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Effects of biochar and wood ash on soil hydraulic properties: A field experiment involving contrasting temperate soils

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ABSTRACT

The application to soils of energy co-products derived from forest biomass (biochar [BC] and wood ash [WA]) with the aim of regulating soil hydraulic conductivity and water availability, thereby reducing soil erosion and increasing resilience to drought, has been suggested as a strategy for climate change mitigation and adaptation. The main objective of this study was to investigate the effects of BC and WA application on the hydraulic properties of contrasting afforested soils in the Atlantic region of the Iberian Peninsula. Two experimental sites were established on acidic soils: site ES-K was established on a loamy soil (SOC% 3.9; pH: 4.8) and site ES-O on a sandy loam soil (SOC% 10.8; pH: 3.8). Biochar derived from *Miscanthus* sp. (pyrolysed at 450 °C: containing 87% C) was applied at rates of 0, 3.5 and 10 Mg ha^{-1} to soil in ES-K and at rates of 0, 10 and 20 Mg ha^{-1} to soil in ES-O. Pine WA (30% C) was applied at rates of 0, 1.5 and 4.5 Mg ha^{-1} to ES-K, and at rates of 0, 4.5 and 9 Mg ha^{-1} to ES-O. Nitrogen- enriched (0.8% N) BC and WA were also applied at rates of respectively 10 Mg ha^{-1} and 4.5 Mg ha^{-1} in both experimental sites. Bulk density, saturated hydraulic conductivity (K_s), porosity and aggregate size distribution were determined and soil water retention curves (SWRCs) constructed. In ES-K, application of N-enriched WA (4.5 Mg ha^{-1}) led to alterations in the SWRCs and reduced the available water capacity (AWC) by 11.5%; the lowest dose of WA (1.5 Mg ha^{-1}) reduced K_s due to pore-clogging. In ES-O, changes were observed in the soil structure after application of BC (20 Mg ha^{-1}) and WA (9 Mg ha^{-1}) as well as after application of the N-enriched materials. However, no effects on available water content or saturated hydraulic conductivity were observed fifteen months after the treatments. Further field research is required to determine the soil specific, long-lasting effects of BC and WA on soil structure and soil hydraulic properties.

1. Introduction

Climate Change (CC) projections remain quite uncertain. However, southern Europe is expected to be affected by more irregular rainfall and longer dry periods in summer (IPCC, 2014). Such events would magnify the risk of drought and soil erosion, thus limiting forest growth and many other ecosystem services provided by forests. New management strategies are therefore needed to increase the resistance and adaptation of forest systems to CC and to maintain ecosystem functions such as water storage and biomass production.

In this context, the application to soil of energy co-products derived from forest biomass has been suggested as a CC mitigation and adaptation strategy (Lehmann and Joseph, 2009; Omil et al., 2011) that may also enable the targets of the Europe 2020 growth strategy (European Commission, 2010) to be met in relation to CC and energy sustainability. The energy stored in biomass can be released through combustion and used as a substitute for fossil fuels to generate energy; the wood ash produced during the process can also be returned to the soil to replace the nutrients exported by harvesting (Demeyer et al., 2001; Pitman, 2006). Biomass can also be pyrolysed for use in this circular economy framework. Pyrolysis of biomass yields a carbon-rich product called biochar that can increase carbon sequestration in soils and improve soil properties (Lehmann and Joseph, 2009; Sohi, 2012). The incorporation of wood-ash or biochar into soil may increase the resistance of soils to flooding and drought in forest ecosystems.

Soil water retention in combination with saturated hydraulic conductivity governs the rate of water flow through soils and determines the vulnerability of soil surface run-off. Several authors have reported that the application of ash to soils has positive effects on soil hydraulic properties, such as increased water holding capacity in coarse textured ash-amended soils (Pathan et al., 2003; Stoof et al., 2010), as well as improved water infiltration and root growth (Yunusa et al., 2006). Negative effects have also been observed, especially in wildfire-related studies, in which e.g. entrapped ash has been reported to cause pore

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clogging (Pitman, 2006; Woods and Balfour, 2010). Although studies of the effects of wood ash amendment on soil physical and hydraulic properties are scarce, Bodí et al. (2014) reviewed several studies conducted on burned ecosystems. Most research concerning wood ash application to forest soils have focused on soil chemical and nutritional status (Augusto et al., 2008; Demeyer et al., 2001; Pitman, 2006). The use of biochar to modify soil hydraulic properties has also been investigated (Ajayi et al., 2016; Jeffery et al., 2015). Some authors conclude that biochar may cause clay-rich soils to drain more rapidly and sandy soils to drain more slowly (Barnes et al., 2014; Hardie et al., 2014). Other authors concluded that biochar application improves soil water retention (Basso et al., 2013), especially in tropical soils (i.e. highly weathered, coarse-textured, acidic soils; Glaser et al., 2002). The effect is mainly attributed to higher porosity, surface area and sorption capacity relative to other types of soil organic matter (SOM) (Downie et al., 2009; Glaser et al., 2002). Yet other authors reported no consistent direct improvement derived from biochar application (Carvalho et al., 2014), or simply no effect (Jeffery et al., 2015). The above-mentioned findings clearly indicate that the effects of biochar or wood-ash on soil hydraulic properties depend on the type of soil. Soil hydraulic properties are important in determining the partitioning of precipitation between infiltration and overland flow, which affects water storage in the subsurface soil and thus plant available water. Understanding how both biochar and wood-ash influence the hydraulic properties of different soil types is essential. However, the use of sieved repacked soils in the study of soil physical characteristics is of particular concern. In trials with repacked soils, the soil structure, pore architecture and pore size distribution (and therefore field capacity, available water content, infiltration, hydraulic conductivity and drainable porosity values) are artefacts of the sieving and repacking processes and bear little resemblance to in situ soil properties. Studies conducted under field conditions are therefore needed in order to improve our understanding of this topic. Nonetheless, the findings may be highly variable, particularly in forest soils (Hendrayanto et al., 1999), which contain rock fragments, root systems and living organisms, as well as organic matter at different stages of decomposition (Ilek and Kucza, 2014).

