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Fire effects on soils: the human dimension

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Soils are among the most valuable non-renewable resources on the Earth. They support natural vegetation and human agro-ecosystems, represent the largest terrestrial organic carbon stock, and act as stores and filters for water. Mankind has impacted on soils from its early days in many different ways, with burning being the first human perturbation at landscape scales. Fire has long been used as a tool to fertilize soils and control plant growth, but it can also substantially change vegetation, enhance soil erosion and even cause desertification of previously productive areas. Indeed fire is now regarded by some as the seventh soil-forming factor. Here we explore the effects of fire on soils as influenced by human interference. Human-induced fires have shaped our landscape for thousands of years and they are currently the most common fires in many parts of the world. We first give an overview of fire effect on soils and then focus specifically on (i) how traditional land-use practices involving fire, such as slash-and-burn or vegetation clearing, have affected and still are affecting soils; (ii) the effects of more modern uses of fire, such as fuel reduction or ecological burns, on soils; and (iii) the ongoing and potential future effects on soils of the complex interactions between human-induced land cover changes, climate warming and fire dynamics.

This article is part of the themed issue 'The interaction of fire and mankind'.

1. Introduction

Soil is the 'living, breathing skin of the Earth' [1]. It allows the growth of terrestrial vegetation and thus supports, directly or indirectly, most forms of life on the Earth's land surface, including our own kind. Soils have enabled the development of human agro-ecosystems and the associated acceleration of human population growth [2,3]. They also represent the largest terrestrial organic carbon stock, and act as stores and filters for water [4,5]. The time to form a fully developed soil can range from centuries to millions of years, and, therefore, soils are considered one of the most valuable non-renewable resources on planet Earth [2].

The occurrence of fire is closely linked to soils. Without soils, there would be very limited vegetation cover on the Earth and hence very little, if any, of the more than 400 million ha [6] that, on average, burn across its land surface every year would be affected by fire. The interactions between soils and fire, however, go much deeper, even in the literal sense. Fire can directly influence soil properties through heating and combustion processes (figure 1), and indirectly through the changes to its vegetation cover and enhanced redistribution of soil through accelerated post-fire erosion [25,26]. Indeed fire is currently regarded by some as the seventh soil-forming factor (in addition to time, organisms, parent material, climate, topography and man), having influenced soil development and properties since the advent of vegetation fires over 400 Ma [27]. The rise of human societies has exerted a strong influence on the fire–soil interaction. On the one hand, for several thousand years humans have used fire as a vegetation-management or land-clearing tool, introducing or increasing fire impacts in some ecosystems [3,5,8,28–34]. On the other hand, landscape fragmentation and conversion to agricultural and urban

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Box 1. Human-induced fires.

In this article, we focus on 'human-induced' fires. With this term, we refer to fires ignited by humans for a specific purpose, mainly land management. These fires have distinct characteristics compared to 'natural' wildfires: (i) In seasonal climates, they can occur at almost any time, but are often ignited prior to, or early in, the fire season(s), whereas natural fire occurrence peaks in the dry (hot) periods [7]. (ii) Their frequency is often higher than that of natural fires [8,9]. (iii) The area burnt by a single fire is usually smaller than for wildfires [10,11]. (iv) Owing to points (i)–(iii), the intensity of human-induced fires is usually lower [10]. (v) They tend to occur in the proximity of human settlements and infrastructures [12]. However, it is important to recognize that in many regions of the world human ignitions, whether accidental or arson, can be the cause of wildfires, which mostly share the characteristics of wildfires following non-human ignitions such as lightning.

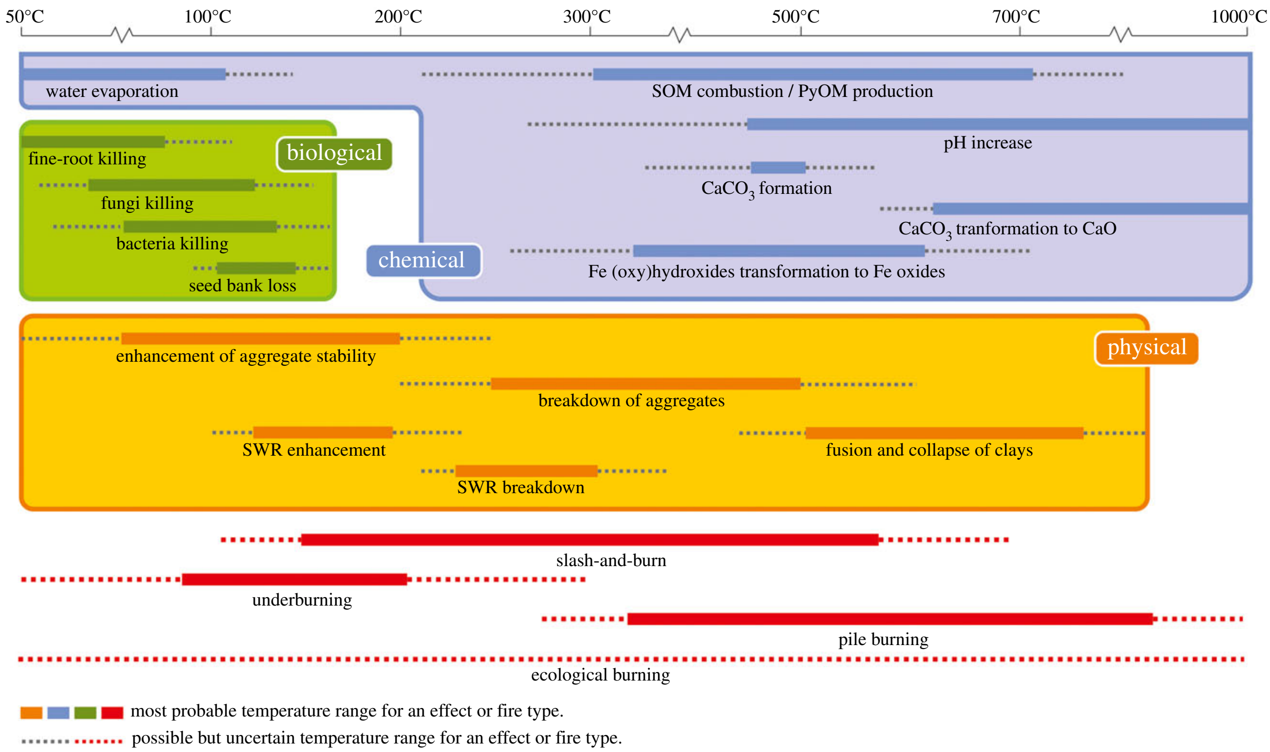

Figure 1. Effects on the biological, chemical and physical properties of soil and associated temperature ranges reached near the mineral soil surface for different types of human-induced fires (slash-and-burn, underburning, pile burning and ecological burning). See box 1 for a definition of 'human-induced' fires. The temperature ranges provided are broad estimates. Specific temperatures and associated soil effects will depend on the characteristics of each fire and soil. Temperature scale is nonlinear. SOM: soil organic matter; PyOM: pyrogenic organic matter; SWR: Soil water repellency. Data derived from [13–24].

land has decreased forest, shrub and grassland covers and their associated fire occurrence from large parts of the Earth surface [35] (figure 2). Over the last century, advances in fire suppression and fuel management, but also afforestation, increased ignition opportunities, and invasion of alien plants has led to further changes in fire occurrence and behaviour in many parts of the world [38,39]. Indeed, of the fires that currently burn *ca* 4% of Earth's vegetated land surface every year, up to 95% are directly caused by humans in densely populated areas such as Europe or Southeast Asia [40,41]. Furthermore, human-induced climate change is already affecting fire occurrence and behaviour in some regions with much more pronounced changes to be expected in the future [42,43]. These direct and indirect human interferences with fire, vegetation (i.e. fuels) and climate affect the role fire has played and will play in the development and functioning of soils.

