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INTRODUCTION

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Ash and fire, char, and biochar in the environment

Abstract

Fire is an extreme event leading to rapid and dramatic losses of carbon (C), nutrients, and ballast elements from ecosystems and leaving ash and char on the soil surface. This affects soil processes, properties, and functions. Similar effects can be induced by applying biochar—the product of artificial pyrolysis of plant materials and organic wastes. The nutrients in ashes remaining after a fire or in biochar after pyrolysis will be leached within a few years, and only the highly condensed material will remain in the soil over centuries and millennia.

This Special Issue (SI) is devoted to *ash, fire, char*, and *biochar in the environment*, with a special focus on soil processes and properties. We begin by comprehensively summarizing the positive and negative effects of fire, ash, char, and biochar on the physical, chemical, and biological properties of soils. We then review the 15 papers contributing to this SI. The first group of studies focuses on reconstructing fires during the Holocene and then linking them to human activities and land use. These studies clearly concluded that the fire frequency strongly increased with human invasion and occupation, and that charcoal properties are useful in reconstructing anthropogenic activities. The second group of studies is mainly devoted to changes in physical, chemical, and biological soil properties as well as to interactions between soil functions depending on fire, ash, and char properties. The final group describes the effects of biochar on soil properties and functions such as nutrient availability, C sequestration, microbial diversity and community structure, and heavy metal fixation. The overall conclusion is that fire and the remaining ash and char as well as the application of biochar have short- and long-term consequences for soil. Despite the dramatic effects of fire on vegetation, these factors have many positive effects on soil properties and functions, whereby the influences extend from local, landscape, and regional scales to the global scale.

1 | BACKGROUND

Fire is a natural or anthropogenically induced extreme event leading to very fast and dramatic losses of carbon (C), nutrients, and ballast elements from ecosystems and leading to long-term consequences for the properties and functioning of ecosystems. With the exception of polar environments, fires are common in all ecosystems (Glinka, 1914) but are especially frequent in the boreal and Mediterranean realms (López-Sáez, Vargas, Ruiz-Fernández, Blarquez, & Alba-Sánchez, 2018; Pereira, Rein, & Martin, 2016). Fire effects on ecosystems are very complex. They not only reduce or completely eliminate aboveground biomass but also impact the full range of belowground physical, chemical, and microbially mediated processes (Liu et al., 2018; Luo et al., 2018; Neary, Klopatek, DeBano, & Ffolliott, 1999), increase runoff and soil erosion in the immediate period after the fire (Shakesby & Doerr, 2006; Thomaz, 2018), and, in the case of severe and recurrent fires, give prolonged consequences at the landscape and regional levels (Figure 1).

Ash and char are products of organic matter combustion either during fire events or under controlled conditions (e.g., biochar and wood ash generated in biomass power plants). Fires have acted as a natural physical force impacting ecosystems throughout Earth's history, but especially as a factor accompanying human invasion into ecosystems and anthropogenic land use (Carracedo et al., 2018; López-Sáez et al., 2018). Ash and char, as fire products, leave a strong long-term footprint in all ecosystems (Pereira, Jordan, Cerda, & Martin, 2015). Fires release large amounts of carbon dioxide (CO_2) and organic compounds into the atmosphere. In turn, the char remaining on the ground sequesters C in soils and sediments over millennia (Kuzyakov, Bogomolova, & Glaser, 2014; Leifeld et al., 2018; Wang, Xiong, & Kuzyakov, 2016). In contrast to char, ash is rich in several nutrients such as calcium, magnesium, potassium, sulfur, and certain micronutrients (e.g., iron and manganese), which are available for plant growth (Table 1). Low-to-moderate fire severities have less significant impacts on soils and can be beneficial over the short term (e.g., by increasing soil nutrients). In contrast, high fire severities and intensities strongly impact soil properties by completely removing litter layer and high organic matter mineralization. The result is strong soil degradation. In the immediate period after fire, ash covers the soil and is an important source of nutrients. This strongly influences the physical, chemical, and biological properties of soils (Table 1).

Every year, tons of biochar[1] and wood ash are produced from waste and energy production. This can be used to improve soil properties, among them water retention, pH increase, nutrient availability,

[1]Char and biochar are differentiated here as products of incomplete combustion by natural fires of any vegetation or by slow artificial pyrolysis of any biomass or organic wastes, respectively. Biochar may be amended by organic (e.g., composted) or mineral (e.g., nutrient) additives.

