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RESEARCH ARTICLE

SMOLDERING COMBUSTION AND GROUND FIRES: ECOLOGICAL EFFECTS AND MULTI-SCALE SIGNIFICANCE

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ABSTRACT

Although fires in wetlands would seem to be rare or impossible by definition, these ecosystems do occasionally experience fire. A common feature of fires in wetlands is smoldering combustion in organic soils, such as peat and muck. Increasing occurrence and size of these events from the Arctic to the tropics has been matched by increasing research interest, yet our understanding of smoldering lags behind that of flame-based combustion. Smoldering fires represent hazards to human health and safety locally, and global ecological concerns due to their potential for carbon release. Additionally, ecological effects of smoldering ground fires are generally perceived to be negative, particularly where their historical frequencies are thought to be low. This synthesis describes some aspects of smoldering combustion, and discusses some of the particular ecological aspects of ground fires, focusing on examples from the southeastern United States. We suggest that despite the well-recognized negative aspects of ground fires, there may exist under-recognized ecological benefits that should be further studied and weighed against known hazards posed by these events.

Keywords: ground fire, hydrology, muck, organic soil, peat, smoldering combustion, wetland

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INTRODUCTION

Fires in wetlands frequently occur in the form of smoldering fires in the deep organic soils that accumulate in these ecosystems. Where frequently burned uplands commonly occur adjacent to wetlands, fires can occur in wetlands with surprising frequency. In the southeastern USA, pine flatwoods adjacent to marshes or swamps can contribute ignition sources that result in fires as frequently as every decade (Wade *et al*. 1980, Abrahamson and Hartnett 1990, Snyder 1991). However, during prolonged drought conditions, the organic soils found in many wetlands may dry sufficiently to ignite and burn (de Groot 2012). Such fires, variously called ground fires, peat fires, or muck fires, are the result of smoldering combustion in organic soils. They typically occur rarely, but produce substantial ecological effects and hazards for human health and safety. Different in many ways from the dramatic conflagrations often pictured in the news, these slow-motion wildfires pose unique challenges and hazards that make them worthy of special consideration.

SMOLDERING COMBUSTION

In contrast to flaming combustion, which typically lasts a fraction of an hour at a given location, smoldering is a flameless form of combustion that occurs when oxygen reacts with the surface of solid fuels (Ohlemiller 1995). This form of combustion typically takes place at much lower temperatures than flaming combustion (500 °C to 700 °C versus 1500 °C to 1800 °C; Rein *et al*. 2008). In addition to occurring to some extent in woody fuels, smoldering is chiefly the type of combustion found in duff (e.g., Varner 2005), peat, and muck, and characterizes fires found in ecosystems in which these soils or fuel types dominate during dry conditions. In desiccated mucks and peats, smoldering can occur under surprisingly high soil-moisture contents, depending less on parent material than on mineral content (Frandsen 1997, Benscoter 2011, Watts 2013). In these fuels, combustion occurs as two sets of chemical reactions, known as Regimes I and II. In Regime I, pyrolysis and partial oxidation of the fuel takes place, resulting in dehydration and charring. In Regime II, char oxidation occurs, reducing the pyrolyzed fuel to ash (Hadden *et al*. 2012). These combustion reactions can continue in deep organic soils for many days, or even months in cases such as the Kalimantan peat fires in Indonesia in 1997 (Page *et al*. 2002, Usup *et al*. 2004), and Georgia's Okefenokee Swamp fire (Florida Times-Union 2012). Indeed, the capability of organic materials to experience the spontaneous initiation of smoldering at nearly ambient temperatures under favorable conditions has been posited as an explanation for the occurrence of some long-burning fires in coal seams around the world, which qualify smoldering fires as the largest and longest-running fires on Earth (Stracher and Taylor 2004).

When ground fires do become established, they are notoriously difficult to control or extinguish. One reason for this is the tendency of smoldering to proceed deep into the soil (depending on such conditions as soil moisture and organic content), and to spread laterally far underground away from obvious features such as vents that indicate combustion (Rein 2009). The result may be extensive burning of soil far below the surface, with little indication of the extent or location of smoldering (Rein *et al*. 2008). Additionally, the tendency of organic soils to become hydrophobic (i.e., repel water) when desiccated means that application of water, foam, or other agents often results in pooling on the surface, with only slow percolation downward toward the site of combustion. Regardless of their ability to penetrate, any suppression agent must be applied in logistically prohibitive amounts to be effective.

