nature geoscience

LETTERS

PUBLISHED ONLINE: 5 DECEMBER 2010 | DOI: 10.1038/NGEO1027

Recent acceleration of biomass burning and carbon losses in Alaskan forests and peatlands

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Climate change has increased the area affected by forest fires each year in boreal North America[1,2]. Increases in burned area and fire frequency are expected to stimulate boreal carbon losses[3–5]. However, the impact of wildfires on carbon emissions is also affected by the severity of burning. How climate change influences the severity of biomass burning has proved difficult to assess. Here, we examined the depth of ground-layer combustion in 178 sites dominated by black spruce in Alaska, using data collected from 31 fire events between 1983 and 2005. We show that the depth of burning increased as the fire season progressed when the annual area burned was small. However, deep burning occurred throughout the fire season when the annual area burned was large. Depth of burning increased late in the fire season in upland forests, but not in peatland and permafrost sites. Simulations of wildfire-induced carbon losses from Alaskan black spruce stands over the past 60 years suggest that ground-layer combustion has accelerated regional carbon losses over the past decade, owing to increases in burn area and late-season burning. As a result, soils in these black spruce stands have become a net source of carbon to the atmosphere, with carbon emissions far exceeding decadal uptake.

Previous modelling results suggest that increasing fire frequency in boreal regions controls forest composition, increases greenhouse-gas emissions, and serves as a main determinant of boreal carbon (C) balance[3–5]. However, the net effect of burning on boreal C stocks is determined by both fire frequency and severity, and the consequences of climate-mediated changes in the fire regime for rates of biomass consumption are uncertain[6]. Although advances in remote sensing have provided more accurate information on annual area burned across the boreal biome[7], the vulnerability of boreal biomass to severe burning remains difficult to quantify.

A large portion of the boreal C pool is stored in moss, litter and peat layers that are partially or entirely consumed during fires. Combustion of this ground-layer biomass was estimated to represent more than 85% of the total fuels consumed during Canadian forest fires[8]. In addition to affecting C emissions, the severity of ground-layer biomass burning controls several ecosystem processes, including regulation of soil climate and respiration[9], maintenance of permafrost[10] and forest succession[11]. Previous studies investigating the factors that regulate ground-layer burning have concluded that climate change is not likely to cause more severe burning in boreal forests[12]. However, studies so far have not adequately considered the vulnerability of large C pools in permafrost and peatland regions to burning. The availability of ground-layer fuels in boreal ecosystems is highly dynamic because of seasonal changes in thaw depth and the drying of ground-layer biomass (Supplementary Fig. S1). Also, as the density and cumulative C storage of soils increases nonlinearly with depth, the C pool of ground-layer biomass vulnerable to burning increases dramatically during a fire season. Owing to limited data on burn severity during late-season fires, particularly in ecosystems with thick organic soils (>20 cm) (Supplementary Table S1), the potential influence of climate change and increased fire activity on boreal C loss and trace-gas emissions may be underestimated.

To examine variation in biomass burning, we collected data on the depth of ground-layer combustion from 178 distinct Alaskan forest and peatland sites dominated by black spruce (*Picea mariana* (Mill.) B.S.P.) (Supplementary Table S2). These ecosystems represent two-thirds of all forest cover in interior Alaska. The depth-of-combustion values presented here are based on more than 18,000 measurements of ground-layer biomass depth (including moss, litter, organic soils and peat) collected within 31 fire events that burned between 1983 and 2005, mostly in the past 10 years. Results from this study show that the depth of ground-layer burning was controlled in part by an interaction between the seasonality of fire and the annual area burned (Table 1). The depth of ground-layer burning tended to increase with time through the fire season (Fig. 1a), probably as a result of both drier fuel conditions and greater fuel availability occurring with seasonal ice thaw (Supplementary Fig. S1). However, during large-fire years (with large annual area burned), deeper burning occurred throughout the fire season (Fig. 1a). Thus, the timing of fire was important to the depth of ground-layer burning in small-fire years, but was less important during large-fire years as the depth of burning remained severe (deep) throughout the fire season (Fig. 1b). Across individual fire events, the depth of ground-layer burning varied by a seasonality × fire-size interaction ($F_{1,223} = 8.42$; $p = 0.004$; random-effects variance fire = 3.5, site = 21.2). Depth of burning varied with fire size during early-season burning ($F_{1,189} = 0.008$, $p = 0.008$, random-effects variance fire = 6.9, site = 10.1; Fig. 2) but tended to remain high during late-season burning with no relationship with fire size ($p = 0.31$). Large-fire years in Alaska occur as a result of increased late-season burning[2] associated with weather conditions such as warm springs[13] followed by a dry summer[14]. Under these conditions, our results suggest that deep ground-layer burning early in the fire season serves as an indicator of the severe burning that will continue for several months.

