LETTER

doi:10.1038/nature24668

Fire frequency drives decadal changes in soil carbon and nitrogen and ecosystem productivity

Adam F. A. Pellegrini[1], Anders Ahlström[1,2], Sarah E. Hobbie[3], Peter B. Reich[4,5], Lars P. Nieradzik[6], A. Carla Staver[7], Bryant C. Scharenbroch[8], Ari Jumpponen[9], William R. L. Anderegg[10], James T. Randerson[11] & Robert B. Jackson[1,12]

Fire frequency is changing globally and is projected to affect the global carbon cycle and climate[1–3]. However, uncertainty about how ecosystems respond to decadal changes in fire frequency makes it difficult to predict the effects of altered fire regimes on the carbon cycle; for instance, we do not fully understand the long-term effects of fire on soil carbon and nutrient storage, or whether fire-driven nutrient losses limit plant productivity[4,5]. Here we analyse data from 48 sites in savanna grasslands, broadleaf forests and needleleaf forests spanning up to 65 years, during which time the frequency of fires was altered at each site. We find that frequently burned plots experienced a decline in surface soil carbon and nitrogen that was non-saturating through time, having 36 per cent (±13 per cent) less carbon and 38 per cent (±16 per cent) less nitrogen after 64 years than plots that were protected from fire. Fire-driven carbon and nitrogen losses were substantial in savanna grasslands and broadleaf forests, but not in temperate and boreal needleleaf forests. We also observe comparable soil carbon and nitrogen losses in an independent field dataset and in dynamic model simulations of global vegetation. The model study predicts that the long-term losses of soil nitrogen that result from more frequent burning may in turn decrease the carbon that is sequestered by net primary productivity by about 20 per cent of the total carbon that is emitted from burning biomass over the same period. Furthermore, we estimate that the effects of changes in fire frequency on ecosystem carbon storage may be 30 per cent too low if they do not include multidecadal changes in soil carbon, especially in drier savanna grasslands. Future changes in fire frequency may shift ecosystem carbon storage by changing soil carbon pools and nitrogen limitations on plant growth, altering the carbon sink capacity of frequently burning savanna grasslands and broadleaf forests.

Fire regimes have been altered by changes in climate and land use, and are predicted to change further as temperatures rise and populations grow[1–3]. In consequence, the response of ecosystems to long-term alterations in fire frequency—that is, either more frequent burning or fire suppression—will be essential to the future of the terrestrial carbon sink[3,6]. Although carbon fluxes to the atmosphere from combusting plant biomass have been well characterized[7], uncertainties remain concerning the responses of soil carbon and nutrient pools[4,5], which also regulate plant primary productivity[8].

On the one hand, increased burning may decrease soil organic matter, as repeated burning reduces organic inputs to soils and leads to declines in soil carbon (C) and nutrients[9–11]. On the other hand, increased burning may enrich C and nutrient concentrations in soils by promoting the establishment of more-productive plant species[12] and the leaching of ash downwards into soils[13]. Observations generally illustrate that single fires deplete pools of C and nutrients in the surface litter layer and, in some cases, in shallow organic horizons[14,15]. Critically, however, studies that document changes in soils over short timescales or in response to a single fire (see, for example, refs 13, 14) offer limited insight into long-term changes in the larger mineral soil pools as a result of shifting fire regimes, particularly in soils below the top few centimetres; such soils are generally not subject to direct consumption[16] and are influenced more by fire-induced changes in plant inputs and microbial activity[10,17]. Thus generalized long-term effects of changes in fire frequencies on soil C and nitrogen, and on their controlling mechanisms, remain unclear, with contrasting results observed in studies of different regions or ecosystems[10,11,17].

A lack of consensus on the long-term response of soils to fire limits our ability to predict how vegetation productivity may change as fire alters soil nutrient availability. Over the short-term, single fires can stimulate plant productivity[18]; however, over the longer-term, potential declines in soil nutrients with increased fire frequency[9–11] have been hypothesized to suppress productivity, although long-term evidence for this effect is limited[11]. These interactions may determine whether fire reduces ecosystem C storage by depleting soil C and nutrients, which may reduce plant growth and turnover, further constraining C storage in the ecosystem (Supplementary Fig. 1).

Here, we evaluate these interactions by examining how long-term differences in fire frequency alter soil C and nutrients and accompanying shifts in plant productivity, using three approaches. First, we use a meta-analysis of data from 48 sites worldwide (Fig. 1a) to test how frequent burning alters soil C and nutrients over time spans as long as 65 years. We then evaluate our results using an independent dataset from 16 additional field sites, which were not replicated at the site scale (and thus were not included in the meta-analysis), but collectively are valuable given the high number of sites and standardized data collection. Finally, we use our results to validate an individual-based dynamic global vegetation model (the DGVM LPJ-GUESS-BLAZE) for quantifying the effect of fire-driven nutrient losses on vegetation productivity and the degree to which soils contribute to ecosystem-level changes in C.

The sites included in the meta-analysis compared the effects of changes in long-term fire frequencies on C and nutrients in the upper soil layer (0–20 cm depth); the average treatment length was 30 years and ranged from 9–65 years. Sites generally contained plots that either experienced elevated fire frequency (4.3 ± 0.6 times more than the estimated historical mean for that ecosystem, calculated over the length of the study) or were protected from fire (complete fire exclusion in all but one case), which we refer to hereafter as 'elevated' and 'protected' treatments, respectively (see Supplementary Information). Sites covered

[1]Department of Earth System Science, Stanford University, Stanford, California 94305, USA. [2]Department of Physical Geography and Ecosystem Science, Lund University, Lund, Sweden. [3]Department of Ecology, Evolution, and Behavior, University of Minnesota, St Paul, Minnesota 55108, USA. [4]Department of Forest Resources, University of Minnesota, St Paul, Minnesota 55108, USA. [5]Hawkesbury Institute for the Environment, Western Sydney University, Sydney, New South Wales, Australia. [6]Centre for Environmental and Climate Research, CEC, Lund University, Lund, Sweden. [7]Department of Ecology and Evolutionary Biology, Yale University, New Haven, Connecticut 06520, USA. [8]College of Natural Resources, University of Wisconsin–Stevens Point, Stevens Point, Wisconsin 54481, USA. [9]Division of Biology, Kansas State University, Manhattan, Kansas 66506, USA. [10]Department of Biology, University of Utah, Salt Lake City, Utah 84112, USA. [11]Department of Earth System Science, University of California–Irvine, Irvine, California 92697, USA. [12]Woods Institute for the Environment and Precourt Institute for Energy, Stanford University, Stanford, California 94305, USA.