Here we aim to explore the human dimension in the interactions between fire and soils. First, we summarize the main effects of fire on soils (§2), and then focus specifically on how traditional uses of fire, such as slash-and-burn or vegetation clearing, have affected and still are affecting soils (§3). The effects of more modern uses of fire on soils, such as fuel reduction or ecological burns, are examined in §4 followed by a discussion of the ongoing and potential future effects on soils of the complex interactions between human-induced land cover changes, climate warming and fire dynamics (§5).

2. Fire effects on soils: a brief review

Fire can substantially alter soil characteristics both directly during burning and indirectly during the post-fire recovery period. These effects have been covered extensively in a series of reviews [14,18,19,21,23,25,26,44–49] and are therefore only briefly summarized here. The heat transfer from combustion of biomass and necromass above the soil and combustion of live and dead organic matter in the soil itself leads to some of the most common direct changes to the soil. These are generally dependent on the temperature the

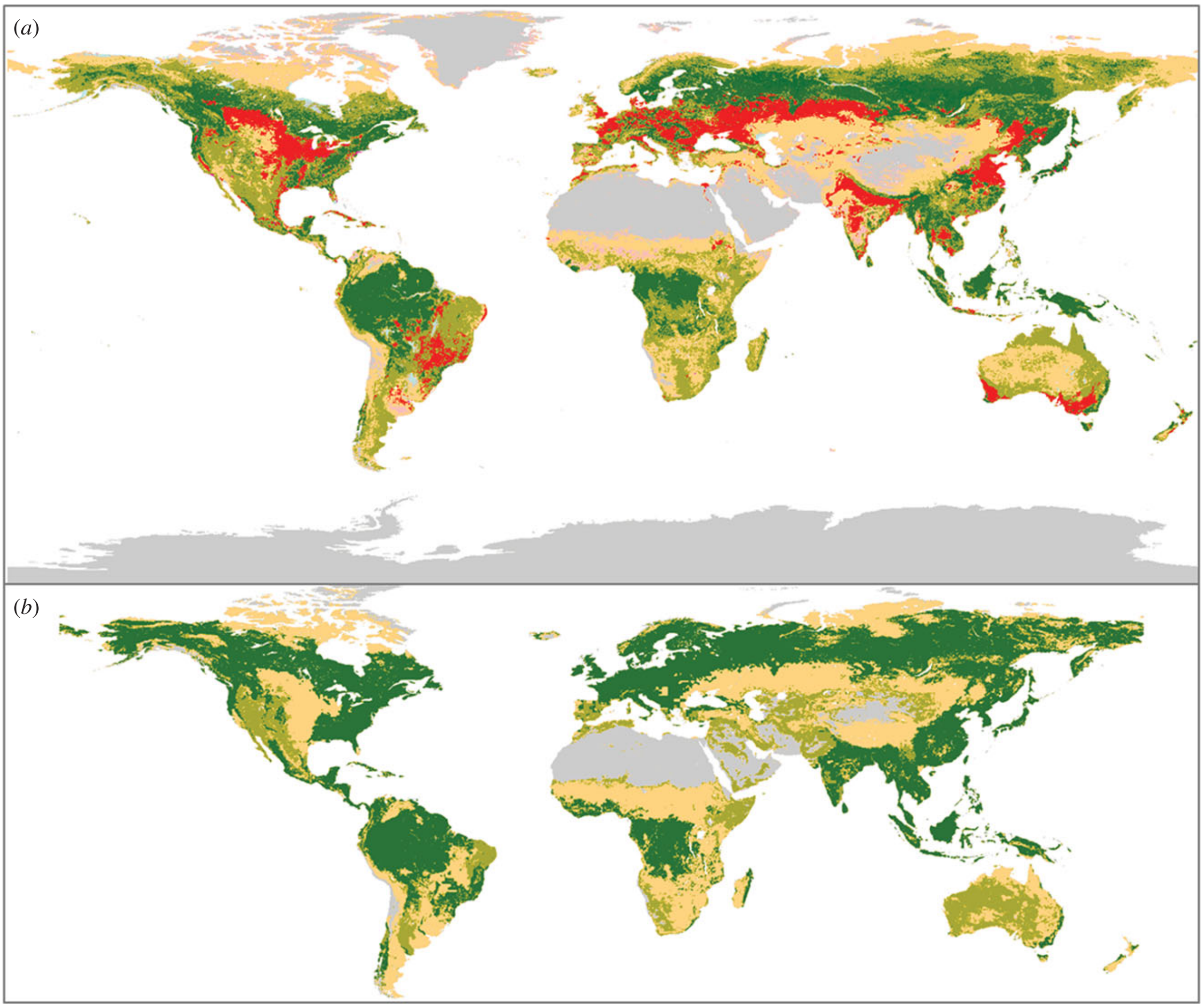

Figure 2. Current (*a*) and potential natural (*b*) global land cover under present climatic conditions, showing the extent of forests and woodlands (dark green), shrublands and open woodlands (pale green), grass biomes (orange), croplands and urban areas (red), croplands and mixed vegetation (pink) and bare land or ice/snow (grey). Data source: Current land cover map derived from GLCNMO2008 [36]; Global potential natural vegetation map derived from Ramankutty & Foley [37].

soil reaches, as illustrated in figure 1, which provides broad estimates of temperature ranges and associated effects on the biological, chemical and physical properties of soil. It is, however, important to recognize that the specific changes, and their magnitude, will be driven not only by temperature, but also by other fire parameters, such as heating duration and oxygen availability [15,50], and the characteristics of the soil (e.g. organic matter content, moisture content, mineral composition and thermal properties [22,25,49,51]). The main changes at lower temperatures (below 200°C) affect mostly biological properties (e.g. reduction of microbial biomass and destruction of the seed bank and fine roots, figure 1), although physical properties such as soil water repellency and aggregate stability can also be altered (figure 1). At higher temperatures (above 200°C), chemical properties are affected through combustion of soil organic matter and production of pyrogenic organic compounds and increases in soil pH, and physical properties also change, with alterations in water repellency and aggregate stability (figure 1). Even transformations of soil minerals can occur when high temperatures (above 350°C) are reached, for example, under logs or slash piles (figure 1). The combination of all these changes typically results in a more friable and erodible soil [25,49].

Importantly, soil temperature during burning does not normally exceed 100°C until the soil water is evaporated [52] (figure 1). Furthermore, soils are poor conductors of heat [16]. Therefore, even a very intense-flaming fire consuming most of the available ground and above-ground fuel may only lead to limited heat penetration into the soil [51,53]. Thus, unless fires are very slow moving, or large amounts of ground fuel are consumed (e.g. pile burning), the direct alterations summarized above are typically confined to the top few millimetres or centimetres of the soil [16,18]. In addition to this, soil temperature reached and duration of heating can vary substantially even over small scales [50], so direct effects of fire on soils can be spatially very heterogeneous.

Some of the even more consequential changes to the soil are indirect and often occur gradually in the post-fire period. This fact is easily overlooked when studying burnt areas shortly after fire, or when examining impacts of heat or burning on soil material in the laboratory. The most studied post-fire effect is that of enhanced erosion and hence thinning of soils on hillslopes [25]. The loss of protective vegetation and litter, combined with a loss in soil structure and, in some cases, enhancement of water repellency, result in more of the rainfall impacting the soil

Box 2. The role of fire in *Terra preta* soils and Nordic dark earths.