Much of the boreal biome is located in the discontinuous permafrost zone, where the presence of frozen ground in some portions

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Table 1 | Controls on depth of burning in Alaskan forests.

Term	Fixed effects *F* value	Df (Num, Den)	*P*
Annual area burned	9.51	1,242	0.002
Julian date	0.00	1,242	0.95
Landscape class	2.39	4,242	0.05
Annual area burned × Julian date	7.27	1,242	0.01
Julian date × landscape class	2.14	5,242	0.06
Area burned × landscape class	2.83	4,242	0.03
Julian date^2	0.01	1,242	0.93
Julian date^2 × landscape class	2.38	5,242	0.04
Term	**Random effects Variance**	**LRT**	
Fire identity	19.84	$\chi_1{}^2 = 64.1; p = 0.01$	
Site identity	18.55	$\chi_1{}^2 = 12.7; p = 0.05$	

Parameters of a mixed-effects model analysing depth of burn observations from 178 black spruce sites across interior Alaska. The significance of the random effects was assessed through a likelihood ratio test (LRT).

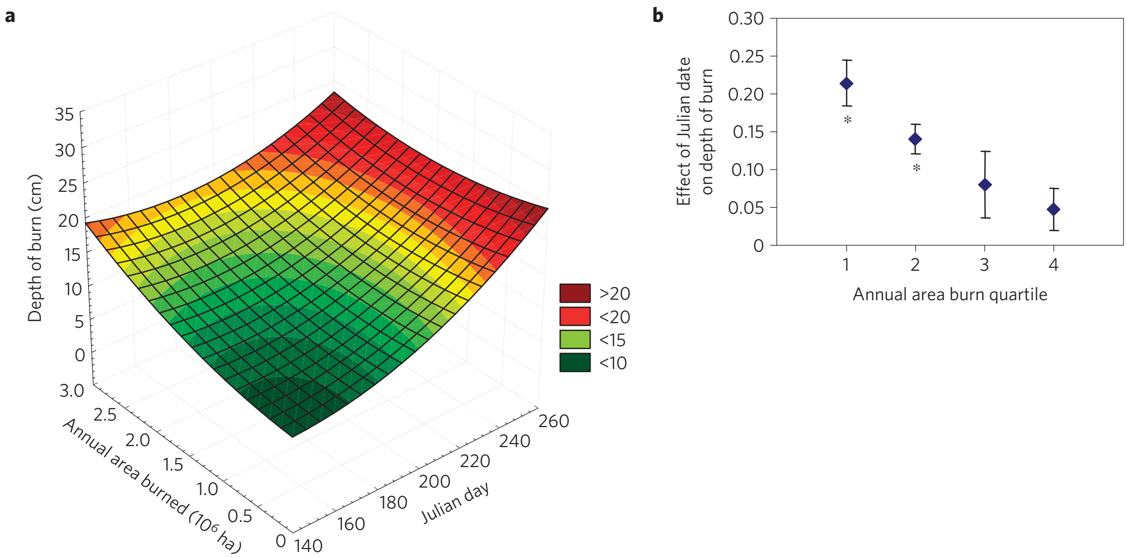

Figure 1 | Fire-regime effects on the severity of biomass burning. a, Depth of ground-layer fuel combustion (cm) is controlled in part by an interaction between annual area burned (ha) and the timing of burning (Julian date) (Table 1). **b**, The slope of the relationship between Julian date and mean depth of ground-layer fuel combustion for each site (centimetre per day) is higher in small-fire years than in large-fire years (quartile 1, <107,500 ha; quartile 2, 107,500–413,100 ha; quartile 3, 413,100–1,291,200 ha; quartile 4, >1,291,200 ha). ∗ indicates slopes that are significantly different from zero ($p < 0.0001$; data are mean slopes ±1 standard error).

