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www.publish.csiro.au/journals/ijwf *International Journal of Wildland Fire*, 2005, **14**, 339–342

Preface

Fire effects on soil system functioning: new insights and future challenges

Stefan H. Doerr[A,B,E] *and Artemi Cerdà*[C,D]

[A]University of Wales Swansea, Department of Geography, Singleton Park, Swansea SA2 8PP, UK.
[B]CSIRO Land and Water, PO Box 1666, Canberra, ACT 2601, Australia.
[C]Department of Geography, Universitat de València, 46010 Valencia, Spain.
[D]Instituto Pirenaico de Ecología, Consejo Superior de Investigaciones Científicas, 50080 Zaragoza, Spain.
[E]Corresponding author. Email: s.doerr@swan.ac.uk

Abstract. Fire affects entire ecosystems – their flora, fauna, the atmosphere and soil. Research on the effects of fire to date has focussed primarily on the former three, whereas effects on the soil system have seen less attention. Burning and resulting post-fire environmental conditions can alter the functioning of soils physically (e.g. aggregate stability, pore size, distribution, water repellency and runoff response), chemically (e.g. nutrient availability, mineralogy, pH and C : N ratios) and biologically (e.g. biomass productivity, microbial composition and carbon sequestration). These fire-induced alterations have typically been examined in isolation by researchers in separate disciplines despite the sometimes strong relationship between some of these physical, chemical and biological effects. This special issue brings together studies from diverse disciplines, focussing on a wide spectrum of fire effects on the soil system. Here we aim to summarise, evaluate and set into context some of the new insights arising from these studies. A case is made for enhanced cross-disciplinary collaboration and the use of multi-scale research approaches in order to meet existing and future research challenges in this diverse field.

Additional keywords: erosion; hydrology; microbes; nutrients.

Introduction and background

Studies on the effects of fire on ecosystems have traditionally focused predominantly on fire effects on flora, fauna and more recently also on the atmosphere. During the last few decades, however, there has been an increasing awareness that wildfires and prescribed fires can also have profound effects on the functioning of the soil system. Both the direct effects of fire and also the overall changes to the ecosystem encountered in a post-fire situation can lead to short-, medium- and long-term changes in the soil. These relate to soil functioning in the physical, biological and chemical sense and can include, for example, changes to aggregate stability, pore size distribution, water repellency and runoff response; alterations in mineralization rates, biomass production, microbial species composition and carbon sequestration; and furthermore changes in C : N ratios, pH and nutrient availability (DeBano *et al.* 1976; Chandler *et al*. 1983; Neary *et al*. 1999; González-Pérez *et al*. 2004). These effects have typically been studied in isolation by researchers from diverse disciplines, and progress towards a comprehensive understanding of wildfire effects on soils has been held back by comparatively limited cross-disciplinary interaction and opportunities for exchange.

As major opportunity for cross-disciplinary exchange, a special session entitled 'Fire Effects on Soil System Functioning' was held at the first *European Geosciences Union Symposium* in Nice, France, in 2004 (29 April) following some of the most severe fire seasons in Europe, North America and Australia. This volume of the *International Journal of Wildland Fire* comprises 12 invited papers from this session, covering both immediate and longer-term (up to one decade) effects of fire on soil physical, chemical and biological characteristics. Approaches encompass burning or heating experiments under tightly controlled laboratory conditions as well as experimental and prescribed fires in the field, with study areas or sampling sites being located in Europe, North America and Australia. In addition to reporting on key advances in their research areas, authors were asked to focus on the wider implications of their findings and to identify major research gaps and future research directions in their respective disciplines. Of particular value within the scope of this special issue is also the fact that some of the papers featured here use a multidisciplinary approach within the given study, bridging, for example, biological and erosion effects, or soil hydrological and chemical alterations. The first series of papers focus primarily on soil chemical and

 10.1071/WF05094 1049-8001/05/040339

Fig. 1. Forest fires in August 2005 spreading into Coimbra, one of the major cities in Portugal. The combination of prolonged severe drought, strong winds and the presence of forest plantations with non-native tree species in much of the region led to unusually severe and widespread fires, resulting in on-site effects not only in rural, but also in some urban areas. (Photograph courtesy of Antonio Ferreira.)

biological aspects, followed by studies covering soil physical and hydrological issues with particular emphasis on those affecting soil erosion. Soil erosion is also being addressed from a post-fire modelling and land management aspect in the final two papers.