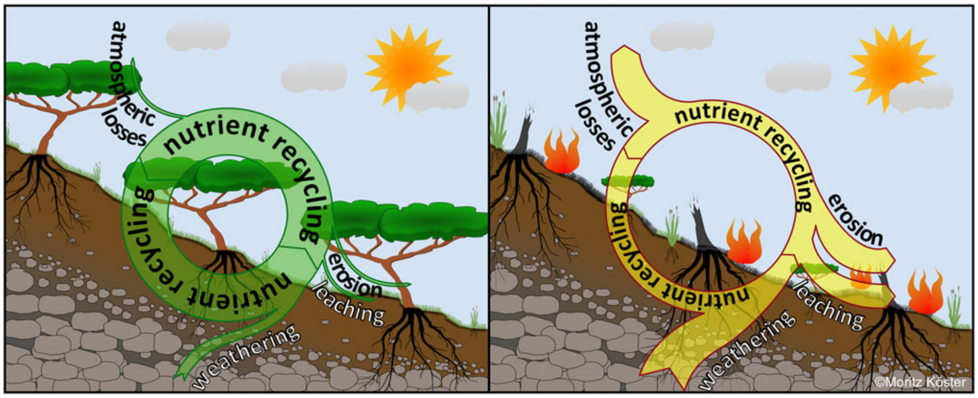

FIGURE 1 Main fluxes and cycles of elements before and after the fire. Left: Ecosystems under steady state with dominance of nutrient (re) cycling. During and after the fire (right), most elements are lost from the ecosystem, and new nutrients are mobilized from soil and parent material by weathering and accumulated in the topsoil. Figure courtesy of Moritz Köster [Colour figure can be viewed at wileyonlinelibrary.com]

aggregation, microbial activity, and root growth (Table 1). Such strategies would represent a win–win geoengineering strategy for C sequestration over the long term. This Special Issue (SI) brings together the latest research from across the Earth and environmental sciences on ash and char and their impacts on soils.

Severe fires reduce soil cover and induce instantaneous losses of a high proportion of those elements important for microorganismic and plant growth (Figure 1). Ash and char can promote or dampen these processes depending on ash properties, topography of the burned area, and postfire meteorological conditions. The nutrients and sediments mobilized from the soils and saprolite due to the vegetation loss expose deep soil layers and mobilize the nutrients and sediments located there (Figure 1). Erosion losses reshape the surface and bring saprolite closer to the surface, accelerating nutrient mobilization. This mobilization is especially active in the first postfire years until the vegetation recovers. This reflects (a) disturbance of the quasi-equilibrium between the elements in the soil solution and the solid phase existing before the fire, (b) rapid early succession of plant and microbial communities towards species specialized on very fast and effective uptake of mineral nutrients remaining after the fire, and (c) a slow switch from nutrient acquisition immediately after the fire to recycling with increasing time after the fire. Conservative estimations showed that the rock weathering directly induced by fire may be 10–100 times more intensive than frost action over the long term (Ballais & Bosc, 1994). Accordingly, fires increase system connectivity and are important geomorphological agents: They directly affect weathering bedrock surfaces, change soil structure and properties, and indirectly modify the effects of soil and vegetation on hydrological and Earth-shaping processes (Shakesby & Doerr, 2006).

One hundred years ago, Glinka (1914) was the first to recognize the importance of pyrogenic C (PyC): "There was almost no soil profile, in which charcoal particles did not occur in the upper horizon." In contrast to many other topics in soil science, the importance of ash and fire, char, and biochar for processes in soils was recognized only two to three decades ago (Figure 2), that is, nearly no papers before 1995. Since then, these issues have become hot topics in soil and environmental sciences, making this SI topical and timely.

2 | OVERVIEW OF THE PAPERS IN THE SPECIAL ISSUE

The SI collected 13 papers with three main focuses: (a) natural fires, reconstruction of paleofires, and land use history; (b) consequences of fires for soil properties, water fluxes, and erosion; and (c) physical, chemical, and biological processes after biochar application to soil.

