the second interpretation of the CMB technique is based on ‘burnt carbon’ involving either atmospheric emission or resulting in an ashed or charred residue after exposure to fire (C_{post} in Fig. 1) with both of these ultimate fates being represented as a percentage of burnt carbon.

The explicit and incorrect assumption of the ‘consumed biomass’ CMB method (top pathway in Fig. 1) is that all burnt carbon is volatilized and emitted to the atmosphere^{20,25,28}. In contrast, the ‘burnt carbon’ CMB method (bottom pathway in Fig. 1) correctly accounts for burnt carbon remaining as a residue after a vegetation fire. Many vegetation fire research studies have shown that not all burnt fuel carbon is volatilized and emitted to the atmosphere^{17,26,29–34}. The need to take into account the full-carbon budget of vegetation fires has been raised previously^{21,35,36}, yet vegetation fire emission studies generally do not measure CC_{post} (with $CC_{\text{post}} > CC_{\text{pre}}$ for charred post-fire material^{30,31,34}), which precludes use of the ‘burnt carbon’ CMB method and this leads to an overestimation bias of emissions for the ‘consumed biomass’ method relative to the ‘burnt carbon’ method.

To avoid this bias with the ‘consumed biomass’ CMB approach, it is necessary to multiply its EF by the fraction of burnt fuel carbon emitted to the atmosphere, $\Sigma C_{\text{emit}}/C_{\text{fuel}}$ (ref. 16), where ΣC_{emit} is the mass of emitted carbon and C_{fuel} is the mass of fuel carbon burnt (Supplementary Table 1). Only if all burnt fuel carbon is emitted to the atmosphere (that is, $\Sigma C_{\text{emit}}/C_{\text{fuel}} = 1$, which is very unlikely to be achieved in a real fire), would these two methods agree without inclusion of the correction factor. Otherwise, estimates of emissions using the ‘consumed biomass’ approach will be overestimated (that is, relative to the ‘burnt’ carbon approach), represented by the difference between complete volatilization and emission of carbon to the atmosphere, and the true fraction of carbon volatilized and emitted to the atmosphere ($\varepsilon = 1 - \Sigma C_{\text{emit}}/C_{\text{fuel}}$).

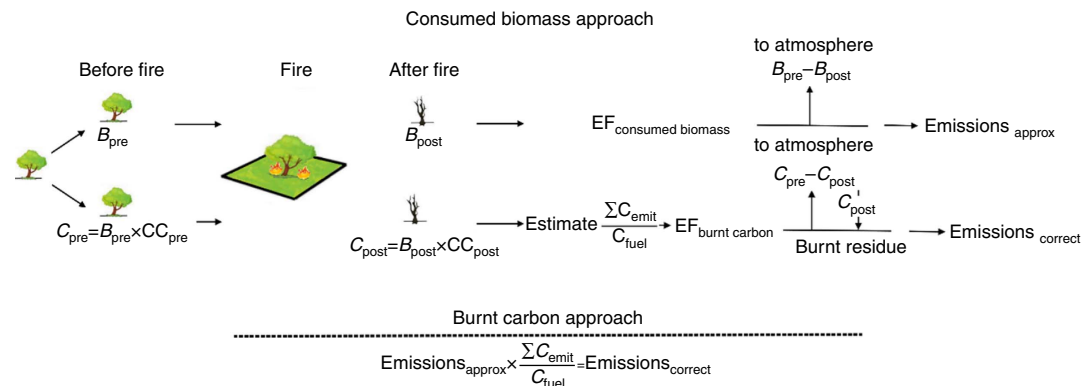


Figure 1 | A diagrammatic illustration of how biased emission estimates from fire occur. A schematic of the two different ways the carbon mass balance technique has been interpreted and applied in vegetation fire emission studies. C_{pre} and B_{pre} denote pre-fire carbon and biomass fuel, CC_{pre} and CC_{post} represent pre- and post-fire carbon content, and C_{post} and B_{post} denote post-fire carbon and biomass fuel, respectively. $\Sigma C_{emit}/C_{fuel}$ represents the correction factor required for the burnt carbon accounting framework. $Emissions_{approx}$ represents approximate emissions estimated using the consumed biomass approach and $Emissions_{correct}$ represents emission estimates using the burnt carbon approach. EF denotes emissions factor with the estimate depending on what accounting framework is used (that is, consumed biomass or burnt carbon).