New insights

In the first study of this special issue, Goforth *et al*. (2005) examine the distribution patterns of woodash and the spatial extent and properties of thermally altered soil at severely burned sites with different tree-densities in California. Up to 1.5 t ha^{-1} of $CaCO_3$ were deposited in ash over the sites and at parts of the land surface, soils were sufficiently heated to redden to a depth of up to 60 mm and cause the thermal production of maghaemite (γ-Fe_2O_3). These fire-induced changes in the soil are thought to persist over time and influence soil genesis. The authors suggest that it may therefore be possible to reconstruct the long-term patterning of the degree of soil heating and thus infer past fire severities over a landscape by determining the spatially heterogeneous accumulation of thermally produced iron oxides in soils. The feasibility of such an approach is supported to some degree by results obtained in a parallel, independent study by Blake *et al*. (2005), who used magnetic enhancement to determine the degree of soil heating under different fire severities in Australian Eucalypt forest.

D'Ascoli *et al*. (2005) examine the effect of experimental fires of different severity on the soil microbial community in Mediterranean maquis terrain in Italy. As might be expected, the initial reduction in microbial community activity was more pronounced at the more severely burnt site. Functional diversity of the population, however, recovered quickly at both sites, whereas the reduction of the fungal fraction of microbial carbon and active mycelia, together with the increase of microbial biomass carbon during the first 3 months after fire, suggest a stronger and longer lasting effect of fire on fungi than on bacteria. The results indicate a rapid recovery of functional diversity in soil after burning despite the persistent reduction of microbial community activity and the change in its structure. At the same sites, DeMarco *et al*. (2005) examine the effects of these experimental burns on soil organic matter, nutrient and trace element dynamics also in relation to soil microbial activity. Nutrient and soil organic matter contents were increased for both fire severities, indicating the ecological importance of fire for soil fertility in this comparatively harsh Mediterranean environment. Increased stabilization of soil organic matter fractions after the burns demonstrate the potential importance of fire in longer-term carbon sequestration by the soil system.

A prescribed fire, conducted in grassland for the maintenance of a fire break in Mediterranean north-eastern Spain, is examined by Úbeda *et al*. (2005) in relation to its impact on soil quality (pH, carbon and nutrients). Here, fire intensity was low and surface soil temperatures did not exceed 200°C. All parameters measured showed a significant increase immediately after the fire. One year later, pH and total carbon had returned to pre-fire levels, nitrogen and phosphorous were above, whereas potassium levels had decreased to below pre-fire levels. Overall, the one prescribed fire did not appear to adversely affect the soil; however, the authors suggest that in this environment, the practice of annual burning may not allow sufficient time for the soils to fully recover between such burns.

The potential effects of fires with different severities on soil bacterial and fungal activity in Mediterranean soils from eastern Spain are examined by Guerrero *et al*. (2005) using heating experiments under controlled laboratory conditions. In contrast to the above studies, this experimental approach excludes any additional input of nutrients or organic matter from deposited ash into the soil. Fungi and bacteria showed different sensitivity to the direct effect of heating, with fungi being more detrimentally affected. The experiments indicate that, despite its initial fatal effect, heating the soils to temperatures $<400°C$ produces an enrichment of available nutrients and thus a stimulation of bacteria, whereas higher soil temperatures appear to have overall more detrimental effects on microorganisms until the recovery of vegetation occurs.

