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Human impacts on 20th century fire dynamics and implications for global carbon and water trajectories

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A R T I C L E I N F O

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A B S T R A C T

Fire is a fundamental Earth system process and the primary ecosystem disturbance on the global scale. It affects carbon and water cycles through changing terrestrial ecosystems, and at the same time, is regulated by weather and climate, vegetation characteristics, and, importantly, human ignitions and suppression (i.e., the direct human effect on fire). Here, we utilize the Community Land Model version 4.5 (CLM4.5) to quantify the impacts of changes in human ignition and suppression on fire dynamics and associated carbon and water cycles. We find that the impact is to significantly reduce the 20th century global burned area by a century average of 38 Mha/yr and by 103 Mha/yr at the end of the century. Land carbon gain is weakened by 17% over the 20th century, mainly due to increased human deforestation fires and associated escape fires (i.e., degradation fires) in the tropical humid forests, even though the decrease in burned area in many other regions due to human fire suppression acts to increase land carbon gain. The direct human effect on fire weakens the upward trend in global runoff throughout the century by 6% and enhances the upward trend in global evapotranspiration since ~1945 by 7%. In addition, the above impacts in densely populated, highly developed (if population density > 0.1 person/km^2), or moderately populated and developed regions are of opposite sign to those in other regions. Our study suggests that particular attention should be paid to human deforestation and degradation fires in the tropical humid forests when reconstructing and projecting fire carbon emissions and net atmosphere-land carbon exchange and estimating resultant impacts of direct human effect on fire.

1. Introduction

Fire is a global phenomenon and the primary ecosystem disturbance on the global scale (Bowman et al., 2009). Fires burn around 400 Mha of vegetated area each year (Randerson et al., 2012; Giglio et al., 2013; Chuvieco et al., 2016; van der Werf et al., 2017). On average, fire damages about half of tree stems, almost all the leaves, and 10–15% of roots when it passes through a region (Arora and Boer, 2005; van der Werf et al., 2017). In addition to the immediate fire impacts, fire also exerts a legacy effect on land ecosystems that can last for decades and even > 100 years (Amiro et al., 2006; Bond-Lamberty et al., 2004, 2007; Kashian et al., 2013).

Fire affects global land carbon and water budgets mainly by two pathways: by altering ecosystem functioning and by emitting trace gases (Randerson et al., 2006; Bowman et al., 2009). Earlier quantitative assessments reported that, through the first pathway, fire reduced global land carbon gain by 0.05–2.2 Pg C/yr (Li et al., 2014; Yue et al., 2015; Poulter et al., 2015; Yang et al., 2015; Wang, 2017), increased the 20th century global runoff by 600 km^3/yr (Li and Lawrence, 2017), and warmed land surface air by 0.18 °C primarily due to reduction in latent heat flux (Li et al., 2017). Fire emissions of trace gases and aerosols can also affect the radiation energy budget, climate, air quality, and nutrient cycle of land ecosystems (Chen et al., 2010; Ward et al., 2012; Clark et al., 2015; Val Martin et al., 2015).

Fire is driven by weather and climate, vegetation dynamics, and human activities. Humans change fire regimes directly through their role in igniting wildfires, using fire as a means for deforestation and agricultural waste management, and suppressing both natural and anthropogenic fires (Bowman et al., 2011; Scott et al., 2016; Andela et al., 2017). Humans can also affect fire behavior indirectly by altering climate and weather, fuel amount and connectivity through grazing animals and fragmenting landscapes, and atmospheric composition (e.g. CO_2 and nitrogen concentration, aerosol burden) (Archibald, 2016; Andela et al., 2017). Given that changes in climate/weather generally tend to increase global fires during the 20th and 21st centuries (Flannigan et al., 2009; Liu et al., 2010; Pechony and Shindell, 2010;

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Huang et al., 2015; Knorr et al., 2016a), concerns have grown about how human activities might affect fire regimes. Because historical reconstructions can be constrained by observations and both fire activities and socioeconomic conditions have exhibited distinct changes during the 20th century, investigation of the historical direct human effect on fire can help understand the benefits and drawbacks associated with different methods of future fire management.

Several prior studies have quantified the direct human effect on fire, but shown large differences. Pechony and Shindell (2010), for example, concluded that humans increased the global burned area before ~1945 and decreased it thereafter. Li et al. (2013) and Knorr et al. (2016a), however, found that the direct human effect suppressed global burned area throughout the entire 20th century. Knorr et al. (2016b) reported that the direct human effect suppressed the global fire carbon emissions during the whole 20th century, a result that was not consistent with Kloster et al. (2010), who found a negligible direct human effect on emissions. In addition, we are not aware of any study to date that has quantified the impact of the direct human effect on fire for land water and carbon cycles (apart from the impact on fire carbon emissions).

Here, we quantify the 20th century direct human effect on global fires utilizing the Community Land Model version 4.5 (CLM4.5). In addition, we extend prior studies by estimating, for the first time, the impacts of human intervention in fire on historical land carbon and water budgets. Improved understanding of the regional and global consequences of the direct human effect on fire is important for water resources management, to understand challenges with respect to low-carbon economy targets, and for general understanding of global environmental change.

