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Alistair M.S. Smith

University of Idaho, alistair@uidaho.edu

Andrew T. Hudak

Rocky Mountain Research Station, ahudak@fs.fed.us

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Estimating combustion of large downed woody debris from residual white ash

Alistair M. S. Smith^{A,C} and Andrew T. Hudak^B

^ADepartment of Forest Resources, University of Idaho, Moscow, ID 83844-1133, USA.

^BRocky Mountain Research Station, USDA Forest Service, Moscow, ID 83843, USA.

Telephone: +1 208 883 2327; fax: +1 208 883 2318; email: ahudak@fs.fed.us

^CCorresponding author. Telephone: +1 208 885 1009; fax: +1 208 885 6226; email: alistair@uidaho.edu

Abstract. The production of residual white ash patches within wildfires represents near-complete combustion of the available fuel and releases a considerable quantity of gases to the atmosphere. These patches are generally produced from combustion of large downed woody debris (LDWD) such as fallen trees and snags. However, LDWD are generally ignored in calculations of fuel combusted within environments where surface fires dominate (e.g. southern African savannas). To assess the potential of fractional white ash cover as a remotely sensed measure of LDWD combustion, both the proportion of the surface covered by white ash and the combustion completeness required to produce white ash must be quantified. An aerial photograph of woodland savanna fires in north-western Zimbabwe was analysed to estimate the proportion of white ash cover within a typical satellite sensor pixel. The proportion loss on ignition (LOI) of wood samples from the study area was measured and combined with previous estimates of mean tree biomass. The proportion of white ash within the aerial photographs was 0.2% (± 0.06), which corresponded to an additional 67 320 kg ha⁻¹ of biomass combusted above that typically recorded as combusted from a surface fire in this environment (~ 7000 kg ha⁻¹). This analysis should be repeated in other savannas and forests, where pre-fire fuel loads and post-fire fractional white ash cover may be higher.

Additional keywords: burned area; carbon; emission estimates; loss on ignition; remote sensing; savanna.

Introduction

Of all the biomes, forests and their associated detritus and soils have the greatest potential to store carbon (Harmon and Marks 2002). Large downed woody debris (LDWD) accounts for at least 10–20% of forest carbon budgets (Muller and Liu 1991; Turner *et al.* 1995; Delaney *et al.* 1998), yet is currently ignored in carbon emission estimates from wildfires (Brown 2002). As such there is an urgent need to quantify the amount and distribution of LDWD at the scale they can be accurately measured on the ground and through high-resolution aerial imagery. The challenge is scaling such estimates to the scale of moderate resolution satellite pixels (i.e. 10–500 m), which remains the most cost-effective approach to assessing the extent of fires, especially those that are large and occur in remote areas (Zhang *et al.* 2003).

Regional studies assessing biomass combusted (and carbon volatilized) within wildfires have generally been based on extrapolated relationships between remotely sensed measures of the area burned and field measurements of fuel and fire characteristics (Kasischke and Bruhwiler 2003). A considerable body of past research has investigated the application

of remote sensing techniques to measure burned area (e.g. Pereira 1999; Smith *et al.* 2002; Hudak and Brockett 2004), but larger uncertainties continue in the field characterizations of fuels (Kasischke and Bruhwiler 2003). In particular, pre-fire biomass density and the proportion of fuel combusted are highly variable across small spatial extents (Keane *et al.* 2001).

In both savanna woodlands and forests, combustion of LDWD leaves a ghost log, or white ash residue in the shape of the former log on a black ash background (Fig. 1). Where combustion is incomplete following wildland fires, vegetation is typically covered in a black carbon residue termed char or black ash (Robinson 1991); where combustion is complete, white mineral ash remains (Stronach and McNaughton 1989). Following forest fires, the spatial density of white ash patches has been observed to increase with increased fire severity (Hudak *et al.* 2004). Similarly after savanna fires, a greater abundance of white ash has been observed to correspond to a higher pre-fire fuel load (Landmann 2003). Therefore, a measure of white ash per unit area could be considered a quantitative indicator of LDWD combusted. Furthermore,

