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PERSPECTIVE

Fire as a Soil-Forming Factor

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Abstract In the span of a human generation, fire can, in theory, impact all the land covered by vegetation. Its occurrence has many important direct and indirect effects on soil, some of which are long-lasting or even permanent. As a consequence, fire must be considered a soil-forming factor, on par with the others traditionally recognized, namely: parent material, topography, time, climate, living beings not endowed with the power of reason, and humans.

Keywords Fire · Soil · Pedogenesis · Soil-forming factors · Charcoal · Soil organic matter

INTRODUCTION

Earth has been rightly defined an "intrinsically flammable planet" (Bowman et al. 2009), although Earth's flammability is confined where both fuel and oxygen are available, hence to about 110 millions km^2 of vegetated land, representing less than 22 % of Earth's surface (Loveland et al. 2000). Global burned area per year clusters around 3.5 millions km^2 (Tansey et al. 2008; Giglio et al. 2010), i.e., 3.2 % of the "combustible" land. Assuming that every year fire involves different areas, it means that cumulatively all of the vegetated land is burned in about 31 years, something more than a single human generation! In reality, wildfires often run on ecosystems particularly prone to burn, while other ecosystems seldom burn. Where fire is frequent it is a driving force for the takeover of land by fire-adapted plant communities. The global impact of fire on vegetation is so marked that in a hypothetic world without such an ecological factor, closed forests would be double than the present ones (Bond et al. 2005). As terrestrial plants grow almost exclusively on soil and most soils sustain plant growth, there is a mutual relationship between fire and soil. Fire effects on soil are major, although largely disregarded compared to the ones on aboveground biomass. A widespread perception is that soils undergoing fire just experience a temporary removal of the top organic horizon, which eventually induces a pulse of soil fertility because of the supply of available nutrients previously locked into living or dead organic tissues (this is actually one of the reasons why farmers light fire on harvested fields since the dawn of civilizations). It is also believed that the charcoal left on the ground from incomplete combustion of woody materials participates in increasing soil fertility. Aside from this, soil would be not substantially affected by fire occurrence and plant recolonization would be a proof of it. On the contrary, fire has much complex and variegated effects on the whole set of soil properties (Certini 2005; Neary et al. 2005). Some of them are relatively short-term, such as the decrease in biotic activity, the increase in pH, the darkening of the ground—which implies reduced albedo and, thus, a different temperature soil regime—and the frequent formation of a continuous water-repellent layer a few cm beneath the surface—which greatly alters the soil moisture regime and promotes runoff and erosion. Other soil properties, however, can suffer long-lasting or even permanent modifications. For example, the top organic layer, which is part of the fuel for combustion, generally suffers substantial loss (Certini et al. 2011) and its complete recovery may require many years, provided that land use does not change and erosion does not occur (Fig. 1). The residues of combustion show deep structural transformations (González-Pérez et al. 2004). What is not completely oxidized to ash is often transformed to charcoal, a heterogeneous mixture of thermally altered biomacromolecules (Knicker et al. 2008), whose more refractory pool can last intact in natural environments for centuries or even millennia (Titiz and

Fig. 1 A forest soil after a winter wildfire is still waiting for being revegetated. Incipient gullies formed by water erosion are recognizable by their lighter color due to charcoal removal (courtesy of Gianluca Giovannini)