2.1 | Natural fires, reconstruction of paleofires, and land use history

The first group of contributions focuses on processes induced by natural fires and on reconstructing paleofires and land use history. Fire evidence has been found since the Silurian Period (420 million years ago), but the frequency increased after humans learned to manipulate fire for hunting, farming, cooking, manipulating metals, conquering territories, and protecting themselves from predators. This makes fires very good indicators of anthropogenic effects on ecosystems (Pereira et al., 2016). Because of very slow decomposition rate of PyC (Kuzyakov et al., 2014), charcoal in soils and sediments is very frequently used for reconstructions. Charcoal records in peat bogs enabled reconstructing fire dynamics throughout the last 3,000 years in central Iberia (López-Sáez et al., 2018). During 1,400–1,240 years BP, anthropogenic fire control between the Late Roman and Visigothic periods was related to the cultivation of olive trees in the valleys and a greater human impact in high-mountain areas. During the Muslim period (1,240–850 cal. year BP), however, fire dynamics became asynchronous. Accordingly, fire activity increased after the agricultural revolution and was enormously variable during the late Holocene in response to both short-term and long-term regional and global climate, vegetation dynamics, and land use changes (López-Sáez et al., 2018).

Fire disturbs the vegetation, and since the Neolithic, it has become an irreplaceable tool for opening up forest spaces and maintaining pastures (Carracedo et al., 2018). Fire impacts depend on climate, land use, topography, and the ecosystem being affected. In regions such as Cantabria, where agriculture and livestock have spread since prehistory, fires are closely related to human land uses. The history of fires and vegetation since the Neolithic in the Cantabrian

TABLE 1 Immediate (direct) and subsequent (indirect) effects of fire, ash, char, or biochar on soil properties

Properties		Fire			Ash			Char and biochar		
		L	M	H	L	M	H	L	M	H
Physical	Particle size			⇧						⇧
	Hydrophobicity		⇧	⇩	⇧	⇧	⇩	⇧	⇧	⇧
	Water holding capacity		⇩	⇩	⇩	⇩	⇧	⇧	⇧	⇧
	Infiltration rate		⇩	⇩	⇩	⇩	⇩		⇧	⇧
	Swelling/shrinking									⇩
	Porosity		⇩	⇩			⇩		⇧	⇧
	Aggregates		⇩	⇩		⇧	⇧			⇧
Chemical	C, N content			⇩	⇧	⇧	⇩	⇧	⇧	⇩
	Extractable cations		⇧	⇧	⇧	⇧	⇧		⇧	⇧
	Stable C							⇧	⇧	⇧
	Extractable micronutrients	⇧	⇩	⇩	⇧	⇧	⇧			⇩
	pH		⇧	⇧		⇧	⇧	⇧	⇧	⇧
	Electrical conductivity		⇧	⇩	⇧	⇧	⇩			⇧
	SOM decomposition		⇩	⇩	⇧	⇧	⇧		⇧	⇧
	Aeration, redox						⇧	⇧	⇧	⇧
	Emission of CO_2, N_2O	⇧	⇧	⇧	⇧	⇧	⇧	⇧	⇧	⇧
	Cation exchange capacity		⇩	⇩				⇧	⇧	⇧
	Ballast elements	⇩	⇩	⇩	⇧	⇧	⇧		⇧	⇧
	Sorption surface		⇩	⇩				⇧	⇧	⇧
	Sorption of toxicants					⇩	⇩	⇧	⇧	⇧
	Carbonate formation			⇧	⇧	⇧	⇧			⇧
	Carbonate dissolution			⇩	⇩	⇩	⇩			⇩
	C sequestration		⇩	⇩		⇧	⇩	⇧	⇧	⇧
	Organo-mineral interactions		⇩	⇩	⇧	⇧	⇧	⇧	⇧	⇧
	Root litter input	⇩	⇩	⇩	⇧	⇧	⇧	⇧	⇧	⇧
Biological	Soil macro fauna abundance	⇩	⇩	⇩	⇧	⇩	⇩	⇧	⇧	⇧
	Microbial abundance	⇩	⇩	⇩	⇧	⇧	⇩	⇧	⇧	⇧
	Activities of all enzymes	⇩	⇩	⇩	⇧	⇧	⇩	⇧	⇧	⇧
	Microbial diversity	⇩	⇩	⇩	⇧	⇧	⇩	⇧	⇧	⇩
	Fungi/bacteria	⇩	⇩	⇩	⇧	⇧	⇩	⇧	⇧	⇧
	Saprophytic fungi	⇩	⇩	⇩				⇧	⇧	⇧
Vegetation	Ground cover	⇩	⇩	⇩	⇧	⇧	⇩			
	Biomass productivity	⇩	⇩	⇩	⇧	⇧	⇧	⇧	⇧	⇩
	Root growth	⇩	⇩	⇩	⇧	⇧		⇧	⇧	⇧
	Rhizodeposition	⇩	⇩	⇩	⇧			⇧	⇧	⇧
	Nutrient uptake	⇩	⇩	⇩	⇧	⇧	⇧		⇧	⇧
Other	Wind erosion		⇧	⇧		⇧	⇧			⇩
	Water erosion	⇧	⇧	⇧	⇧	⇧	⇧	⇩	⇩	⇩
	Runoff element losses		⇧	⇧	⇧	⇧	⇧		⇩	⇩
	Open element cycles		⇧	⇧		⇧	⇧		⇩	⇩
	Weathering		⇧	⇧	⇩	⇩	⇩		⇧	⇧