Practically speaking, it is therefore usually not feasible to deliver sufficient water to extinguish ground fires. A number of additional control techniques are employed, but all have their potential drawbacks. Where road access is available, heavy equipment is sometimes used to cut firelines in desiccated muck or peat (Figure 1). However, the depth of the organic layer—sometimes meters deep—means that this can be time consuming and expensive. Also, the integrity of the fireline can be compromised if the smoldering front passes underneath it in undetected organic soil. In wetlands as in uplands, the cutting of fire lines can have negative ecological impacts that remain long after the fire is out. Specialized lance-shaped nozzles on hoses are sometimes used to deliver water laterally from the end of a pointed tip, which is shoved into the ground in an attempt to access the site of smoldering. This method requires much time and water as well. Additives such as guar gum, chemical suppressant, or detergent for its wetting properties, have been employed by firefighters in attempts to quench ground fires. However, the efficacy of chemical additives, retardants, and gels in re-

Figure 1. Many passes of this bulldozer were required to cut a fireline to mineral soil through the thick peat at this ground fire in northern Florida, USA.

ducing the resources required to extinguish peat fires has not been established, and managers should weigh their perceived benefits against the potential for environmental harm from their application to sensitive areas.

HUMAN AND ENVIRONMENTAL HAZARDS

Many reasons exist to attempt to control or extinguish ground fires, many due to the human costs of these events. The smoke from ground fires is produced abundantly day and night, in contrast to wildfires consisting primarily of flames—the latter type of combustion being heavily influenced by diurnal weather patterns. With its production independent of atmospheric convection, ground fire smoke can accumulate during periods of stable atmospheric conditions, causing reductions in visibility on roadways (Figure 2). Low-lying areas are particularly susceptible to the accumulation of smoke and fog, and many vehicle accidents attributable to this dangerous combination occur at night, when smoke from smoldering fires continues to be produced but tends to linger due to calm wind conditions (Abdel-Aty *et al*. 2011).

Figure 2. Smoke from ground fires often dissipates slowly, and contributes to serious degradation of visibility on roadways.

Smoke from ground fires is a concern for human health in addition to motorist safety. Although smoke from fires is only one source of atmospheric pollutants, wildland fire smoke contains various classes of particulate matter (See *et al*. 2007, Monroe *et al*. 2009). Among these, particulate matter with average particle sizes of 2.5 microns or smaller—referred to as $PM_{2.5}$—is considered particularly harmful for cardiovascular health because of the ease with which these particles pass into the body, and their large surface area on which toxic compounds may be adsorbed (Brunekreef and Holgate 2002). Ground fires produce more of this class of airborne pollutant than other types of wildfires (Muraleedharan *et al*. 2000); this characteristic, along with the persistent nature of the fires themselves and the tendency of the smoke to remain near the ground, makes smoke from ground fires a threat to smoke-sensitive populations such as the elderly, children, and asthmatics (Rappold *et al*. 2011).

ECOLOGICAL EFFECTS

The persistence of smoldering fires, despite their lower temperatures, can ultimately transfer more heat to surrounding soils and plants than flaming combustion (Kreye *et al*. 2011). The combination of heating, direct consumption of roots embedded in organic soils, and organic soil loss to combustion can result in significant damage and mortality to trees (Ewel and Mitsch 1978, Hartford and Frandsen 1992, Stephens and Finney 2002, Watts *et al*. 2012). The potential damage to trees from soil consumption is compounded by the frequent tendency of ground fires to burn substantially deeper into soils at the base of trees (Figure 3). This phenomenon has been noted by a number of authors (e.g., Miyanishi and Johnson 2002, Hille and Stephens 2005, Rein *et al*. 2008). Theorized reasons for this phenomenon include interception of rainfall by tree canopies, resulting in lower soil moisture under the drip line (Hille and Stephens 2005); this effect would be magnified by further withdrawal of soil moisture within the tree's root zone. The tendency of organic soils to shrink during desiccation could also cause the formation of air ducts as drying soils pull away from roots; these conduits would enhance consumption of the soil, and the absence of direct contact with tree roots, which are often left largely intact following the smoldering of soil around tree bases.

Figure 3. Consumption of organic soil around the root zone of this tree indicates the depth of burn, and soil loss. Hydroperiod in the consumed area will be longer due to the elevation change caused by the fire.

In the case of some ecosystems, such as cypress swamps, ground fires may leave some pond cypress (*Taxodium distichum* var. *imbricarium* [Nutt.]) or bald cypress (*Taxodium distichum* var. *distichum* [L. (Rich.)]) alive, while killing potential competitors. In this way, fires of moderate severity can be a mechanism of continued dominance by cypress in swamps. Alternatively, in the case of severe ground fires, smoldering can cause shifts in community composition from forested ecosystems to marshes (Duever 1984, Casey and Ewel 2006). One proposed mechanism for conversion from swamp to marsh following smoldering fires is that deep smoldering during exceptionally dry periods kills large cypress trees, the majority of whose roots are situated within the relatively deep (1 m to 2 m or more) peat in the interiors of swamps (Gunderson 1977). Additionally, because germination and seedling survival of both varieties of cypress are inhibited by extended flooding and deep water (as described in bald cypress by Day *et al*. 2006), consumption of peat soil may cause the hydroperiod at a site to increase sufficiently such that a shift from domination by cypress to marsh communities could occur at a site subject to smoldering following a return to nominal hydrologic regimes. Analogous changes likely occur in other biomes in which microtopographic changes caused by smoldering might result in changes to vegetation communities arising from alterations in local hydrology or microclimate.