2. Model platform

2.1. General information

CLM4.5 is the latest released version of the CLM family (Oleson et al., 2013). CLM is the land component of the Community Earth System Model (CESM), and has been widely used for global change research and investigation of key land processes and their drivers and impacts. CLM4.5 with its carbon-nitrogen biogeochemical version (CLM4.5-BGC) integrates biophysical and biogeochemical processes and vegetation structure dynamics of the land surface into a single and physically consistent framework, and has the capacity to model the impact of transient land cover and land use change. It represents the land surface as a hierarchy of subgrid types, including vegetated, glacier, lake, and urban landunits. The vegetated land unit is further divided into plant functional types (PFTs).

The fire module in CLM4.5 includes four components: agricultural fires in cropland, deforestation and degradation fires in tropical closed forests, non-peat fires outside cropland and tropical closed forests, and peat fires (Fig. S1). The fire module utilized in this study is based on the version used in CLM4.5 (see Li et al., 2012, 2013 for detailed description and evaluation) with two changes: (1) a modified scheme is used to estimate the dependence of fire occurrence and spread on fuel wetness for non-peat fires outside cropland and tropical closed forests (Li and Lawrence, 2017); (2) the dependence of burned area fraction in cropland on fuel load is removed. The two changes have been included in the forthcoming CLM5 (D. M. Lawrence, in prep). After the calculation of burned area fraction, fire impacts are estimated, including biomass and peat burning, which emits carbon and nitrogen (C/N) to the atmosphere directly, and plant-tissue mortality, which leads to C/N transfer among C/N pools. Estimates of biomass burning and plant-tissue mortality are based on PFT-dependent combustion completeness factors and fire mortality factors (Table S1).

2.2. Modeling the direct human effect on fire in CLM4.5

In the fire scheme, parameterization of the direct human effect on fire is based on or is inspired by earlier studies (Chuvieco et al., 2008; van der Werf et al., 2009; Pechony and Shindell, 2009; Le Page et al., 2010a, 2010b; Aldersley et al., 2011; Bowman et al., 2011; Magi et al., 2012) in combination with relationship analyses between satellite-based fire products (MODIS fire counts and GFED3 burned area) and socioeconomic conditions (population density and real GDP per capita)/tropical deforestation rates (see Li et al., 2013 for details). The parameterization of human dimension is supported by several quantitative studies on the direct human effect on fire based on various fire products and at various scales and regions (Bistinas et al., 2013; Andela and van der Werf, 2014; Le Page et al., 2015; Hantson et al., 2015; Archibald et al., 2008; Archibald, 2016; Andela et al., 2017). The parameterization is simply described as follows.

(1) Agricultural fires: These fires are ignited only by humans. The burned area fraction increases with lower population density and lower real Gross Domestic Product (GDP) per capita, representing that less populated and less developed regions are more likely to use fires as a cheap and effective means of removing agricultural waste. Fire seasonality is prescribed by assuming agricultural fires occur only at the first rainless time step in the peak month of GFED3 crop fire emissions.
(2) Human deforestation and associated escape fires (i.e., degradation fires) in tropical closed forests: These fires are triggered by anthropogenic deforestation, and can spread beyond the deforested region. Burned area fraction increases with deforestation rate and dryness of environmental conditions. Tropical closed forests are defined as grid cells with fractional coverage of tropical tree PFTs higher than 60%. The deforestation rate is obtained directly from the land use and land cover change (LULCC) data used in CLM4.5 (Lawrence et al., 2012) and defined as the decrease in the fractional coverage of tropical tree PFTs.
(3) Human potential ignitions and suppression outside cropland and tropical closed forests: Potential human ignitions increase with population density. Humans suppress both anthropogenic and natural fires. The model includes two suppression rates (SR1 and SR2, varying between 0.0 and 1.0), both of which increase with population density and real GDP per capita where population density > 0.1 person/km^2. SR1 represents human suppression on fire occurrence (e.g., fire prevention through public education, fuel management, rules and regulation), and human ignitions = human potential ignitions × SR1; SR2 represents human suppression of fire spread (e.g., fire fighting, building fire breaks, early fire detection).

2.3. Land carbon and water budgets

The net carbon exchange between atmosphere and terrestrial ecosystems in CLM4.5 is:

$$NE = NPP - HR - FE - Clh \tag{1}$$

where net primary production (NPP) is equal to the gross primary production (GPP, carbon uptake by biosphere via photosynthesis) minus autotrophic respiration (AR, the carbon lost due to maintenance and growth respiration of live plant tissues), heterotrophic respiration (HR) is the land carbon loss due to the decomposition of litter and soil organic matter, FE and Clh are carbon loss from biosphere due to biomass burning and land use (wood harvest included), respectively. For NE, a positive value represents that terrestrial ecosystems gain carbon.

The terrestrial large-scale water balance, on an annual time scale, can be simply written as

$$Pr = ET + RO \tag{2}$$

given that the changes in land water storage as snow and soil moisture are small.

Pr is the precipitation (snow and rain); evapotranspiration (ET) is