Quantification of the correction factor. To quantify the magnitude of this overestimation, we obtained empirical estimates from the literature^{17,29–34} (Supplementary Table 1) of the fraction of burnt fuel carbon emitted to the atmosphere or the fraction of burnt carbon retained in post-burn residues (and in one case both emissions and residues), to determine the likely values of ϵ in various vegetation types around the globe. ϵ values range from a minimum of 0.4% in a savanna ecosystem³⁴ to a maximum of 50% in a temperate forest³⁴. On the basis of 40 records (Fig. 2), the median ϵ value is 4.0% with the interquartile range (25th–75th percentiles) spanning the interval 2.0–12.0%.

Discussion

In terms of estimating global emissions from vegetation fires, the widely used Global Fire Emissions Database²², and others such as the Fire INventory from NCAR²³, and IPCC good practice guidelines for national greenhouse gas inventories¹³ rely on the ‘consumed biomass’ approach for reporting EFs. If we use the median ϵ value of 4.0% and apply this to the globally averaged annual carbon emissions from 2001 to 2010 of 2.5 Pg (ref. 7), the overestimation of emissions (that is, for the ‘consumed biomass’ approach compared with the ‘burnt carbon’ approach) amounts to ~100 Tg (1 Tg = 1×10^{12} g) of carbon per year, with an uncertainty range (25th–75th percentiles) of 50–300 Tg. Furthermore, the ‘consumed biomass’ approach (which assumes 100% volatilization of burnt carbon) precludes the ability to quantify the efficacy of any direct management of fire for post-fire residues for mitigating net vegetation fire emissions, such as the preferential firing of vegetation fuels for enhanced charred post-fire residues to increase sequestration in the pedosphere.

Altogether, the potential for a 50–300-Tg error in annual global vegetation fire emission estimates highlights that vegetation fire research should be conducted in a more coordinated manner^{1,37}, to ensure the complete biogeochemistry of fire events are adequately represented. Despite recommendations in the literature²¹, measurements of CC_{post} are not routinely made in vegetation fire emission studies. This prevents $\Sigma C_{emit}/C_{fuel}$ from being calculated, leading to an overestimation of emissions for the ‘consumed biomass’ approach relative to the ‘burnt carbon’ approach. Furthermore, this overestimation means that the amount of carbon in burnt residues needs to be adjusted to maintain global carbon mass balance from vegetation fires. Apart from improving global vegetation fire emission estimates, it is envisaged that global studies of CC_{post} will broaden our

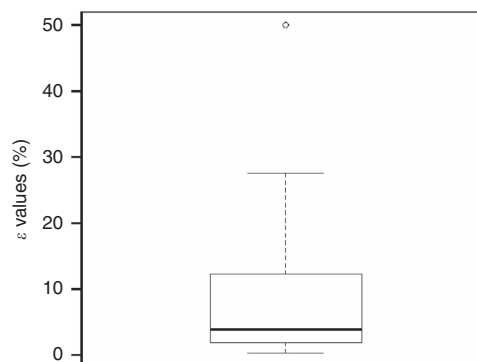


Figure 2 | A box plot of the global ϵ value distribution based on our literature review. The ϵ value is the percentage of carbon exposed to fire (that is, burnt) that remains as a post-fire residue, based on 40 records^{17,29–34} (Supplementary Table 1). The five-number summary for ϵ is: minimum = 0.4%, 25th percentile = 1.98%, median = 3.95%, 75th percentile = 12.0%, maximum = 50% (the single outlier is shown as an open circle). The interquartile range (IQR) = 10.0.

understanding of ecosystem carbon fluxes due to fire, including the potential for managing burnt carbon residues to enhance ecosystem carbon storage and to spawn research efforts exploring the post-fire fate of carbon^{34–36,38}. In particular, such efforts should estimate the global ϵ value with different fire behaviours and ecosystem types, as only a coarse estimate was obtained using current estimates in the literature. In conducting such research, however, it is important to realize that greater uncertainties are present for burnt areas, fuel load and combustion factors from global vegetation fires³⁹.

Methods

EF reporting methods. Examples of studies that have adopted the approximate ‘consumed biomass’ approach to emissions accounting from vegetation fires are ubiquitous^{21–25} (and references therein).

Examples of studies exploring the more complete ‘burnt carbon’ approach are far less common^{16,17,26,27}.