These anthropogenic soils (figure 3*b*) were formed centuries ago by addition of fire residues (charcoal and ash) and other waste materials (biomass waste, excrement, manure and fish bones) to nutrient-poor soils by indigenous communities in tropical (*Terra preta* de Indio, 500–2500 BP [62]) and temperate (Nordic Dark Earth, approximately 3000 BP [63]) regions. These are very fertile soils in comparison with the surrounding natural soils and, therefore, an ancient model of sustainable agriculture in poor soils [62]. They are also increasingly studied as models for long-term carbon sequestration in soils, given that they have accumulated up to 100 times more carbon than the adjacent natural soils, mostly in the form of charcoal [62]. Although it is unlikely that these soils were intentionally created to improve soil fertility at large spatial scales [62], their spatial extent now ranges from less than 1 hectare up to several square kilometres, and it has been estimated that they may cover up to 3% of the total Amazonian region [64].

surface directly and in enhanced surface runoff and erosion [25,26]. This can lead to strongly accelerated losses of surface soil after the fire, with published values of 0.1–41 Mg ha^{-1} per year after moderate to severe fires compared with 0.003–0.1 Mg ha^{-1} in long-unburnt terrain [25]. However, it is important to remember that these enhanced erosion rates are (i) often restricted to the first months to years following fire, and (ii) usually decrease at larger spatial scales due to redeposition within hillslopes or catchments [47,54,55]. Given that surface soil holds the greatest amount of soil organic matter, nutrients and microorganisms, this fire-triggered process could be viewed as ‘soil destruction’. However, it must not be forgotten that soil erosion is a natural process that acts on the land surface irrespective of fire [56]. The resultant redistribution of often organic- and nutrient-rich sediment leads to the accelerated generation of fertile soils at the base of slopes, in riparian zones and floodplains within and well beyond a given burnt area. Only material that is deposited in lacustrine or marine sediment can therefore be considered as being removed from the pedosphere in the longer term [56].

Perhaps less acknowledged are the inputs of new material to the soil that occur after fire and which go beyond the sediment redistribution discussed above. The most obvious among these is the deposition of wildfire ash, the particulate post-fire residue consisting of mineral materials and charred organic components [57]. While some ash is derived directly from charred topsoil, much of it typically originates from the burnt living or dead above-ground biomass [14]. Ash production values up to 150 Mg ha^{-1} have been reported [14]. Some of the ash will be redistributed by wind or water erosion, but some will become incorporated into the soil via infiltrating water or bioturbation. Ash is typically rich in nutrients [14], and hence enhances soil fertility, which is one of the motivations for burning of crops and pastures [58,59]. Further inputs of organic materials also occur in the form of unburnt vegetation killed by the fire, and more importantly, also by incorporation of charcoal produced during the fire. Charcoal and other types of pyrogenic organic matter (e.g. fine charred materials contained in ash) have an enhanced resistance to degradation that allows them to survive in soils for centuries to millennia, and hence can act as long- or medium-term carbon sinks [60]. Recent estimates suggest that vegetation fires annually generate 56–385 Tg yr^{-1} of pyrogenic carbon worldwide, which equates to approximately 0.5% of the annual terrestrial net primary production [48,61]. The potential for fire to increase the fertility of soils has been the focus of much research since the discovery of *Terra preta* in Amazonia (see box 2). Thus, by accelerating the breakdown of living and dead organic matter above the soil and its input (largely in charred forms) into the soil, fire can enhance soil formation [18,65].

A further and even less understood fire-related process which contributes to soil formation is that of increased breakdown of parent material (i.e. rock and regolith) into smaller fragments. The high-temperature gradient caused by fire often leads to spalling, i.e. small rock fragments (mm–cm thick) flaking off from exposed rock surfaces [66]. This weathering process has, for example, been estimated to be 10–100 times more effective over the longer term than frost for locations in southern France that are prone to freeze–thaw weathering [67]. Finally, particularly where fires cause high tree mortality (stand-replacing fires), the accelerated uprooting of trees brings regolith or deep soil to the surface and exposes it to accelerated weathering. For example, following winter storms in a subalpine forest in the southern Rocky Mountains, local soil distribution of 450–600 Mg ha^{-1} has been reported within patches of uprooted trees [68].

Thus, while the soil degradational impacts of fire are often those that are at the forefront of the debate, it is also clear that fire can increase soil fertility, organic carbon content, weathering and, ultimately, soil formation, particularly in areas where limited topography or rapid vegetation cover limit post-fire erosion. In areas of greater topography and where vegetation recovery is slow, fire may lead to accelerated soil erosion, and localized soil degradation will be the medium-term outcome (figure 3*a*). This, however, has to be seen in conjunction with enhanced soil formation in other areas where the soil is redeposited. Thus, on balance, and excluding areas where the occurrence of extremely severe or frequent fires prevent medium-term recovery or *de novo* formation of soil, fire has probably been an important factor driving soil formation in many fire-affected regions around the globe.

3. Fire as a traditional land management tool

Fire is one of the most ancient human tools, and its mastership has contributed enormously to the development of humankind [7,69]. First evidence of the use of fire dates back 1 Myr [70], but records of a widespread control of burning are not evident until 400 000 years ago [71]. Traditional uses of fire are many and very diverse (cooking, illumination, warmth, religious and cultural rituals), but, very importantly, fire allowed humans to exert the first impacts on landscape scales through burning of the land for hunting, vegetation

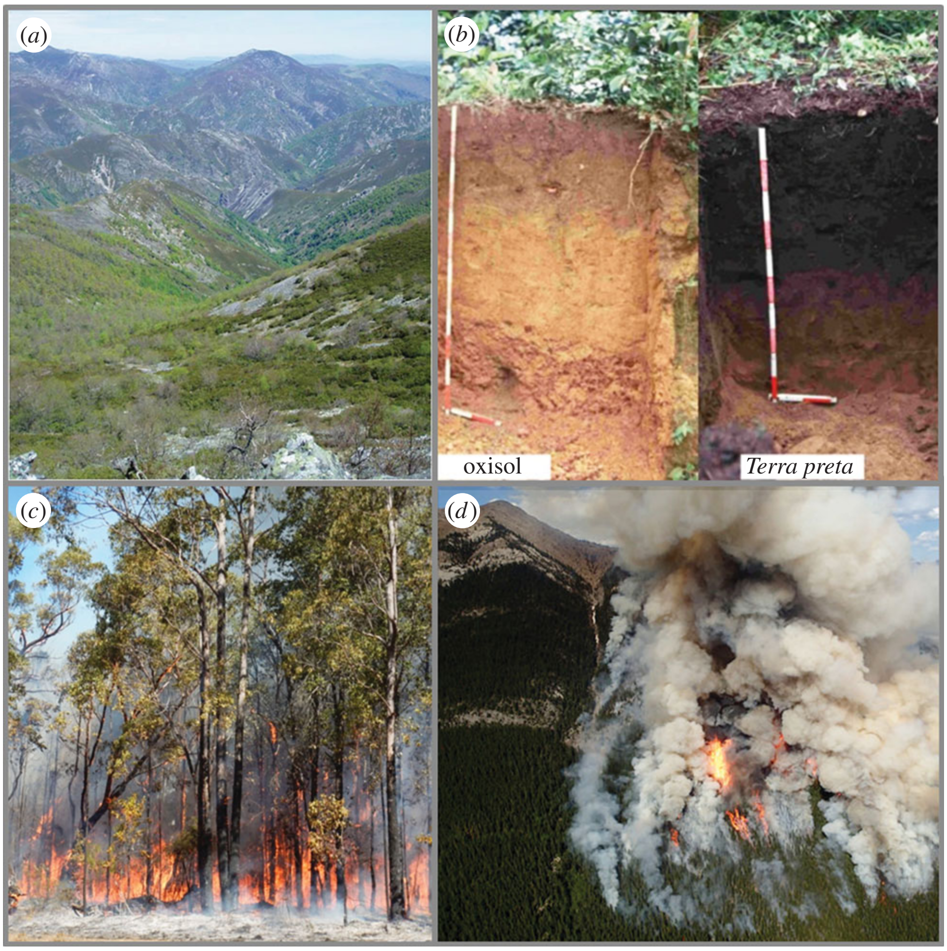

Figure 3. (*a*) Soil erosion caused by recurrent burning for pasture generation (Asturias, northwest Spain). (*b*) *Terra preta* soil, made by addition of charcoal and ash, versus a natural oxisol in Central Amazonia (see box 2; Photo courtesy of B. Glaser). (*c*) Underburning in a dry eucalypt forest with very limited effect on soil (September 2014, southeast Australia). (*d*) High-intensity ecological burn in Jasper National Park (May 2015, Alberta, Canada; Photo by Parks Canada).

modification and, later on, agricultural practices. The traditional (i.e. pre-industrial) uses of fire as a land management tool can be classified into three main types, according to the type of human society that carries out the burning [35]: (i) *Hunter–gatherers*: fire to promote habitat diversity and grass for game, and also to keep landscapes open to facilitate mobility. These are early season low-intensity surface fires with short fire intervals of only a few years; (ii) *Pastoralists*: fire to kill unpalatable species and stop woody encroachment, to promote grass growth and to control parasites and animal movements. These are also low-intensity fires but with a longer return interval (approx. 20 years); (iii) *Farmers*: burning of crop residues after harvest and pastures for domesticated grazers and also to prepare new cropland areas. These have shorter fire intervals (up to several times per year), but are also low-intensity fires with part of the burning happening in slash piles, or even away from croplands (i.e. residues used as house fuels).