Returning to field studies of wildfire effects, the paper by Ferreira *et al*. (2005) studies the changes in the hydrology and the export of dissolved nutrients at three different spatial scales (micro-plot, plot and catchment) following wildfire in pine stands in western Mediterranean Portugal over a 14-month period. The strongly enhanced export of nutrients from the easily detachable ash layer decreases gradually over the first 4 months as a result of exhaustion, after which notable losses are only triggered by extreme rainfall events. The amounts of atmospheric deposition measured nearby are thought to be sufficient to replace the losses measured here within a period of 1–4 years.

The importance of extreme rainfall events are also highlighted in the study by de Luís *et al*. (2005) in which the effects of simulated high-intensity rainfall events on short-term vegetation regeneration (seedling emergence and survival) are examined following experimental fires in gorse shrubland in the dry Mediterranean region of eastern Spain. Perhaps surprisingly, the results indicate that in these gorse shrublands, torrential rainfalls with intensities of over 150 mm h^{-1} do not appear to trigger significant seed loss; however, these for the region not untypical rainfall intensities reduce the survival rate of seedlings through burial or soil erosion. Thus, depending on fire recurrence intervals and the timing of post-fire rainfall, the combination of fire and torrential rain can have a persistent effect on vegetation recovery, contributing to a land degradation process that is thought to become irreversible in this climate and soil system. Rainfall simulations are also used in eastern Spain by Cerdà and Doerr (2005), who monitor the effects of different types of regenerating vegetation on soil hydrological and erosional response following a severe wildfire in pine forest over an 11-year period. As demonstrated previously in a range of studies (see, for example, the review by Neary *et al*. 1999), vegetation recovery led to a strong reduction in overland flow and soil erosion rates; however, these effects varied widely between the different vegetation types examined. In contrast to what might be expected, it was also found that regrowth at the sites regenerating with pine was associated with a persistent rise in overland flow rates over this unusually long monitoring period. This was associated with the development and increase in soil water repellency, which suggests that the common practice of forest establishment is not necessarily always one of the most effective ways of rehabilitating burnt sites. The theme of soil hydrology and water repellency is continued in the study by Hubbert and Oriol (2005), in which post-fire fluctuations in water repellency are examined over a 1-year period in an area affected by a moderate-to-severe wildfire in southern Californian chaparral. During the wetter months, seasonal variations in the degree of surface water repellency were inversely related to antecedent rainfall and soil moisture conditions, an outcome also typical for naturally water-repellent soils unaffected by burning (e.g. Dekker *et al*. 2001). Despite the initial fire-induced increase in surface water repellency, its occurrence decreased to below pre-fire levels 1 year after burning, possibly caused by a combination of factors such as erosion, bioturbation and a reduced replenishment of hydrophobic compounds from vegetation and litter under post-fire conditions.

The following study (Bryant *et al*. 2005) also focuses on variations in soil water repellency. Here, a series of laboratory heating experiments are conducted on soils of different origin to test whether the temperature thresholds for critical changes in water repellency, established in a range of previous studies (see review by DeBano 2000), also apply when soils are heated under oxygen-deprived conditions. The data demonstrate that, for example, the threshold for destruction of water repellency, which is normally around 300°C (DeBano 2000), can be more than 200°C higher in the absence of oxygen. The presence of charcoal (a product of pyrolysis) in burnt soils suggest that oxygen can indeed be limited during a fire, which in turn emphasizes the need for caution when applying the previously established temperature threshold values to the field.