of the landscape promotes thick peat accumulation. Across interior Alaska, variations in slope, aspect and topography result in large differences in solar input and soil temperatures that control the development of permafrost and ground-layer fuel accumulation[15]. To determine if the seasonal patterns in depth of burning were consistent among these different landscape types, we classified sites into five main landscape classes using topographic and hydrological data (Supplementary Methods S1.2), ranging from flat lowlands (poorly drained peatland and permafrost stands) that experience the coldest temperatures and extensive permafrost development to drier forests on flat uplands that receive high insolation and have the smallest amount of permafrost development. Seasonal patterns of burning varied among boreal landscape classes. In the flat uplands and all sloped sites, the depth of ground-layer burning increased with time through the fire season (flat uplands, $F_{1,126} = 24.57$, $p < 0.0001$; south-facing slopes, $F_{1,82} = 8.43$, $p = 0.005$; east- and west-facing slopes, $F_{1,65} = 53.37$, $p < 0.0001$; north-facing slopes, $F_{1,70} = 11.41$, $p = 0.001$). Burning in the flat lowlands did not increase during late-season burning (flat lowlands: $F_{1,42} = 0.57$, $p = 0.46$), probably because moist conditions in the active layer prevent deeper burning.

Our estimates of C losses during the burning of black spruce stands in Alaska are greater than other boreal-fire C emissions. Previous studies have found that ground-layer burning in boreal black spruce forests released an average of 2.5 kg C m^{-2} per fire event (Supplementary Table S1). This is similar to our estimate of early-season C loss, weighted by the proportion of landscape classes in interior Alaska, which was 2.95 ± 0.12 kg C m^{-2} (Table 2). However, much deeper burning during late-season fires resulted in more than a twofold increase in landscape-weighted C losses (Table 2). Late-season burning had a stronger effect on ecosystem C losses in moderately drained forests (that is, sloped classes) than flat uplands, and had no effect on burning in flat lowlands. Combustion tends to be limited by fuel availability in many well-drained forests,

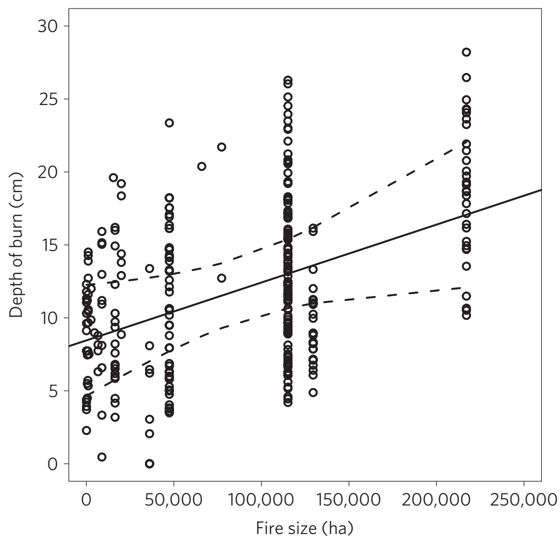

Figure 2 | The effect of fire size on biomass combustion. Depth of burning was positively associated with fire size during early-season burning, but not during late-season burning. The solid line represents the linear regression of fire size on depth of burn during early-season burning (slope, $3.97\times10^{-5}\pm4.60\times10^{-6}$; intercept, 8.45 ± 0.50). Dashed lines represent 95% confidence intervals calculated using the standard error of the slope of mean depth of burn per fire event versus fire size to correct for multiple sites located within individual fires.

whereas in poorly drained peatland and permafrost forests burning typically is regulated by high moisture levels even during dry periods. Thus, moderately drained forests such as our sloped classes are likely to be the ecosystem type in interior Alaska most vulnerable to climate change and changing fire conditions[16].

Although shifts in fire-management resources have stabilized burned area resulting from human-induced fires[2,17], Alaska's fire regime is changing, with a fourfold increase in late-season burning from 2000 to 2009 relative to the previous five decades, primarily due to increases in burned area from climate-driven (lightning-ignited) fires[17]. Our results show that changes in fire-regime characteristics, including increasing total burned area, fire size and late-season burning, each positively affected the severity of ground-layer combustion, increasing boreal C losses beyond the effects of changes in burn area alone (Fig. 3a). Emission estimates that consider variation in burn area but not variation in combustion severity provide reasonable C-emission estimates in small-fire years, but highly underestimate emissions in large-fire years that have occurred in both recent and past decades (Fig. 3b). Because climate-driven burn area and late-season burning have become more common in Alaska over the past decade[17], mean annual C losses from 2000–2009 fires were more than twice the losses that occurred during each of the previous five decades (Fig. 3a). As increases in annual burn area, fire-season length and severe fire weather all have been predicted for boreal regions under climate change[18], it is likely that boreal ecosystems and their C stocks will continue to be subjected to increasing C losses.