The origins of these traditional uses of fire range from ancient to more recent, but all of them still occur today. Burning of crop residues, for instance, remains a fundamental agricultural practice for millions of people around the world, affecting over 20 million ha of croplands every year [6]. Traditional uses of fires have thus been modifying our landscapes for thousands of years. But what are the consequences for soils? As highlighted in the previous section, not all fires impact soils directly through heat transfer and combustion. The traditional uses of fires described above are mainly low-intensity surface fires (i.e. burning of grass and shrubs for grassland regeneration or of ground vegetation for forest maintenance) and are, therefore, mostly conducted under conditions that result in relatively ‘cool’ burns (i.e. at high relative humidity and fuel moisture, and low wind speeds; see box 1). This usually translates into limited direct effects on soils (figure 1). Overall, the greatest impacts of the traditional uses of fire on soils are mainly indirect, via changes in the vegetation cover. Transformation of forests, shrublands or grasslands into agricultural lands brings major impacts in the long term as soils under these types of land covers will evolve differently. For instance, cultivated soils normally lose 25–50% of their ‘natural’ organic carbon stock, due to enhancement of soil organic matter losses through decomposition, leaching and erosion and, at the same time, a decrease in new inputs of organic materials [72].

There are, however, some traditional uses that can have severe direct effects on soils, such as slash-and-burn practices for forest clearance purposes. Here, the forest is cut and subsequently burnt, which can result in high temperatures in the surface soil due to heavy fuel loads (figure 1). Even without pre-fire logging, deforestation fires can lead to dramatic impacts on soils. The arrival of the Māori in the South Island of New Zealand approximately 700–800 years ago serves as an extreme example. It led to losses of around 40% of the island’s forest cover in only a few decades. Fire was the main tool for forest clearance and resulted in enhancement of slope instability and large-magnitude soil erosion events [73]. Furthermore, it also needs to be considered that human-induced low-intensity fires can occasionally escape, resulting in larger and more severe wildfires with much higher impact on soils. In addition to this, the unsustainable use of fire as a landscape management tool, however—for example, burning outside of the appropriate season or using a too short fire recurrence interval—may lead to more damaging impacts on soils (figure 3*a*).

4. Soil impacts from modern prescribed uses of fire

A prescribed fire in the modern sense is any supervised burn conducted to meet specific land management objectives [74,75]. Although their behaviour and outcome will not always differ from those of some of the 'traditional uses' of fire described in §3, they are essentially a modern phenomenon that involves land management agencies. The objectives of prescribed burning are many and very diverse. Here we focus on two types that have become increasingly important in the last few decades: (i) fuel reduction burns and (ii) ecological burns. Other prescribed uses of fire include generation of pastures for cattle, control of weeds, training of firefighters and even wildfire suppression operations such as backfires and burn out [76].

(a) Fuel reduction burns

Also known as hazard-reduction burns, this term refers to 'any planned application of fire [in the landscape] to reduce hazardous fuel quantities, undertaken in prescribed environmental conditions within defined boundaries' [74]. During the last couple of centuries, the Central European approach to wildfire of 100% suppression has reduced, or even excluded, fire occurrence in many ecosystems around the world [77]. This has resulted in unnaturally excessive accumulation of dead and live biomass in some fire-prone environments, with an associated increase in fire hazard. This trend has been exacerbated in some regions by depopulation of rural areas and resulting abandonment of previously managed woodlands, shrublands and pastures and/or spreading of invasive fire-adapted species [38,78]. In these areas fuel reduction burns are, therefore, used to mitigate the risk of severe wildfires. In addition, fuel reduction burns are also used in fire-prone environments like, for example, eucalypt forests in southeast Australia, where the natural fuel loads are very high and the natural fire recurrence interval is relatively short (less than 50 years), posing a substantial risk for human communities [79]. Fuel reduction burns are gaining relevance in the global context as a more economic alternative to mechanical treatments. They are widely used in Australia since the 1950s [79], already the most common fuel reduction practice throughout the USA [16], and still limited but increasingly used in Europe [78].

Fuel reduction burns can basically be divided into: (i) underburning (surface fires in woodlands and grasslands where fire burns ground and understory fuels but does not affect the overstory where present; figure 3*c*); (ii) post-harvest slash-and-burn (coarse fuels are cut, sometimes masticated, left on the ground and burnt); and (iii) pile burning (coarse fuels are cut, piled up and burnt) [16]. These different types of fuel reduction burns have different effects on soils as illustrated in figure 1. These fires are generally carried out within a 'prescription window', i.e. weather and fuel conditions that allow burning successfully, but with a low risk of resulting in an uncontrolled fire. They are, therefore, usually conducted under weather conditions that are not particularly hot, dry or windy. Thus, unless the accumulation of ground fuel available for burning is high, the effects on soils are negligible or very limited (figure 1) [16,78]. For example, Meira-Castro *et al*. [80] examined the effects of underburning in a Portuguese pine plantation. The burn achieved its fuel reduction goal and no changes in soil properties were detected. A thin layer of unburnt litter remained, serving as an insulator during the fire and protecting the soil from post-fire erosion. A notable exception to this is pile burning, where high fuel loads burn for hours, exerting great impacts on the soil (figure 1) [16]. However, these soil impacts are localized and, unless the piles occupy large or sensitive areas, effects are considered as being irrelevant at the landscape scale [16,81].

When addressing the effects of fuel reduction burns on soils, the overall impacts need to be carefully evaluated, taking into account the characteristics and resilience of the specific soil and ecosystem, and the cumulative effects of the prescribed fire regime in the long term [47,82]. In addition to this, the potential effects of the absence of fire should also be considered. In fire-prone areas, wildfire will occur eventually, with fire intensity being typically higher than during fuel reduction burns, and, therefore, soils could be more strongly affected.

(b) Ecological burns

An 'ecological burn' is the burning of vegetation for the preservation or enhancement of ecological processes [74]. The concept of ecological burning is not new [83], but it has not been until recently that awareness of the importance of fire for the conservation of biodiversity and ecological processes has grown substantially [84]. Ecological burns typically aim to restore the natural role of fire in ecosystems where fire has long been suppressed. A good example is the series of large-scale prescribed fires that are currently carried out in several national parks in Canada (figure 3*d*; www.pc.gc.ca/eng/pn-np/mtn/feuveg-fireveg/dirige-prescribed/projet-projects.aspx).

Achieving conservation objectives, however, can be very challenging. They can conflict with other management goals, and, also, sometimes require fire conditions that are simply too risky from a safety perspective. Van Wilgen [85] illustrated the failure of 'safe' prescribed burning to meet conservation objectives through the example of the flowering shrub *Mimetes stokoei*. This South African fynbos species needs high soil temperatures during the fire to complete its life cycle. In 1971 and 1984, two prescribed burns were carried out in the only area where the species still remained but, due to safety limitations, fires could not be made intense enough to lead to germination of the soil seed bank. Luckily for the species, a more intense wildfire burnt the area in 1999 and saved it from extinction. Thus, impacts on soils of ecological burn can vary widely, depending on their objectives. When they successfully emulate natural fire conditions their effects on soils will be as variable as those from wildfires, ranging from negligible to severe (figure 1).