Note. The symbol ⇧ or ⇩ shows the increase or decrease of the respective parameter, pool, or flux at low (L), moderate (M), and high (H) fire severity. The blank space (no symbol) means no effect. The changes are presented only for the soil depth directly affected by fire (upper 5 cm) or the surface soil with the input of ash, char, or biochar. Char and biochar are joined in one column because their effects are very similar. Note that ash usually remains after the fire together with char or will be added together as biochar. Nevertheless, it is important to distinguish the effects of ash (short term, similar to fertilization) and the charcoal/biochar (very long term). The cumulative effects are hard to predict because the effects of fire, ash, and char/biochar matter at various time scales. SOM = soil organic matter.

Mountains was investigated using sedimentary charcoal and pollen data. This yielded data on the role of human activities in the processes shaping ecosystems throughout the Holocene. Asynchrony and quantitative differences in fire patterns at the regional scale were common since the Neolithic, although the type and size of each basin also strongly influenced charcoal accumulation. Maximum charcoal accumulation rates at La Molina were observed between the Neolithic and the Bronze Age but occurred after about 3,500 years BP at El Cueto de la Avellanosa. Consequently, fire has been a key factor in forest retreat and in maintaining open landscapes since the Neolithic (Carracedo et al., 2018).

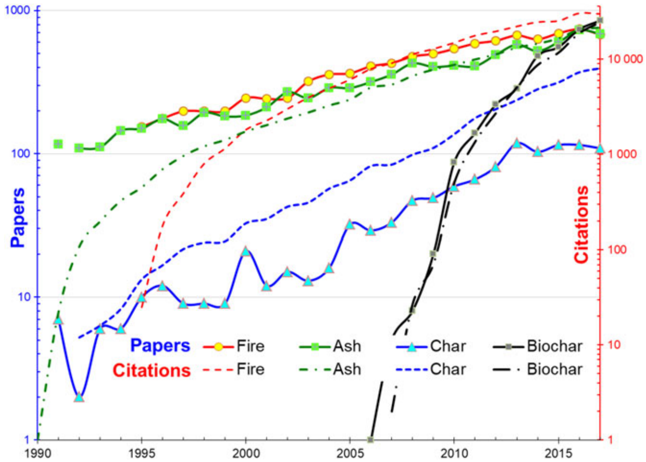

FIGURE 2 Development of publications (left *Y* scale, symbols and solid lines) and citations (right *Y* scale, dash-dotted lines) with the keywords (FIRE or ASH or CHAR or BIOCHAR) and SOIL (data from Web of Science, from 1990 to the end of 2017). Note the logarithmic scales of both *Y* axes [Colour figure can be viewed at wileyonlinelibrary.com]

Human management and exploitation of forest resources increased the fire frequency and the regional input and deposition of PyC (black carbon) on soils. On the basis of the ^{210}Pb age-depth model, the black C deposition was investigated over several key periods over the last 150 years in peatlands of the Great Hinggan Mountains (Northeast China; Gao, He, Cong, Zhang, & Wang, 2018). The black C deposition was between 1.1 and 4.8 mg·year^{-1}·cm^{-2}, similar to that of other peatlands but higher than that of other ecosystems. After the 1980s, fire events decreased as a consequence of fire-suppression policies (Gao et al., 2018).