Northern permafrost soils have sequestered soil C slowly over millennia, and today store approximately 50% of the world's soil organic C pool[19]. We estimate that soils in black spruce stands across interior Alaska have sequestered 5.5 ± 0.8 Tg C annually. This estimate of C uptake in Alaska (55 Tg C/decade) was close to or exceeded decadal C losses due to burning from the 1950s to the 1990s (averaging 49 ± 12 Tg C/decade; Fig. 3a), which is consistent with this region serving as a small, long-term sink of atmospheric C (ref. 20). However, recent changes in the fire regime have intensified late-season burning[17], with fire emissions from 2000 to 2009 (141 ± 6 Tg C) exceeding decadal uptake by 86 ± 16 Tg C. These emissions are equivalent to 16% of the 865 ± 104 Tg of organic soil C that we estimate is stored in black spruce forests and peatlands. Thus, changes in Alaska's fire regime have diminished the boreal C sink and also have caused an acceleration of soil C loss.

This significant shift toward greater fire emissions has implications beyond increasing northern C emissions. Fires can alter surface-energy balance and offset emissions with increased winter and spring albedo. The net effect of boreal wildfire on global radiative forcing was found to have a small cooling effect over an 80 year period due to changing albedo[21], though a smaller short-wave forcing effect was found when scaling surface albedo using satellite observations[22]. Although the impacts of Alaska's changing fire regime on global radiative forcing are likely to be complex, it seems clear that the accelerated ecosystem C losses associated with increased late-season burning (Table 2) will shift the balance towards a positive feedback. The current effects of climate change on the extent and severity of late-season burning, and future effects on the burning of poorly drained areas with deep organic soils, are likely to be critical in determining the net impacts of fire on radiative forcing of the atmosphere.

Over the past decade, an average of 12 million ha burned across the boreal biome each year, and annual burned area is expected to increase by 200–300% over the next 50–100 yr (ref. 5). Changes in fire-regime characteristics that we show are correlated with increases in fire severity in interior Alaska are likely to occur in other boreal regions where burned area has or is predicted to increase. Climate change already is causing degradation of permafrost in boreal ecosystems[23], which enhances ecosystem C loss by stimulating the mineralization of old C (ref. 24). This study suggests that fire-regime changes over the past decade also have caused Alaskan boreal ecosystems to switch from a long-term net soil C sink toward a C source, with recent soil C losses far exceeding decadal uptake owing to an increase in

Table 2 | Depth of burning and ecosystem carbon losses for different fire periods and landscape classes in interior Alaska.

Landscape class	Early-season burning		Late-season burning	
	cm	kg C m^{-2}	cm	kg C m^{-2}
Flat upland (dry) [70]	11.5 ± 0.6	2.60 ± 0.21	15.8 ± 0.6	3.50 ± 0.30
South-facing slopes (dry) [31]	11.4 ± 0.6	3.90 ± 0.29	18.0 ± 2.1	7.11 ± 1.12
East- and west-facing slopes (intermediate) [19]	11.5 ± 0.8	2.15 ± 0.22	31.0 ± 1.3	8.29 ± 0.84
North-facing slopes (wet) [27]	12.4 ± 0.8	3.33 ± 0.27	20.5 ± 3.2	5.56 ± 0.97
Flat lowland (wet) [31]	12.7 ± 1.0	3.26 ± 0.34	13.5 ± 1.9	3.58 ± 0.65
Weighted landscape mean [178]	11.9 ± 1.8	2.95 ± 0.12	21.7 ± 2.8	6.15 ± 0.41

Early-season burning refers to fire activity occurring from May to July whereas late-season burning occurs after 31 July, when fire weather and thaw depth exposes larger soil C pools to burning (Supplementary Fig. S1). Data are means ±1 standard error; numbers of distinct sites used in depth-of-burn estimates are in brackets.