5. Human-induced changes to land cover and climate and their impacts on fire–soil interactions

Human-induced fires have modified many of the world's landscapes for thousands of years [69]. Burning for forest clearance and slash-and-burn practices has been carried out from the beginning of the Holocene; however, at what stage they became important at wide spatial scales is still the subject of debate [86]. Wildfires and human-induced fires are difficult to differentiate in the palaeorecord, and, in most regions of the world, the human role in past fire activity may have been overridden by the stronger and broader influence of climate [87]. However, during the last two centuries, our footprint on the planet has become much easier to trace. In this short period, humanity has changed the world as much as it was changed, for instance, over 200 million in the Mesozoic. Our enormous impact on the Earth may even lead to the 'privilege' of having our own geologic epoch: the Anthropocene [88]. Although this term is still under debate, this epoch is suggested to have begun with the industrial revolution, which was also a 'fire revolution', switching from vegetation burning to burning of fossil fuels. Here, we explore how current human-induced changes in land cover and climate are affecting fire dynamics worldwide and, with that, the impact of fire on soils.

Human activities have greatly altered global land cover, with agricultural and urban lands currently accounting for 39% of the Earth's total ice-free surface [89] (figure 2). The natural vegetation in most of these transformed areas would have been mainly forest, shrubs and grasslands (figure 2). For most of those natural ecosystems, fire occurrence would have been higher than it is in the current agricultural and urban systems. Also very importantly, another 37% of the Earth's total ice-free surface, although not directly used by humans, has also been modified to some extent [89]. Even in those areas where natural land covers have not been drastically changed, human activities may have led to landscape fragmentation, which can decrease the probability of fire to spread [90], and, thus, can reduce the occurrence of large and severe wildfires [32]. Partially due to these human-induced land-cover transformations, current global fire activity is considered to be lower than at any time in the last 2000 years [77,91]. Therefore, we can conclude that human intervention has decreased the effects of fire on soils for a considerable proportion of the global land surface.

Notwithstanding this trend, there is an opposing trend in some areas of the world where human-induced changes to land cover have led to an increase of fire effects on soils. For example, in many parts of Europe, large-scale afforestation or reforestation, often replacing native broadleaf forests with conifer and eucalypt plantations, combined with rural depopulation and abandonment of agricultural lands and pastures, have increased fire incidence in recent decades [39,78] and, therefore, the concomitant effects on soils. In other regions, tree planting programmes for carbon sequestration are threatening to profoundly alter fire regimes, for example, by introducing high-intensity forest fires and their associated impacts on soils into areas not prone to such fires under natural conditions [92,93]. Probably the best example of enhancement of fire effects on soils through anthropogenic landscape modifications are the mega-fires. These extremely severe and extensive wildfires are usually a combination of extreme fire weather and unnaturally high fuel accumulations over large areas as a result of fire exclusion policies and other land management decisions [94]. These mega-fires, which are at least partially human-induced, generally burn at greater intensities than normal wildfires, resulting in higher impacts on soils [95].

In addition to transformations of the land cover, climate change is the other main anthropogenic alteration to fire regimes at the global scale. It has been suggested that the reported increase of CO_2 in the atmosphere 8000 years ago was driven by conversion of forested areas to agricultural lands through human-induced fires [96]. The underlying hypothesis that this and other modifications of the past global climate were caused by human activities is still subject to scientific debate [87]. However, what is widely accepted is that the current climate is changing as a result of anthropogenic emissions of greenhouse gases [97]. The effects of ongoing global warming on fire regimes are very complex [76]: in some ecosystems increased drying will enhance fire (e.g. tropical forest and boreal and tropical peatlands, [98]) whereas in others fire will decrease due to reduced vegetation growth (e.g. drylands). The raised level of CO_2 in itself should, in principle, enhance vegetation growth and thus fuel loads [99]. The outcome, however, would not necessarily be more fire as, for example, in tropical savannas, where this could also translate into an expansion of forest cover to the detriment of grass, decreasing landscape flammability [92].

The effect of climate change on the probability of ignition is also hard to predict. Although there is a projected increase of lightning in some regions of the world, such as at the tropics, North America or northeast Asia [100,101], the relationship of this increase to fire ignitions is not straightforward, as these will also be controlled by other factors such as fuel availability [100] and human activities [77,102]. Moreover, other effects of climate change, such as insect outbreaks or spread of invasive flammable plant species, will also alter fire dynamics. In addition, changes in fire activity themselves will modify vegetation cover and fuel availability, which in turn will affect fire patterns [103].

As outlined in the previous paragraphs, it is difficult to generalize the effects of climate change on global fire dynamics. Notwithstanding this, most global models agree that the severity and length of the fire season will have increased substantially by the end of this century over most of the Earth [43,104]. These changes will probably lead to enhancement of fire activity [105]. Thus, assuming these predictions hold, more fire is to be expected in the warmer future world and, importantly, the fires will overall burn more intensely [43]. We could, therefore, conclude that the resulting effects of fires on soils will also be intensified in many areas. In others, however, clearing of vegetation and expansion of built-up areas will reduce fire in the landscape. The overall future outcome of these opposing trends is uncertain. What seems clear, however, is that the human dimension of fire effects on soils will become even more significant than in the present day. A thorough understanding of the complex interactions between human activity, fire, climate and soils is therefore essential if we aim to preserve our soils as one of the most valuable non-renewable resources on our planet.

6. Conclusion

The existence and fate of fire and soils are closely linked. The presence of soils is a principal prerequisite for the occurrence of fire, and fire can be both a forming and degrading agent for soils. Fire can alter the physical, chemical and biological characteristics of soils both during and after burning. These changes range from negligible to very severe, with their nature and direction depending on many factors and thresholds. In this complex fire–soil interaction, humans have exerted a key role since their early days. After all, fire has been the first human tool that allowed modification of entire landscapes.

Unlike some of the more severe naturally occurring wildfires, most traditional and modern human uses of fire do not usually have significant direct impacts on soils. They can, however, lead to substantial soil alteration through indirect effects including changes in vegetation cover. Human-induced fire has transformed landscapes, but also, human-induced land-use changes have altered fire regimes. Thus, the effects of fire on soils have been, on the one hand, enhanced by human interference in some areas (e.g. through human ignitions and generation of more fire-prone vegetation covers); but on the other hand, have been reduced in other areas (e.g. by replacing fire-prone vegetation with crops). Humans have long been, and will keep on influencing the complex interactions between fire and soils. The advent of climate change now emerges as yet another key anthropogenic factor influencing fire dynamics. The resulting effects on soils will inevitably vary, but if the global projections of more burning hold true, fire is likely to gain further importance as a factor influencing our global soil resources.