Most PyC is very stable against decomposition and therefore accumulates in various ecosystems. During the Holocene, about 436 Pg organic C accumulated in northern peatlands and contributed substantially to the C stocks (Leifeld et al., 2018). PyC amounted to 13.5% of soil C across sites in degraded European peatland sites and accounted for up to 50% at some single sites. The amount of PyC increased significantly with peat age and degradation stage. Selective enrichment of PyC during both peat buildup and decomposition seems to be an important factor fostering PyC accumulation. Leifeld et al. (2018) estimated for the peatlands of the northern hemisphere a PyC stock of 62 (±22) Pg. This indicates a substantial and hitherto unquantified contribution of northern peatlands to global PyC storage.

2.2 | Consequences of fires

The second group of studies investigates the consequences of fires for soil properties, water budget, and fluxes, as well as erosion. Ash remaining on the soil surface after fire reduces the infiltration rate and may increase the erosional losses of the nutrients and ballast elements (Thomaz, 2018). "Black ash" (partially burnt litter produced at low-temperature fires, <300 °C), in comparison with "gray ash" (mainly mineral compounds), contains abundant organic C, acts as mulch cover, protects the soil against erosion, and increases water infiltration. Gray ash (produced at high temperatures, >500 °C) dramatically changes the topsoil hydrology and promotes erosion because its fine particles clog the soil pores, resulting in surface sealing. To protect soil against erosion, farmers in hilly landscapes could use tree trunks as contour-felled log erosion barriers to reduce runoff and soil erosion (Thomaz, 2018).

The effects of wildfires on the soils of the south taiga and forest-steppe environments of Central Russia were investigated with a focus on the quantity and quality of humic acids using spectroscopic methods (^{13}C NMR and electron spin resonance; Abakumov, Maksimova, & Tsibart, 2018). The organic matter of fire-affected superficial soil was characterized by changes in the structural composition and biochemical activity levels. ^{13}C NMR showed a major increase in aromatic compounds and decline of aliphatic chain content in response to fire. The free radicals content and the degree of molecular stabilization assessed with electron spin resonance showed an increase in the radical's portion in postfire soils. The accumulation of aromatic compounds indicates only apparent stabilization of humic acids due to the loss of peripheral alkylic groups, which was confirmed by destabilization of the molecules as illustrated by the increase of free radicals (Abakumov et al., 2018).

Wildfires typically transform vegetation and litter into a heterogeneous layer of ash and charred material covering the soil surface. This can substantially modify the postfire hydrological and erosive response (Prats, de Brito Abrantes, de Oliveira Alves Coelho, Keizer, & de Lima, 2018). The runoff over the surface was lower for all soils with a protective cover of char, ash, stones, or their combination than for bare soil, but ash and char were less effective than stones. Stones were effective in reducing overall erosion rates, whereas ash and char, compared with bare soil, even slightly increased overall erosion rates. Ash and char reduced erosion but only during the first two rain events. The greater efficiency of the combined protective cover reflects synergistic effects between its three components because the stones enhance infiltration and increase flow resistance, thereby hampering detachment of ash and char and/or facilitating their retention (Prats et al., 2018).

Fire determines soil organic matter quantity and quality and the formation of polycyclic aromatic hydrocarbons (PAHs). Rey-Salgueiro et al. (2018) observed the highest PAH levels in the burnt soils of four ecosystems affected by moderate burn severities (maximum temperatures in the forest floor layer 200–400 °C). These high soil PAH levels were attributed to the incomplete combustion of organic matter. At the highest temperatures, the low PAH levels are due to thermal oxidation of these compounds and the adsorption of aromatic compounds on the soil organic matter.

2.3 | Biochar effects

The last group of studies presented in this SI describes various processes after biochar application to soil. Biochar is an important soil conditioner and is increasingly used all over the world. Nonetheless, we still have a very limited understanding of biochar effects on physical, chemical, and especially biological soil properties.

This part starts with an important review by Al-Wabel et al. (2018) describing in detail the effects of biochar properties on soil properties and conditions as well as on agricultural sustainability. This paper summarizes the impacts of pyrolysis conditions and feedstock types on biochar properties and relates them to changes in soil properties. Mechanisms of biochar effects on crop productivity, C sequestration, and nutrient use efficiency are discussed. The review identifies the knowledge gaps, limitations, and future research directions for large-scale use of biochar. It underlines that biochar produced at low temperatures improves mainly nutrient availability and crop yields, whereas high-temperature biochar strongly contributes to long-term soil C sequestration. Notably, biochar is not a panacea and can contribute only in part to crop yield optimization and agricultural sustainability.