If intense rainfall occurs in the future, soils with high hydraulic conductivity will be more capable of reducing run-off, erosion and field waterlogging. Moreover, if water availability is reduced in the future, soils with high water holding capacity will be more resilient. Considering these possibilities, the main objective of this study was to determine how the addition of a biochar or wood ash affected the hydraulic properties of two contrasting afforested soils.

2. Materials and methods

2.1. Study sites and experimental design

This study was conducted in experimental sites established in two forest plantations in the Atlantic region of the Iberian Peninsula. The sites mainly differed in relation to soil type (Table 1). The Karrantza experimental site (ES-K) was established in May 2012 in the eastern side of the Karrantza valley (UTM 30N ETRS 89_ 475081, 4786389) at 280 m a.s.l. This site comprises a *Pinus radiata* D. Don stand seed orchard established in 1996 with a planting distance of 6 × 6 m. The mean annual temperature was around 12 °C and mean annual precipitation around 1200 mm. Four replicates of each treatment (Table 2) were applied in individual plots (8 × 8 m) each including at least three pine trees. The second field trial was established one year later, in August 2013, in the Oiz experimental site (ES-O), on the southern slope of the Oiz Mountains (UTM 30N ETRS 89_ 532673, 4785,572) at 760 m a.s.l. The trial was established in a restored tree plantation of *Quercus pyrenaica* Willd. planted in 2012. The mean annual temperature was around 10 °C and mean annual precipitation around 1100 mm (Euskalmet, 2013). The wood ash and biochar were also applied at higher rates in ES-O (Table 2). Four replicates of each treatment were applied in 3 × 3 m plots, with a minimum buffer distance of 1 m between each. The experimental set-up is summarised in Table 2. Biochar and wood-ash were applied by top-dressing, i.e. by spreading the product on to the soil surface. It was assumed that the products would then be incorporated into the topsoil by natural processes.

Table 1
General characterization of the soil in each experimental site (ES-K and ES-O). Data show means and standard deviation in parenthesis, of different parameters at each experimental site.

	ES-K	ES-O
Soil class (Soil Survey Staff, 2014)	Typic Udorthent	Typic Dystrudept
Texture	Loam	Sandy loam
Sand (%)	36.8 (0.5)	67.9 (4.6)
Silt (%)	39.7 (1.2)	23.8 (1.9)
Clay (%)	23.1 (0.3)	8.3 (1.0)
SOC (%)	3.9 (0.4)	10.8 (3.3)
C:N	14.4 (1.2)	16.8 (1.6)
pH-H_2O	4.8 (0.2)	3.8 (0.01)

SOC: Soil organic carbon; C:N carbon and nitrogen ratio. Texture was measured by laser diffractometry, and total carbon and total nitrogen by a LECO TruSPEC® CHN-S elemental analyser. The TC provided a measure of SOC, considering TC equal to total organic carbon by the absence of carbonates in both soils.

Table 2
Schematic description of the experimental design. Environmental characteristics of each experimental site and treatments (type of amendment, treatment details and code).

Site	Amendment	Treatment	Code
	No addition	Control	Ctrl
ES-K			
P. radiata D. Don.	Biochar	10 Mg biochar ha^{-1} + 0.8% of N	BC(I)N
(20 yr)		10 Mg biochar ha^{-1}	BC(I)
Loamy texture		3.5 Mg biochar ha^{-1} + 0.8% of N	BC(L)
	Wood ash	4.5 Mg wood ash ha^{-1} + 0.8% of N	WA(I)N
		4.5 Mg wood ash ha^{-1}	WA(I)
		1.5 Mg wood ash ha^{-1}	WA(L)
ES-O			
Q. pyrenaica Willd.	Biochar	10 Mg biochar ha^{-1} + 0.8% of N	BC(I)N
(2 yr)		20 Mg biochar ha^{-1}	BC(H)
Sandy loam		10 Mg biochar ha^{-1}	BC(I)
texture	Wood Ash	4.5 Mg wood ash ha^{-1} + 0.8% of N	WA(I)N
		9 Mg wood ash ha^{-1}	WA(H)
		4.5 Mg wood ash ha^{-1}	WA(I)

BC: Biochar, WA: Wood ash; (L): Low dose, (I): intermediate dose, (H): high dose; N: nitrogen addition.

Biochar (BC) was produced by pyrolysis of *Miscanthus* sp. at 450 °C in a Pyreg® pyrolysis unit. The wood ash (WA) was produced by combustion of *Pinus radiata* D. Don harvest residues in a commercial boiler. The amounts of biochar and wood ash applied to the soil were equivalent in terms of the Calcium (Ca) content, considering a ratio of the Ca in WA to that in BC of 2.5. The calcium content of biochar and wood ash was balanced in order to generate similar liming effects as well as to equalize particle binding by Ca bridges and the clay flocculating potential (Wuddivira and Camps-Roach, 2007). The nitrogen (N) content of the enriched treatment for both co-products was the amount of ammonium nitrate relative to the 0.8% of the biochar applied. The main properties of the wood ash and biochar used in this study are shown in Table 3.

2.2. Soil sampling and processing

In each experimental site, 28 undisturbed soil cores (D = 53 mm, h = 50 mm) were sampled from the first 5 cm of soil profile (after