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References

1. Logan WB. 1995 *Dirt: the ecstatic skin of the earth*. New York, NY: Riverhead Books.
2. Lal R. 2015 Restoring soil quality to mitigate soil degradation. *Sustainability* **7**, 5875–5895. (doi:10.3390/su7055875)
3. Pyne SJ. 2016 Fire in the mind: changing understandings of fire in Western civilization. *Phil. Trans. R. Soc. B* **371**, 20150166. (doi:10.1098/rstb.2015.0166)
4. Scharlemann JP, Tanner EV, Hiederer R, Kapos V. 2014 Global soil carbon: understanding and managing the largest terrestrial carbon pool. *Carbon Manag*. **5**, 81–91. (doi:10.4155/cmt.13.77)
5. Martin DA. 2016 At the nexus of fire, water and society. *Phil. Trans. R. Soc. B* **371**, 20150172. (doi:10.1098/rstb.2015.0172)
6. Randerson JT, Chen Y, Van Der Werf GR, Rogers BM, Morton DC. 2012 Global burned area and biomass burning emissions from small fires. *J. Geophys. Res. Biogeosciences* **117**, G04012. (doi:10.1029/2012JG002128)
7. Bowman DMJS, O'Brien JA, Goldammer JG. 2013 Pyrogeography and the global quest for sustainable fire management. *Annu. Rev. Environ. Resour*. **38**, 57–80. (doi:10.1146/annurev-environ-082212-134049)
8. Swetnam TW, Farella J, Roos CI, Liebmann MJ, Falk DA, Allen CD. 2016 Multi-scale perspectives of fire, climate and humans in western North America and the Jemez Mountains, USA. *Phil. Trans. R. Soc. B* **371**, 20150168. (doi:10.1098/rstb.2015.0168)
9. Bowman DMJS *et al.* 2011 The human dimension of fire regimes on Earth. *J. Biogeogr*. **38**, 2223–2236. (doi:10.1111/j.1365-2699.2011.02595.x)
10. Archibald S, Lehmann CER, Gómez-dans JL, Bradstock RA. 2013 Defining pyromes and global syndromes of fire regimes. *Proc. Natl Acad. Sci. USA* **110**, 6445–6447. (doi:10.1073/pnas.1211466110)
11. Hantson S, Lasslop G, Kloster S, Chuvieco E. 2015 Anthropogenic effects on global mean fire size. *Int. J. Wildl. Fire* **24**, 589–596. (doi:10.1071/WF14208)
12. Faivre N, Jin Y, Goulden ML, Randerson JT. 2014 Controls on the spatial pattern of wildfire ignitions in Southern California. *Int. J. Wildl. Fire* **23**, 799–811. (doi:10.1071/WF13136)
13. Badía D, Martí C. 2003 Effect of simulated fire on organic matter and selected microbiological properties of two contrasting soils. *Arid L. Res. Manag*. **17**, 55–69. (doi:10.1080/15324980301594)
14. Bodí MB, Martin DA, Balfour VN, Santín C, Doerr SH, Pereira P, Cerdà A, Mataix-Solera J. 2014 Wildland fire ash: production, composition and eco-hydro-geomorphic effects. *Earth-Sci. Rev*. **130**, 103–127. (doi:10.1016/j.earscirev.2013.12.007)
15. Bryant R, Doerr SH, Helbig M. 2005 Effect of oxygen deprivation on soil hydrophobicity during heating. *Int. J. Wildl. Fire* **14**, 449–455. (doi:10.1071/WF05035)
16. Busse MD, Hubbert KR, Moghaddas EEY. 2014 *Fuel reduction practices and their effects on soil quality*. General Technical Report PSW-GTR-241, 156 pp.U.S. Department of Agriculture, Forest Service, Pacific Southwest Research Station, Albany, CA.
17. Campbell A, Schwertmann U, Campbell P. 1997 Formation of cubic phases on heating ferrihydrite. *Clay Miner*. **32**, 615–622. (doi:10.1180/claymin.1997.032.4.11)
18. Certini G. 2005 Effects of fire on properties of forest soils: a review. *Oecologia* **143**, 1–10. (doi:10.1007/s00442-004-1788-8)
19. Doerr SH, Shakesby RA, Walsh RPD. 2000 Soil water repellency: its causes, characteristics and hydro-geomorphological significance. *Earth Sci. Rev*. **51**, 33–65. (doi:10.1016/S0012-8252(00)00011-8)
20. Gualtieri AF, Venturelli P. 1999 *In situ* study of the goethite-hematite phase transformation by real time synchotron powder diffraction. *Am. Mineral*. **84**, 895–904. (doi:10.2138/am-1999-5-624)
21. Hart SC, DeLuca TH, Newman GS, MacKenzie MD, Boyle SI. 2005 Post-fire vegetative dynamics as drivers of microbial community structure and function in forest soils. *For. Ecol. Manage*. **220**, 166–184. (doi:10.1016/j.foreco.2005.08.012)
22. Ketterings QM, Bigham JM, Laperche V. 2000 Changes in soil mineralogy and texture caused by slash-and-burn fires in Sumatra, Indonesia. *Soil Sci. Soc. Am. J*. **64**, 1108. (doi:10.2136/sssaj2000.6431108x)
23. Mataix-Solera J, Cerdà A, Arcenegui V, Jordán A, Zavala LM. 2011 Fire effects on soil aggregation: a review. *Earth-Sci. Rev*. **109**, 44–60. (doi:10.1016/j.earscirev.2011.08.002)
24. Thomaz EL, Antoneli V, Doerr SH. 2014 Effects of fire on the physicochemical properties of soil in a slash-and-burn agriculture. *Catena* **122**, 209–215. (doi:10.1016/j.catena.2014.06.016)
25. Shakesby RA, Doerr SH. 2006 Wildfire as a hydrological and geomorphological agent. *Earth-Sci. Rev*. **74**, 269–307. (doi:10.1016/j.earscirev.2005.10.006)
26. Moody JA, Shakesby RA, Robichaud PR, Cannon SH, Martin DA. 2013 Current research issues related to