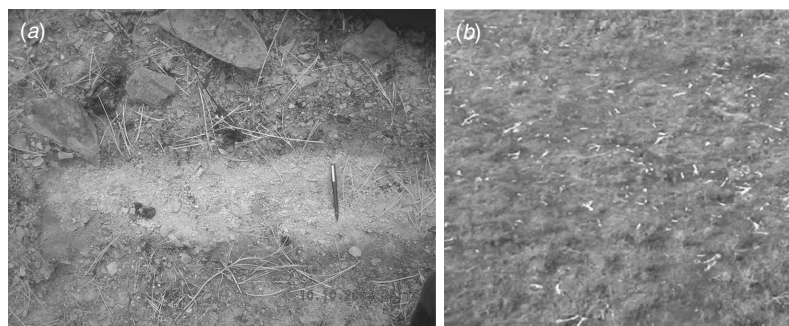


Fig. 1. Production of white ash from LDWD in a southern African woodland savanna at the scale of an (a) individual log, or 'ghost log', and (b) oblique digital aerial photograph showing white LWDW deposits on a black ash background in north-western Zimbabwe. Photograph covers an area $\sim 120 \text{ m} \times 60 \text{ m}$ in size, equating to $\sim 4 \times 2$ Landsat Thematic Mapper pixels.

the albedo (i.e. brightness) of the post-fire surface could indicate pre-fire fuel load, combustion completeness, and mass of carbon volatilized, although white ash assessment must be prompt as it is quickly removed by meteorological processes following fires (Robinson 1991). Quantification of the spatial variation and density of white ash could also be used to parameterize emissions models by providing a spatial measure of the biomass combusted and thus gases volatilized within burned areas (Kasischke and Bruhwiler 2003).

This paper provides a preliminary assessment of the quantity of LDWD combusted per unit area burned in a southern African woodland savanna, using estimates of both the typical cover fraction of white ash and the combustion completeness required to produce such white ash.

Methods

Study area and aerial imagery

Eight small ($5 \text{ m} \times 5 \text{ m}$) experimental fires were carried out in woodland savanna sites of light-moderate canopy cover in Chobe National Park (CNP), north-eastern Botswana, at the end of the 2001 dry season (16–22 October 2001). Vegetation in this landscape consisted of an open woodland savanna matrix interspersed with pockets of open grassland. The main species were the grass *Dactyloctenium giganteum* and the tree *Baikiaea plurijuga* (Smith *et al.* 2005). A preliminary assessment of the proportion of white ash within a neighboring (within 90 km) savanna woodland in north-western Zimbabwe that burned under similar conditions was assessed using a single digital aerial photograph. This photograph had an approximate spatial resolution of 30 cm and was acquired 19 October 2000. A subset of $\sim 120 \text{ m} \times 60 \text{ m}$ ($\sim 4 \times 2$ Landsat Thematic Mapper pixels) was randomly selected within the burned area (Fig. 1b) and used within this preliminary analysis. The white ash patches in the aerial photograph were segmented using simple DN thresholding, and their cumulative area summed, in order to determine the proportion of white ash. The DN threshold (205) was selected as the value at

which the presence of the background was visibly minimized, while the majority of the white ash from LDWD remained.

Fuels and loss on ignition measurements

The available fine fuel load (i.e. excluding LDWD) within each experimental plot was estimated by clipping the herbaceous biomass within five $0.25 \text{ m} \times 0.25 \text{ m}$ quadrats (randomly selected from within a firebreak 2 m wide surrounding each experimental plot) to the soil level. Five additional post-fire samples were collected at fixed points within each plot. Samples of white ash (collected beside a fallen, combusted tree) and uncombusted woody debris were collected and processed for loss on ignition (LOI).

Proportion LOI was measured following the procedure of Stronach and McNaughton (1989). Each white ash and wood sample was weighed and placed in a muffle furnace for 12 h at 100°C , then reweighed to obtain dry fuel mass. Samples were then reheated to 500°C in the same furnace for another 18 h to reduce them to incombustible mineral ash. The samples were then removed from the furnace and rapidly reweighed, to minimize reabsorption of atmospheric moisture. Proportion LOI of each sample was then calculated using Eqn (1):

$$LOI = \frac{(Mass_{Pre-Furnace} - Mass_{Post-Furnace})}{Mass_{Pre-Furnace}} \quad (1)$$

Biomass of fallen trees was estimated using mean values across all woody species, previously measured in the same savanna vegetation type in eastern Botswana (Tietema 1993).