EF reporting fundamentals. Estimating emissions from vegetation fires involves multiplying the amount of fuel consumed⁶ by an EF (ref. 24). The amount of fuel consumed is obtained by multiplying the area burnt (A) by the fuel load (B) and a combustion factor (CF). The basis of the CMB technique is that for the dominant carbonaceous species emitted in a plume (usually CO_2 , CO and CH_4), excess mixing ratios (that is, molar concentrations above background) are measured.

Then, emission ratios are calculated by normalizing (that is, dividing) the excess mixing ratio of the species of interest to the excess mixing ratio of a reference gas, or in some cases the sum of the excess mixing ratios of total emitted carbon⁴⁰. An EF is then obtained by dividing the emission ratio for the species of interest by that of the emitted and detected carbon

Conversion of the consumed biomass method to burnt carbon. Using the 'consumed biomass' interpretation of an EF (an approximation that assumes that all fuel carbon is volatilized and emitted to the atmosphere), emissions for the X th carbon-based species (E_X) can be calculated by multiplying the area burnt, the fuel load and the combustion and EFs together via:

$$E_X = A \times B \times CF \times EF_X \quad (1)$$

In equation (1), EF_X , reported on a kg species X per kg consumed basis, is defined by¹⁸:

$$EF_X = C_{pre} \times U_C \times \frac{C_X}{C_T}, \quad (2)$$

where U_C is a conversion factor used to convert between atomic and molar masses, C_X is the number of moles of species X and C_T is the total number of carbon moles emitted to the atmosphere.

Assuming that CO_2 is used as a reference gas for the normalization of emission ratios (that is, other choices include CO or CH_4 (ref. 16) or total emitted carbon⁴⁰), C_X/C_T is given by:

$$\frac{C_X}{C_T} = \frac{\frac{\Delta C_X}{\Delta CO_2}}{\sum_{j=1}^N NC_j \times \frac{\Delta C_j}{\Delta CO_2}}, \quad (3)$$

where ΔC_X represents the difference between the plume and ambient mixing ratios for species X , and NC_j represents the number of carbon atoms in species j , with summation being performed across the total number of carbon species N .

Alternatively, using the 'burnt carbon' interpretation, emissions for the X th (that is, carbon based) species are given by:

$$E_X = A \times B \times CF \times C_{pre} \times U_C \times EF_X. \quad (4)$$

In equation (4), assuming again that CO_2 is used as a reference gas, EF_X (defined as the percentage of burnt carbon emitted as species X) is defined by¹⁷:

$$EF_X = \frac{\sum C_{emit} \times \frac{\Delta C_X}{\Delta CO_2}}{\sum_{j=1}^N NC_j \times \frac{\Delta C_j}{\Delta CO_2}}, \quad (5)$$

where $\sum C_{emit}$ is the mass of fuel carbon emitted to the atmosphere from j different carbon species, and C_{fuel} is the mass of fuel carbon burnt.

Note that:

$$\frac{\sum C_{emit}}{C_{fuel}} = \frac{C_{pre} - C_{post}}{C_{pre}} = \frac{B_{pre}CC_{pre} - B_{post}CC_{post}}{B_{pre}CC_{pre}} = 1 - \frac{B_{post}CC_{post}}{B_{pre}CC_{pre}}. \quad (6)$$

Consequently, the only way that the equation (1) can equal equation (4) is if equation (2) is multiplied by $\sum C_{emit}/C_{fuel}$ (ref. 16). The presentation here focused on carbon-based species, but similar calculations can be performed for nitrogen-based species (such as N_2O).

Global estimates of the correction factor. A broad literature search was conducted using the Web of Science, Scopus and Google Scholar databases to parameterize this quantity. Literature searches were motivated by listings of major field-based vegetation fire emission campaigns commencing in the 1980s and ending with the Fire Lab at Missoula Experiments (Supplementary Table 1). On the basis of our literature search, in Supplementary Table 1, we parameterise the global ε value for different ecosystems and fuel types, as well as for different fire types, fuel sampling methods, carbon residue sampling methods and carbon residue quantification methods. A statistical summary of our ε value database is provided in Fig. 2 and its caption.

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Author contributions

A.L.S. suggested undertaking this project of highlighting different interpretations of the CMB technique. S.H.R. suggested a graphical representation of different interpretations

of the CMB technique. N.C.S. prepared Figs 1 and 2 and Supplementary Table 1, and wrote the manuscript with contributions from all co-authors.

Additional information

Supplementary Information accompanies this paper at <http://www.nature.com/naturecommunications>

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