post-wildfire runoff and erosion processes. *Earth-Sci. Rev*. **122**, 10–37. (doi:10.1016/j.earscirev.2013.03.004)
27. Certini G. 2014 Fire as a soil-forming factor. *Ambio* **43**, 191–195. (doi:10.1007/s13280-013-0418-2)
28. Scott AC, Chaloner WG, Belcher CM, Roos CI. 2016 The interaction of fire and mankind. *Phil. Trans. R. Soc. B* **371**, 20160149. (doi:10.1098/rstb.2016.0149)
29. Scott AC, Chaloner WG, Belcher CM, Roos CI. 2016 The interaction of fire and mankind: Introduction. *Phil. Trans. R. Soc. B* **371**, 20150162. (doi:10.1098/rstb.2015.0162)
30. Power MJ, Whitney BS, Mayle FE, Neves DM, de Boer EJ, Maclean KS. 2016 Fire, climate and vegetation linkages in the Bolivian Chiquitano seasonally dry tropical forest. *Phil. Trans. R. Soc. B* **371**, 20150165. (doi:10.1098/rstb.2015.0165)
31. Hardiman M, Scott AC, Pinter N, Anderson RS, Ejarque A, Carter-Champion A, Staff RA. 2016 Fire history on the California Channel Islands spanning human arrival in the Americas. *Phil. Trans. R. Soc. B* **371**, 20150167. (doi:10.1098/rstb.2015.0167)
32. Bliege Bird R, Bird DW, Codding BF. 2016 People, El Niño southern oscillation and fire in Australia: fire regimes and climate controls in hummock grasslands. *Phil. Trans. R. Soc. B* **371**, 20150343. (doi:10.1098/rstb.2015.0343)
33. Archibald S. 2016 Managing the human component of fire regimes: lessons from Africa. *Phil. Trans. R. Soc. B* **371**, 20150346. (doi:10.1098/rstb.2015.0346)
34. Davies GM *et al.* 2016 The role of fire in UK peatland and moorland management: the need for informed, unbiased debate. *Phil. Trans. R. Soc. B* **371**, 20150342. (doi:10.1098/rstb.2015.0342)
35. Pfeifer EM, Spessa A, Kaplan JO. 2013 A model for global biomass burning in preindustrial time: LPJ-LMfire (v1.0). *Geosci. Model Dev*. **6**, 643–685. (doi:10.5194/gmd-6-643-2013)
36. Japan A. of & University CC. organizations In press. GLCNMO2008; Geospatial Information. See www.iscgm.org/gm/glcnmo.html
37. Ramankutty N, Foley J. 1999 Estimating historical changes in global land cover: Croplands from 1700–1992. *Glob. Biogeochem. Cycles* **13**, 997–1027. (doi:10.1029/1999GB900046)
38. Balch JK, Bradley BA, D'Antonio CM, Gómez-Dans J. 2013 Introduced annual grass increases regional fire activity across the arid western USA (1980–2009). *Glob. Chang. Biol*. **19**, 173–183. (doi:10.1111/gcb.12046)
39. Pausas JG, Keeley JE. 2009 A burning story: the role of fire in the history of life. *Bioscience* **59**, 593–601. (doi:10.1525/bio.2009.59.7.10)
40. Page SE, Hooijer A. 2016 In the line of fire: the peatlands of Southeast Asia. *Phil. Trans. R. Soc. B* **371**, 20150176. (doi:10.1098/rstb.2015.0176)
41. San-Miguel-Ayanz J, Moreno JM, Camia A. 2013 Analysis of large fires in European Mediterranean landscapes: lessons learned and perspectives. *For. Ecol. Manage*. **294**, 11–22. (doi:10.1016/j.foreco.2012.10.050)
42. Westerling ALR. 2016 Increasing western US forest wildfire activity: sensitivity to changes in the timing of spring. *Phil. Trans. R. Soc. B* **371**, 20150178. (doi:10.1098/rstb.2015.0178)
43. Flannigan M, Cantin AS, De Groot WJ, Wotton M, Newbery A, Gowman LM. 2013 Global wildland fire season severity in the 21st century. *For. Ecol. Manage*. **294**, 54–61. (doi:10.1016/j.foreco.2012.10.022)
44. Neary DG, Ryan KC, DeBano LF. 2005 Wildland fire in ecosystems: effects of fire on soils and water. *Gen. Tech. Rep. RMRS-GTR-42-vol.4*, pp. 250. Ogden, UT: US Department of Agriculture, Forest Service, Rocky Mountain Research Station.
45. Debano LF. 2000 The role of fire and soil heating on water repellancy in wildland environments: a review. *J. Hydrol*. **231–232**, 195–206. (doi:10.1016/S0022-1694(00)00194-3)
46. González-Pérez JA, González-Vila FJ, Almendros G, Knicker H. 2004 The effect of fire on soil organic matter—a review. *Environ. Int*. **30**, 855–870. (doi:10.1016/j.envint.2004.02.003)
47. Shakesby RA. 2011 Post-wildfire soil erosion in the Mediterranean: review and future research directions. *Earth-Sci. Rev*. **105**, 71–100. (doi:10.1016/j.earscirev.2011.01.001)
48. Santín C, Doerr SH, Kane ES, Masiello CA, Ohlson M, de la Rosa JM, Preston CM, Dittmar T. 2016 Towards a global assessment of pyrogenic carbon from vegetation fires. *Glob. Chang. Biol*. **22**, 76–91. (doi:10.1111/gcb.12985)
49. Neary DG, Klopatek CC, DeBano LF, Ffolliott PF. 1999 Fire effects on belowground sustainability: a review and synthesis. *For. Ecol. Manage*. **122**, 51–71. (doi:10.1016/S0378-1127(99)00032-8)
50. Santín C, Doerr SH, Merino A, Bryant R, Loader NJ. 2016 Forest floor chemical transformations in a boreal forest fire and their correlations with temperature and heating duration. *Geoderma* **264**, 71–80. (doi:10.1016/j.geoderma.2015.09.021)
51. Hartford R, Frandsen W. 1992 When it's hot, it's hot . . . or maybe it's not! (Surface flaming may not portend extensive soil heating). *Int. J. Wildl. Fire* **2**, 139. (doi:10.1071/WF9920139)
52. Campbell G, Jungbauer JJ, Bidlake W, Hungerford R. 1994 Predicting the effect of temperature on soil thermal conductivity. *Soil Sci*. **158**, 307–313. (doi:10.1097/00010694-199411000-00001)
53. Stoof CR, Moore D, Fernandes PM, Stoorvogel JJ, Fernandes RES, Ferreira AJD, Ritsema CJ. 2013 Hot fire, cool soil. *Geophys. Res. Lett*. **40**, 1534–1539. (doi:10.1002/grl.50299)
54. Cerdà A, Brazier R, Nearing M, de Vente J. 2013 Scales and erosion. *Catena* **102**, 1–2. (doi:10.1016/j.catena.2011.09.006)
55. Cerdà A, Lasanta T. 2005 Long-term erosional responses after fire in the Central Spanish Pyrenees: 1. Water and sediment yield. *Catena* **60**, 59–80. (doi:10.1016/j.catena.2004.09.006)
56. Morgan RPC. 2005 *Soil erosion & conservation*. Oxford, UK: Blackwell Publishing.
57. Santín C, Doerr SH, Shakesby RA, Bryant R, Sheridan GJ, Lane PNJ, Smith HG, Bell TL. 2012 Carbon loads, forms and sequestration potential within ash deposits produced by wildfire: new insights from the 2009 'Black Saturday' fires, Australia. *Eur. J. For. Res*. **131**, 1245–1253. (doi:10.1007/s10342-012-0595-8)
58. Nigh R, Diemont SAW. 2013 The Maya milpa: Fire and the legacy of living soil. *Front. Ecol. Environ*. **11**, e45–e54. (doi:10.1890/120344)
59. Pereira P, Jordán A, Cerdà A, Martin D. 2015 Editorial: the role of ash in fire-affected ecosystems. *Catena* **135**, 10–12. (doi:10.1016/j.catena.2014.11.016)
60. Santín C, Doerr SH, Preston CM, González-Rodríguez G. 2015 Pyrogenic organic matter production from wildfires: a missing sink in the global carbon cycle. *Glob. Chang. Biol*. **21**, 1621–1633. (doi:10.1111/gcb.12800)
61. Bird MI, Wynn JG, Saiz G, Wurster CM, McBeath A. 2015 The pyrogenic carbon cycle. *Annu. Rev. Earth Planet. Sci*. **43**, 273–298. (doi:10.1146/annurev-earth-060614-105038)
62. Glaser B, Birk JJ. 2012 State of the scientific knowledge on properties and genesis of Anthropogenic Dark Earths in Central Amazonia (terra preta de Índio). *Geochim. Cosmochim. Acta* **82**, 39–51. (doi:10.1016/j.gca.2010.11.029)
63. Wiedner K, Schneeweiß J, Dippold MA, Glaser B. 2015 Anthropogenic Dark Earth in Northern Germany—The Nordic Analogue to terra preta de Índio in Amazonia. *Catena* **132**, 114–125. (doi:10.1016/j.catena.2014.10.024)
64. McMichael CH, Palace MW, Bush MB, Braswell B, Hagen S, Neves EG, Silman MR, Tamanaha EK, Czarnecki C. 2014 Predicting pre-Columbian anthropogenic soils in Amazonia. *Proc. R. Soc. B* **281**, 20132475. (doi:10.1098/rspb.2013.2475)
65. Knicker H. 2011 Pyrogenic organic matter in soil: its origin and occurrence, its chemistry and survival in soil environments. *Q. Int*. **243**, 251–263. (doi:10.1016/j.quaint.2011.02.037)
66. Blackwelder E. 1927 Fire as an agent in rock weathering. *J. Geol*. **35**, 134–141. (doi:10.1086/623392)
67. Ballais J, Bosc M. 1994 The ignifracts of the Sainte-Victoire Mountain (Lower Provence, France). In *Soil erosion and degradation as a consequence of forest fires* (eds M Sala, JL Rubio), pp. 217–227. Spain: Logroño.
68. Wohl E. 2013 Redistribution of forest carbon caused by patch blowdowns in subalpine forests of the Southern Rocky Mountains, USA. *Glob. Biogeochem. Cycles* **27**, 1205–1213. (doi:10.1002/2013GB004633)
69. Gowlett JAJ. 2016 The discovery of fire by humans: a long and convoluted process. *Phil. Trans. R. Soc. B* **371**, 20150164. (doi:10.1098/rstb.2015.0164)
70. Berna F, Goldberg P, Horwitz LK, Brink J, Holt S, Bamford M, Chazan M. 2012 PNAS Plus: microstratigraphic evidence of *in situ* fire in the Acheulean strata of Wonderwerk Cave, Northern Cape province, South Africa. *Proc. Natl Acad. Sci. USA* **109**, E1215–E1220. (doi:10.1073/pnas.1117620109)
71. Roberts RG, Bird MI. 2012 Homo 'incendius'. *Nature* **485**, 586–587. (doi:10.1038/nature11195)
72. Lal R. 2008 Soil carbon stocks under present and future climate with specific reference to European ecoregions. *Nutr. Cycl. Agroecosyst*. **81**, 113–127. (doi:10.1007/s10705-007-9147-x)