Results

In the experimental burn plots, fine fuel loads varied between 2000 and 9930 kg ha^{-1} and the typical quantities of fuel combusted (excluding LDWD) varied between 937 and 7370 kg ha^{-1} . These results resembled those from previous studies in similar environments (Table 1). The proportion LOI of the white ash collected from the combusted fallen tree

Table 1. Mean fine fuel loads combusted in southern African savanna fires

Location	Environment	Load (kg ha ⁻¹)	Combusted (%)	Reference
Botswana	Savanna grassland	2000–9930	65 ± 21	Smith <i>et al.</i> (2005)
South Africa	Savanna parkland	6500–10 000	~56 ± 14	Landmann (2003)
Zambia	Dambo grassland	2220–5950	64 ± 38	Hely <i>et al.</i> (2003)
Zambia	Flood plain grassland	3640–4690	50 ± 24	Hely <i>et al.</i> (2003)
Zambia	Semi-arid Miombo woodland	5100 ± 396	88 ± 2	Shea <i>et al.</i> (1996)
Zambia	Fallow Chiemene	7353 ± 708	71 ± 5	Shea <i>et al.</i> (1996)
Zambia	Moist Miombo woodland	5772 ± 328	74 ± 4	Shea <i>et al.</i> (1996)
South Africa	Savanna parkland	3892–7084	87 ± 5	Shea <i>et al.</i> (1996)

was virtually zero (i.e. <0.1 g from a sample of 30 g). The proportion LOI of unburned wood was 0.88 (± 0.10).

The average proportion of white ash cover measured in the aerial photographs was 0.2% (± 0.06). This estimate of fractional white ash cover was used to estimate LDWD consumed within the extent of the photos.

Approximately 55 (± 15) individual fallen trees were identified within a ~60 m × 60 m area in the aerial photograph (lower half of Fig. 1b), which translates to a fallen tree density of ~153 trees ha⁻¹. The mean biomass of each tree was estimated to be 500 kg, as measured by Tietema (1993).

By combining this information, a preliminary measure of the tree fuel load combusted per ha was obtained:

$$TFL = LOI_T \times Load_T \times \rho_{T(Fallen)}, \quad (2)$$

where LOI_T was the mean loss on ignition of the trees (i.e. wood = 0.88), $Load_T$ was the mean biomass load of each tree (i.e. 500 kg), and $\rho_{T(Fallen)}$ was the fallen tree density (i.e. 153 trees ha⁻¹).

The calculated $TFL = 67\,320$ kg ha⁻¹ thus approximated the upper limit of LDWD combusted in this woodland savanna. This measurement exceeded by nearly 10-fold the combusted fine fuel load (~7000 kg ha⁻¹) measured by Smith *et al.* (2005) and others (Trollope *et al.* 1996; Brown 2002; Table 1). This upper limit of LDWD combusted equates to potential upper bounds of 6059 kg and 1 683 000 kg of additional fuel combusted within single Landsat Thematic Mapper (30 m spatial resolution) and MODIS (500 m spatial resolution) pixels respectively.

Discussion

This result demonstrates that accurate assessment of fractional white ash cover may be crucial for accurately estimating emissions from such fires. Remote quantification of the spatial density and distribution of residual white ash cover could greatly reduce current uncertainties in the spatial density and distribution of LDWD, and their consequent carbon (and nitrogen) pyrogenic emissions. The wide-scale assessment of LDWD via the detection of white ash by DN thresholding of aerial photography will, however, be limited by the ability to discriminate such white ash patches

from bright soils or salt pans, exposed rock outcrops, solar illumination conditions, and sensor characteristics such as the spatial-resolution of the imagery and the type of sensor applied (i.e. digital or film cameras). In addition, DN thresholding is an arbitrary process with the precise DN value requiring reselection with each new image. To potentially overcome such issues, spectral mixture analysis (e.g. Wessman *et al.* 1997; Drake *et al.* 1999) or other remote sensing techniques could be applied to quantify white ash fractional cover, provided the imagery is acquired immediately after burning (before wind and water disperse the white ash), and with sufficiently high resolution to feasibly resolve the white ash fraction. Quantifying the white ash fraction and its range of variability from remotely sensed data would then facilitate large-scale estimates of carbon emissions from wildland fires that could be corrected for the presence of combusted LDWD. Such remote estimates could also enable large-scale fuel load reduction and snag production estimates, which are currently necessary for numerous fire management users.

Conclusions

The white ash collected for LOI analysis was mineral ash produced through the near-complete combustion of a fallen tree. The proportion LOI of unburned wood indicated that 88% (on average) of the wood biomass is volatilized to produce white ash. Although white ash patches were found to cover only 0.2% (on average) of the ground surface, the LDWD indicated by these patches may constitute >90% of the total pyrogenic emissions in this woodland savanna. These results highlight the need for field and remotely sensed surveys to quantify the pre-fire density and distribution of LDWD, and the post-fire density and distribution of residual white ash patches. Such data may prove critical for accurately estimating pyrogenic emissions and balancing the carbon budget in woodland savannas and forests.

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