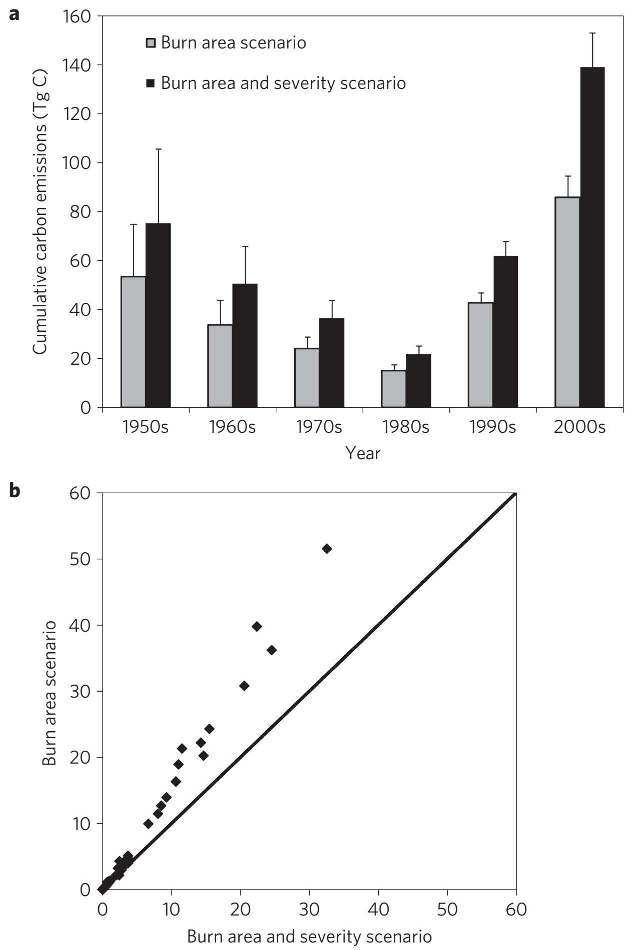

Figure 3 | Increases in both burned area and fire severity accelerate regional C losses. a, Following previous studies that model emissions using an average combustion rate, ground-layer burning released an average of 4 ± 1 Tg C yr^{-1} from 1950 to 2009 (grey bars). Data from this study increased mean emissions (1950–2009) to 7 ± 1 Tg C yr^{-1} (black bars). Data are decadal average emissions ±1 standard error. **b**, With increasing burn area, data on burn severity become more important to regional C emissions. Data are annual emissions in Tg C yr^{-1} from 1950 to 2009. The line represents a 1:1 relationship.

late-season burning. Soil C losses from the boreal biome will increase dramatically if warming continues to affect thawing of permafrost, exposing deeper C pools to rapid loss through burning. In turn, deeper burning events are likely to further accelerate permafrost degradation[23], potentially triggering a positive feedback between permafrost thaw and severe fire activity. Such feedback has the potential to override any cooling effects associated with historic disturbance[21] and has significant implications for greenhouse-gas emissions in northern regions.

Methods

The depth of burning of ground-layer fuels was measured in 178 black-spruce-dominated sites established within 31 wildfire events in interior Alaska (Supplementary Table S2, Fig. S2). Depth of burn was quantified using adventitious roots as a marker for pre-fire organic soil depth[25], combustion rods[26] or comparison of organic soil depth in paired burned versus unburned stands[27]. We used the 2001 National Land Cover Dataset to estimate the area of black spruce forests in interior Alaska, and a digital elevation model to categorize these stands into five landscape classes varying in hydrology and permafrost development. Depth-of-burn data were analysed using a mixed-effects model with landscape class, aspect, total annual area burned, date of burning and fire weather variables[28] as fixed effects, and site and fire identity as random variables to control for multiple plots within a site and multiple sites located within a single fire event, respectively.

To explore the interaction between annual area burned and timing of fire (Table 1), we split the data into quartiles on the basis of the area of land burned each year, and used a separate linear-regression model on each quartile to examine the effects of Julian date on depth of burn (Fig. 1b). We also used separate regression models to analyse the effects of annual area burned and Julian date on depth of burn for each landscape class. We analysed fire seasonality (early- versus late-season burning) and fire-size effects on depth of burn using a mixed-effects model. Analyses were carried out on log-transformed fire size to reduce heteroscedasticity in residuals, but are shown (Fig. 2) on the raw scale.