73. McWethy DB *et al.* 2010 Rapid landscape transformation in South Island, New Zealand, following initial Polynesian settlement. *Proc. Natl Acad. Sci. USA* **107**, 21 343–21 348. (doi:10.1073/pnas.1011801107)
74. Australian Fire and Emergency Services Authorities Council. 2012 *Bushfire Glossary. Technical report*, pp. 28. http://www.afac.com.au/services/glossary/bushfire (accessed on 10 December 2015).
75. Stacey R. 2012 *European Glossary for Wildfires and Forest Fires. European Commission Technical Report*, pp. 138. http://rib.msb.se/Filer/pdf/26885.pdf (accessed 10 January 2016).
76. Scott AC, Bowman DMJS, Bond WJ, Pyne, Stephen J, Alexander ME. 2014 *Fire on earth: an introduction*. New York, NY: John Wiley & Sons, Ltd.
77. Doerr SH, Santín C. 2016 Global trends in wildfire and its impacts: perceptions versus realities in a changing world. *Phil. Trans. R. Soc. B* **371**, 20150345. (doi:10.1098/rstb.2015.0345)
78. Fernandes PM, Davies GM, Ascoli D, Fernández C, Moreira F, Rigolot E, Stoof CR, Vega JA, Molina D. 2013 Prescribed burning in southern Europe: Developing fire management in a dynamic landscape. *Front. Ecol. Environ*. **11**, e4–e14. (doi:10.1890/120298)
79. Burrows N, McCaw L. 2013 Prescribed burning in southwestern Australian forests. *Front. Ecol. Environ*. **11**, e25–e34. (doi:10.1890/120356)
80. Meira-Castro A, Shakesby RA, Espinha Marques J, Doerr SH, Meixedo JP, Teixeira J, Chaminé HI. 2015 Effects of prescribed fire on surface soil in a Pinus pinaster plantation, northern Portugal. *Environ. Earth Sci*. **73**, 3011–3018. (doi:10.1007/s12665-014-3516-y)
81. Rhoades CC, Fornwalt PJ, Paschke MW, Shanklin A, Jonas JL. 2015 Recovery of small pile burn scars in conifer forests of the Colorado Front Range. *For. Ecol. Manage*. **347**, 180–187. (doi:10.1016/j.foreco.2015.03.026)
82. Muqaddas B, Zhou X, Lewis T, Wild C, Chen C. 2015 Long-term frequent prescribed fire decreases surface soil carbon and nitrogen pools in a wet sclerophyll forest of Southeast Queensland, Australia. *Sci. Total Environ*. **536**, 39–47. (doi:10.1016/j.scitotenv.2015.07.023)
83. Stocker G, Mott J. 1981 Fire in the tropical forests and woodlands of northern Australia. In *Fire and the Australian Biota* (eds A Gill, R Groves, I Noble), pp. 425–439. Canberra, Australia: Australian Academy of Science.
84. Penman TD *et al.* 2011 Prescribed burning: How can it work to conserve the things we value? *Int. J. Wildl. Fire* **20**, 721–733. (doi:10.1071/WF09131)
85. Van Wilgen BW. 2013 Fire management in species-rich Cape fynbos shrublands. *Front. Ecol. Environ*. **11**, e35–e44. (doi:10.1890/120137)
86. Zennaro P *et al.* 2015 Europe on fire three thousand years ago: arson or climate? *Geophys. Res. Lett*. **42**, 5023–5033. (doi:10.1002/2015GL064259)
87. Marlon JR, Bartlein PJ, Daniau AL, Harrison SP, Maezumi SY, Power MJ, Tinner W, Vanniére B. 2013 Global biomass burning: a synthesis and review of Holocene paleofire records and their controls. *Quat. Sci. Rev*. **65**, 5–25. (doi:10.1016/j.quascirev.2012.11.029)
88. Crutzen PJ, Stoermer EF. 2000 The 'Anthropocene'. *Glob. Chang. Newsletters* **41**, 17–18.
89. Ellis EC, Klein Goldewijk K, Siebert S, Lightman D, Ramankutty N. 2010 Anthropogenic transformation of the biomes, 1700 to 2000. *Glob. Ecol. Biogeogr*. **19**, 589–606. (doi:10.1111/j.1466-8238.2010.00540.x)
90. Archibald S, Staver AC, Levin SA. 2012 Evolution of human-driven fire regimes in Africa. *Proc. Natl Acad. Sci. USA* **109**, 847–852. (doi:10.1073/pnas.1118648109)
91. Prentice IC. 2010 The burning issue. *Science* **330**, 1636–1637. (doi:10.1126/science.1199809)
92. Bond W, Zaloumis NP. 2016 The deforestation story: testing for anthropogenic origins of Africa's flammable grassy biomes. *Phil. Trans. R. Soc. B* **371**, 20150170. (doi:10.1098/rstb.2015.0170)
93. Veldman JW *et al.* 2015 Where tree planting and forest expansion are bad for biodiversity and ecosystem services. *Bioscience* **65**, 1011–1018. (doi:10.1093/biosci/biv118)
94. Williams J. 2013 Exploring the onset of high-impact mega-fires through a forest land management prism. *For. Ecol. Manage*. **294**, 4–10. (doi:10.1016/j.foreco.2012.06.030)
95. Mastrolonardo G, Rumpel C, Forte C, Doerr SH, Certini G. 2015 Geoderma Abundance and composition of free and aggregate-occluded carbohydrates and lignin in two forest soils as affected by wild fi res of different severity. *Geoderma* **245–246**, 40–51. (doi:10.1016/j.geoderma.2015.01.006)
96. Ruddiman WF. 2003 The anthropogenic greenhouse era began thousands of years ago. *Clim. Change* **69**, 261–293. (doi:10.1007/s10584-005-7278-0)
97. IPCC. 2013 CLIMATE CHANGE 2013. The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, 1535.
98. Turetsky MR, Benscoter B, Page S, Rein G, Van Der Werf GR, Watts A. 2015 Global vulnerability of peatlands to fire and carbon loss. *Nat. Geosci*. **8**, 11–14. (doi:10.1038/ngeo2325)
99. Donohue RJ, Roderick ML, McVicar TR, Farquhar GD. 2013 Impact of CO_2 fertilization on maximum foliage cover across the globe's warm, arid environments. *Geophys. Res. Lett*. **40**, 3031–3035. (doi:10.1002/grl.50563)
100. Krause A, Kloster S, Wilkenskjeld S, Paeth H. 2014 The sensitivity of global wildfires to simulated past, present, and future lightning frequency. *J. Geophys. Res. Biogeosciences* **119**, 312–322. (doi:10.1002/2013JG002502)
101. Romps DM, Seeley JT, Vollaro D, Molinari J. 2015 Projected increase in lightning strikes in the United States due to global warming. *Science* **346**, 851–854. (doi:10.1126/science.1259100)
102. Liu Z, Yang J, Chang Y, Weisberg PJ, He HS. 2012 Spatial patterns and drivers of fire occurrence and its future trend under climate change in a boreal forest of Northeast China. *Glob. Chang. Biol*. **18**, 2041–2056. (doi:10.1111/j.1365-2486.2012.02649.x)
103. Westerling AL, Turner MG, Smithwick EAH, Romme WH, Ryan MG. 2011 Continued warming could transform Greater Yellowstone fire regimes by mid-21st century. *Proc. Natl Acad. Sci. USA* **108**, 13 165–13 170. (doi:10.1073/pnas.1110199108)
104. Liu Y, Stanturf J, Goodrick S. 2010 Trends in global wildfire potential in a changing climate. *For. Ecol. Manage*. **259**, 685–697. (doi:10.1016/j.foreco.2009.09.002)
105. Jolly WM, Cochrane MA, Freeborn PH, Holden ZA, Brown TJ, Williamson GJ, Bowman DMJS. 2015 Climate-induced variations in global wildfire danger from 1979 to 2013. *Nat. Commun*. **6**, 7537. (doi:10.1038/ncomms8537)