Sanford 2007; Robin et al. 2013). Charcoal may represent a substantial fraction of soil organic matter in fire-prone ecosystems and as such strongly affect several soil properties (Knicker 2011). It has been also suggested that charcoal is able to stimulate the degradation of the native soil organic matter (Wardle et al. 2008). Phosphorous released from the burned organic matter, if not promptly taken up by the sprouting stumps or colonizing vegetation, precipitates as mineral forms, apatites or Fe- and Al-phosphates depending on pH. Stones on the ground may break because of inhomogeneous thermal dilation (Fig. 2). The mineral components of soil not only undergo physical weathering but also modifications of their composition. A few minerals are peculiar ramifications of wildfires, because they form in soil through thermal transformation of other minerals. One of these is maghemite, a magnetic Fe-oxide that occurs, in the presence of oxygen and organic matter, at the expense of other iron oxides or hydroxides, such as ferrihydrite (Campbell et al. 1997) or goethite (Clement et al. 2011). Conversely, some minerals decompose at temperatures plausible in wildfires, such as kaolinite—perhaps the most common clay mineral in soils—that collapses at 500–550 °C (Ulery et al. 1996; Yusiharni and Gilkes 2012). Peak temperatures during fire and related transformations of minerals and organics occur in the top centimeter of soil only. However, with time, "pyrogenic" products drift downwards or laterally, possibly on adjacent unburned soils as well. The indirect impact of fire on soil may surpass the direct one. In particular, if a prompt plant recolonization misses, the topsoil can be removed by erosion or mudslides (Shakesby and Doerr 2006; Shakesby 2011). There are soils where fire plays a so marked role in molding their features (Fig. 3), that they could be meaningfully called *Pyrogenic soils*, on the wake of *Anthropogenic soils*, which are the ones prominently affected by human activities. Based on such an evident impact, it is licit wondering whether fire can be considered a soil-forming factor on par of the others until now accepted. Since the birth of *pedology*—from the Greek pedon "soil" and logos "knowledge"—five factors were recognized to contribute to soil formation. In fact, Vasilij Dokuchaev, the father of pedology, referred to the soil as a three-dimensional entity located at Earth's surface with morphology and unique physical, chemical, and biological properties acquired by the interaction, through *time*, among *organisms*, *rock*, and *climate* on a given *topographic position*.

Fig. 2 Some common outcomes of fire: the "cooked" outer layer of a quartzite stone was fragmented and modified in composition, as revealed by the unnatural white tinge. All around the stone, there is a carpet of charcoal, which is the residue of incomplete combustion of woody materials