Data from 296 soil pedons from 43 distinct mature black spruce stands (>70 years since the most recent stand-replacing fire) in interior Alaska were used to establish relationships between depth and cumulative ground-layer C accumulation for each landscape class (Supplementary Table S3). Power-law relationships appropriately dealt with nonlinearities and heteroscedasticity in the linear and exponential soil C storage data (Supplementary Fig. S4). These data were used with depth of ground-layer combustion at each site to estimate C emissions. We quantified the depth and C pools associated with surface charred organic layers, and subtracted these charred C pools from our estimates of wildfire C emissions. The mean values of ecosystem C loss for both early- and late-season burning from this study (Table 2), standardized by the mean depth of ground-layer burning, are comparable to previous estimates of C loss during boreal fires (Supplementary Table S1).

We used two fire emission scenarios to explore the importance of the severity of biomass burning on regional C losses in Alaskan black spruce ecosystems. Both scenarios use the same area of fire perimeters from 1950 to 2009 (ref. 17) and assume that the fraction of area burned within fires was 0.8 for large-fire years (>500,000 ha), 0.6 for intermediate-fire years (200,000–500,000 ha) and 0.3 for small-fire years (<200,000 ha; ref. 17). The burned-area scenario relied on an average combustion rate (2.5 kg C m^{-2}/fire; Supplementary Table S1) following previous modelling studies[6], whereas the burned area + severity scenario used combustion rates from Table 2 and published fire seasonality[17]. To calculate standard errors of both ecosystem and regional C emissions, we used basic coding functions in *R* to carry out a non-parametric ordinary bootstrap using 5,000 resamplings of each dataset.

Fire emissions from this study were compared with estimates of soil C uptake across interior Alaska. We used literature values to estimate an average soil C accumulation rate in between fire events (stands ranging in age from 1 to 198 years post-fire) for Alaskan forests of 30 ± 3 g C m^{-2} yr^{-1} (intercept = $2{,}098\pm204$ g C; $F = 77.17$; $p < 0.001$; $R^2 = 0.65$), and multiplied this rate by the 18.5 million ha of black spruce forests in interior Alaska to estimate that Alaskan black spruce ecosystems sequester 5.5 ± 0.8 Tg C yr^{-1}. We found no evidence of faster soil C accumulation rates in young stands or declining C uptake in older stands as has been demonstrated in patterns of boreal forest net ecosystem productivity. However, our estimate of regional soil C uptake in general agrees with modelled estimates of net ecosystem productivity across Alaska, which range from 0 to 9 Tg C yr^{-1} including fire emissions in the 1990s (range includes net ecosystem productivity with and without CO_2 fertilization)[29]. We used the average soil C accumulation rate along with stand-age information to calculate a regional organic soil C stock of 865 ± 104 Tg C across the black spruce ecosystems across interior Alaska. Our estimate of the organic soil C stock of Alaskan black spruce stands agrees well with a new soil C database compiled for Alaska[30], which suggests that evergreen forests (which are predominantly black spruce) in interior Alaska store approximately 815 Tg C in organic soils (K. Johnson, personal communication). Full methods and associated references are available in the Supplementary Information file.

Received 27 July 2010; accepted 2 November 2010; published online 5 December 2010

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Acknowledgements

We thank L. Ness for remote sensing analyses, A. McAdam for *R* programming, E. Ellicott, G. Shetler, C. Treat and N. French for laboratory and field assistance and M. Flannigan, B. DeGroot, D. McGuire and S. Liu for helpful comments. This study was supported by NASA (grant NNG04GD25G), the Bonanza Creek Long-Term Ecological Research Program and US Forest Service (grant PNW01-JV11261952-231 and NSF DEB-0080609), the Joint Fire Science Program (project 03-1-3-08) and the USGS Mendenhall Postdoctoral and Earth Surface Dynamics Programs.

Author contributions

All authors collected data, and commented on the manuscript at all stages. E. S. Kasichke led the geospatial analyses with help from E.H. E. S. Kane led the compilation of soil carbon data with help from J.W.H., K.L.M. and M.R.T. M.R.T. analysed statistical data, led the overall synthesis and wrote the paper.

Additional information

The authors declare no competing financial interests. Supplementary information accompanies this paper on www.nature.com/naturegeoscience. Reprints and permissions information is available online at http://npg.nature.com/reprintsandpermissions. Correspondence and requests for materials should be addressed to M.R.T.