In addition to this posited effect of smoldering fires on vegetation at the scale of local plant communities, soil-consuming fires could theoretically produce direct hydrologic changes extending beyond the immediate extent of the burned perimeter. In areas of low topographic relief, ground fires may change the volume of depressional isolated wetlands by changing soil elevation, and thus basin bathymetry when these areas are flooded. Given a finite amount of water delivered via precipitation or overland flow in a given year, a change in the storage volume of a wetland following fire (due to changes in the basin depth caused by consumption of soil) may provide increased water availability in the wetland, while water availability to higher-elevation areas of the landscape may be more limited as it more rapidly is drawn to the depressions.

Implications of this feedback to hydrology from smoldering fires extend to wildlife species. Greater water storage or longer hydroperiod may mean that small wetlands may be able to serve for longer periods of time as watering holes for wildlife, or as habitat for their prey, during dry periods. In southern Florida, for example, two federally listed endangered species (the wood stork, *Mycteria americana*, and the Florida panther, *Felis concolor coryi*) may depend on the existence of standing water late in the region's dry season (Fleming *et al*. 1994, Cox *et al*. 2006, Benson *et al*. 2008). The additional stresses on already-imperiled wildlife species due to predicted increases in climatic variability may make drought-condition refugia ever more valuable. Therefore, to the extent that soil-consuming ground fires maintain open water by lowering soil elevations and reducing encroachment of vegetation, there may be an indirect ecological benefit of ground fires in certain areas.

The ecological effects of ground fires extend further beyond direct regional impacts. Organic soils are the result of accumulation of plant biomass, over many decades to centuries or longer, and ground fires can consume much of this in a matter of weeks. Organic soils represent enormous stocks of terrestrial carbon—peatlands, for example, represent only 2% to 3% of the Earth's surface area, yet may comprise a third of the planet's terrestrial carbon (Holden 2005). The enormous carbon stocks found in organic soils can result in ground fires releasing substantial amounts of carbon to the atmosphere (Page *et al*. 2002, Mack *et al*. 2011)—indeed, Langmann and Heil (2004) estimate that peat fires may produce emissions 75% higher per hectare than fires consuming standing vegetation alone. Existing efforts to quantify the potential for carbon sequestration on public lands as a means of mitigating anthropogenic CO_2 emissions (e.g., Depro *et al.* 2008, Failey and Dilling 2010) will further increase interest in soil-consuming fires among managers who may be charged with preventing them or accounting for their effects on ecosystem carbon pools.

CONCLUSION

The determinants, behavior, and effects of smoldering combustion in ground fires are far less understood than those of flaming fires. Most of the work that has occurred focused on organic soils in areas such as Canada and Alaska, where vast areas of peats occur (Benscoter *et al*. 2011, Turetsky *et al*. 2011, de Groot 2012). Much progress has been made in understanding the characteristics of tropical ground fires as well, where human activities such as agricultural clearing directly threaten peatlands in areas such as Indonesia (Page *et al*. 2002) and Borneo. Work in the southeastern US, where peat occurs in both temperate and subtropical biomes, has been limited to pocosin soil in North Carolina (Reardon *et al*. 2007) and cypress soils in Florida (Watts 2013). Despite its smaller areas of peat and muck, the region's large and rapidly growing human population provides reason for concern over local impacts of ground fire emissions; meanwhile, the presence of frequently burned upland ecosystems adjacent to areas of deep organic soils means potential hydrologic changes could increase the prevalence of ground fires in the region.

Future climate change scenarios predict drought events of greater severity and frequency in many areas (IPCC 2007), including those with the potential for ground fires to occur (Running 2006, Liu and Stanturf 2010). These risks of increased ground fires are likely to be compounded by altered local hydrology due to increased water demands and land cover changes resulting from growing human populations. In advance of these likely scenarios, we should improve our fundamental understanding of smoldering combustion, as well as the linkages between the chemistry and physics of smoldering, and the ecological and management implications of ground fires. Important topics to consider include: the scaling of smoldering studies from the lab bench to the stand or marsh; modeling the behavior of ground fires over their duration, to include influences of landscape and environmental heterogeneity; consequences of changes in microtopography to vegetation and hydrology; effects of ground fires on habitat quality for species of concern; and the impacts and effectiveness of control techniques. While many effects of ground fires are broadly accepted as negative, an improved understanding of these events in their local ecological contexts will increase the ability of decision makers to adopt appropriate strategies toward ground fires, and for managers to implement efficient and ecologically appropriate techniques to control them.

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