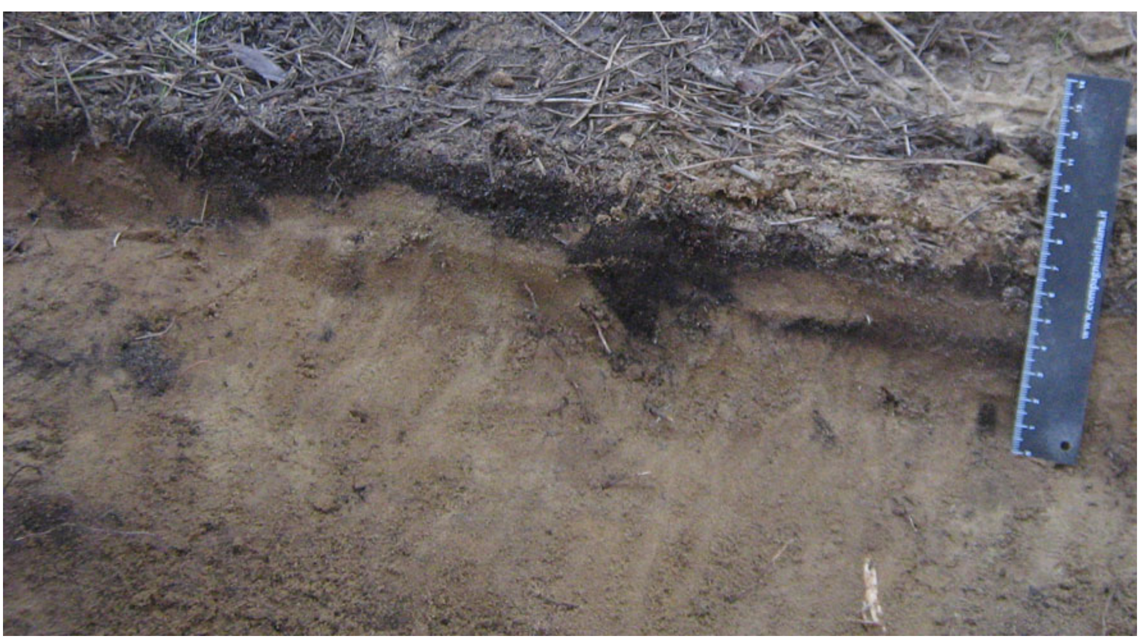

Fig. 3 A soil developed on marine sands sustaining a fire-prone pine forest, shows as main feature a top horizon rich in charred organic matter. Such a soil can be defined *Pyrogenic soil* because of the major influence of fire on pedogenesis, similarly to *Anthropogenic soils* that are mainly a product of human activities. Units are cm

About half a century later, Hans Jenny rigorously redefined these factors and their relationship in his well-known equation, soil = *f* (*time*, *organisms*, *rock*, *climate*, *topography*, …), where the dots indicate possible additional factors (Jenny 1941). Since the 1990s, man began to be recognized as the sixth soil-forming factor (Amundson and Jenny 1991), distinct from the other organisms essentially because he possesses a cultural component that varies from society to society and which operates independently of genotype (Amundson 2006). Fire could be perceived as one of the many ways man influences the pedogenesis, since he lights most of modern fires, voluntarily or involuntarily. Nonetheless, fire is per se independent of man and well before the emergence of people on Earth, it played a key role in plants adaptation and ecosystems distribution (Pausas and Keeley 2009). Furthermore, in spite of the common belief that when there were fewer people there must have been less blazes, the total biomass burning is now lower than at any time in the past 2000 years (Prentice 2010). Actually, man is highly efficacious in fighting fire and in the absence of his intervention, hundreds of square kilometers can burn undisturbed (Mack et al. 2011).

Soil-forming factors do not act independently from each other. Fire would be not an exception in this regard, because it depends on at least vegetation, climate, topography, and man. In turns, fire affects four soil-forming factors: (i) biota, by changing its biomass and specific composition, (ii) (micro)climate, by changing canopy structure, ground albedo, and hydrological processes, (iii) parent material, by consuming organic matter, and forming charcoal and new minerals, (iv) topography, by reshaping the ground morphology, in particular via erosion, (v) man, influencing human ecology and behavior. In affecting other soil-forming factors, fire of course gives an additional, indirect contribution to pedogenesis.

Opponents of the "soil-forming factor fire" hypothesis could question that fire involves soils discontinuously, in terms of both time and space. Concerning its temporal discontinuity, it must be acknowledged that many direct and indirect fire ramifications affect pedogenesis until and beyond the occurrence of a new fire event. Furthermore, in the case of man, the continuity of his direct action has not been considered essential for recognizing him as factor of pedogenesis. One could wonder whether fire ultimately involves all soils. Although most of them actually had such an experience, as confirmed by the usual finding of charcoal in soil and sediments (Schmidt and Noack 2000; Knicker 2011), some other soils may have been never touched by fire because never colonized by vegetation or exceptionally well preserved from flames. However, ubiquity is not strictly required to fire, as a more "orthodox" soil-forming factors—man and the rest of biota—are not necessary to soil to form. In fact, extreme environments on Earth show soils where living organisms are virtually missing or, anyway, play an insignificant role on pedogenesis (Navarro-González et al. 2003; Ugolini and Bockheim 2008; Shanhun et al. 2012). Furthermore, modern definitions of soil instead of revolving around the notion that water, air, organic matter or even life must be present, place emphasis on the occurrence of clear evidences of chemical weathering, viz., any transformation of the original parent material implying changes in composition (Johnson 1998; Certini and Ugolini 2013). Chemical weathering, which does not necessarily require biota-mediated reactions to occur, allows calling soils most of the known extraterrestrial regoliths (Certini et al. 2009), where life was not as yet detected and it is presumably absent.

To conclude, fire does not lack any crucial requisite to be recognized as a factor of pedogenesis on Earth, the seventh one together with parent material, climate, time, topography, living beings not endowed with the power of reason, and humans.

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