Biochar application leads to C storage in soils, but biochar is unevenly distributed among particle-size fractions. The biochar–soil interactions and the redistribution of C in soil fractions was investigated based on a 2-year field experiment (El-Naggar et al., 2018). Biochar application increased C content by 37%, 42%, and 76% in the soil particle-size fractions of 53–250, <53, and 250–2,000 μm, respectively. This result was supported by X-ray fluorescence spectroscopy analysis. The highest C increase was in the coarse sand fraction. Scanning electron microscopy combined with electron dispersive X-ray spectroscopy analysis showed the interactions between soil and biochar, which are attributable to oxidized functional groups (O–C=O, C=O, and C–O) captured by the X-ray photoelectron spectroscopy. The long-term aged biochar is beneficial for soil quality by promoting C storage and facilitating positive biochar–soil interactions (El-Naggar et al., 2018).

The impacts of biochar on microbial abundance as well as on the communities in the rhizosphere and bulk soils were investigated in soybean fields by 16S ribosomal RNA gene sequencing (Liu et al., 2018). The biochar amendment altered soil microbial abundance and community composition. The bacteria in the rhizosphere soil showed clearer responses to biochar addition than did the bacteria in the bulk soil. Consequently, biochar interactions with roots have stronger effects on bacterial populations than has biochar application in root-free soil. This clearly reflects positive effects of biochar on root growth and rhizodeposition. The relative abundance of bacteria taxa remained nearly unaffected, but absolute abundance increased very strongly after biochar application (Liu et al., 2018).

Biochar amendment influences microbial community and functioning not only by providing available organics but also indirectly by decreasing soil acidity by cations in ash. Compound-specific ^{13}C analysis of phospholipid fatty acids (^{13}C-PLFA) was used to determine which microbial group utilized C added with biochar (Luo et al., 2018). C4 *Miscanthus* biochar (δ^{13}C = −12.2‰), prepared at 350 and 700 °C, was applied to a highly acidic soil (pH 3.7, δ^{13}C = −27.7‰) from Rothamsted Research Station and incubated for 14 months. Biochar increased soil pH by 0.6 to 1.4 units. All microbial groups (G+ bacteria, G− bacteria, Actinobacteria, and fungi) were more abundant in the biochar-treated soils. The ^{13}C-PLFA showed that all microbial groups, and especially G+ bacteria, used the C from the biochar350, but not from the biochar700. In conclusion, biochar utilization by microorganisms is largely determined by the pyrolysis temperature controlling the C availability and not by the pH effects (Luo et al., 2018).

Biochar can absorb heavy metals from soil and alleviate soil degradation. The effects of biochar addition on the PLFA contents and linkage of PLFA to heavy metal accumulation in plants were investigated in a microcosm experiment (Liang et al., 2018). The composition of the microbial community in two soils (clay-loamy vs. silt-loamy) and heavy metal accumulation in rice grains and straw were studied. Biochar increased microbial diversity, whereas bacteria (mainly G−) increased more strongly than did fungi in both soils after 98 days of incubation. The high biochar addition rate stimulates aerobic bacteria and decreases the lead, copper, and arsenic uptake in grain and straw. Close interactions between soil type and biochar addition rate were identified for most microbial indicators and for heavy metal uptake by rice (Liang et al., 2018).

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ORCID

Yakov Kuzyakov http://orcid.org/0000-0002-9863-8461
Agustin Merino http://orcid.org/0000-0003-3866-7006

Yakov Kuzyakov[1,2,3]
Agustin Merino[4]
Paulo Pereira[5]

[1]*Tianjin Key Laboratory of Water Resources and Environment, Tianjin Normal University, Tianjin 300387, PR China*
[2]*Institute of Environmental Sciences, Kazan Federal University, 420049 Kazan, Russia*
[3]*Agro-Technology Institute, RUDN University, 117198 Moscow, Russia*
[4]*Department of Soil Science and Agricultural Chemistry, University of Santiago de Compostela, E-27002 Lugo, Spain*
[5]*Environmental Management Laboratory, Mykolas Romeris University, Ateities st. 20, LT-08303 Vilnius, Lithuania*

Correspondence
Y. Kuzyakov, Tianjin Key Laboratory of Water Resources and Environment, Tianjin Normal University, Tianjin 300387, PR China.
Email: ykuzyakov@yandex.com

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