The two remaining papers in this volume focus on post-fire soil erosion in the western USA, a topic that has received considerable attention in the context of soil system science due to its implications for soil fertility, water quality and infrastructure. Benavides-Solorio and MacDonald (2005) report on hillslope-scale sediment production for three wildfires and three prescribed fires determined using sediment fences. Erosion varied with fire severity and was mainly caused by summer convective storms, but it varied also amongst plots within a given fire severity class. Their modeling results show that percentage bare soil and rainfall erosivity, and to a lesser degree fire severity and soil water repellency, explained most of the variability in sediment production rates. This special issue concludes with a study by Robichaud (2005) in which sediment fences as well as rainfall simulations are used in paired catchments to examine the effectiveness of contour-felled log erosion barrier treatments for up to two years following different wildfires at a variety of sites. The barriers evaluated here were particularly effective in reducing runoff and trapping and sediment onsite for low-intensity rainfall events. Their effectiveness, however, is greatly reduced during high-intensity rainfall events and also decreases over time as the sediment storage areas behind the logs become filled and the barrier can no longer trap mobilized sediment. The author stresses that post-fire rehabilitation treatments such as these cannot prevent erosion, but they are effective (and comparatively economic) in reducing overland flow, site soil loss, and sedimentation for some rainfall events.

Emerging and research needs and approaches

Recurring fires have long been characteristic of many parts of the world and it is well known that their impacts on soil-system functioning can be highly variable depending on pre-fire and post-fire conditions and the nature of the burn itself. The in many cases catastrophic, recent fires in Europe (Fig. 1), Australia, North America and elsewhere have once again highlighted the difficulties faced by researchers and land managers in predicting and addressing their on-site and off-site effects. The papers contained in this special issue exemplify a broad range of advances that have been made by applying both established and novel approaches to the study of fire effects on the soil system. The studies, however, also demonstrate clearly that our understanding of fire effects on soil system functioning is far from complete. Findings that are applicable to one region, may not necessarily be applicable to another and the complexity presented by the vast environmental variability amongst fire-prone land worldwide is compounded by changes in climate, vegetation cover and land management, which present us with unprecedented fire behavior and post-fire conditions. One approach to tackle this challenge is to conduct focused studies under well-controlled laboratory conditions, as done for example by Bryant *et al*. (2005) or Guerrero *et al*. (2005), which allow fundamental effects of heating or burning and their applicability to diverse soils to be established. Their outcomes, however, are limited by the fact that some uncertainty can be expected to remain in how well they reflect the more complex and variable conditions in the field. At the other end of the spectrum are studies that use modeling approaches that are widely applicable (e.g. Robichaud 2005). Here, a key challenge is presented in keeping the input simple to facilitate model use and calibration, while at the same time accounting for a wide variability of environmental parameters. The rapid pace of advances in modeling and computing capabilities will undoubtedly further improve the prediction of fire effects; however, a comprehensive understanding of fire effects on the soil system will continue to rely on the outcomes of well-conducted field studies. Based on the promise and limitations presented by studies in this special issue and elsewhere, we argue that an 'ideal' study in this context would be one that: (i) includes comprehensive pre-fire and immediate post-fire data acquisition sufficient for rigorous statistical analysis; (ii) is conducted for a sufficiently long period to allow the longevity of fire impacts to be firmly established; (iii) encompasses sampling sites with different fire and environmental characteristics and a hierarchy of spatial and temporal scales at each representative site; and (iv) is conducted by a team of researchers from a variety of disciplines to maximize their perspective and outcome. Meeting these requirements will be hard to achieve even in well-funded collaborative studies; however, even some steps towards these will facilitate unraveling the complex effects of fire on the physical, biological and chemical aspects of the soil system and their interaction, and will allow the inevitable spatial and temporal uncertainties of the outcomes to be minimized.

Within this special issue, many of the research components highlighted above are tackled in the context of a wide variety of topics, sites and environmental conditions. The contributors have also acknowledged the limitations of their studies and highlighted the emerging research gaps. We trust that this special issue will not only inform the reader about the latest advances in the diverse field of fire effects on soils, but also inspire further cross-disciplinary collaboration amongst researchers across the globe in a field that requires bridging many aspects of fire and soil-related science.

Acknowledgements

S. H. Doerr acknowledges support from NERC Research Grant (NER/A/S/2002/00143) and NERC Advanced Fellowship (NER/J/S/2002/00662), which supported his research during the preparation of this special issue. A. Cerdà was supported by projects GV2005-002 and REN2002-00133/GLO.

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