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Effects of charcoal hearth soil on forest regeneration: Evidence from a two-year experiment on tree seedlings

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ABSTRACT

Production of wood charcoal is a traditional form of forest use that lasted for millennia in most temperate regions, vanishing only some decades ago in the Mediterranean countries. Here, the abandoned charcoal hearths form a network of microhabitats with peculiar vegetation and soil conditions. Previous observational studies showed that establishment of woody species at these sites is severely hindered for unknown reasons. To test the effects of charcoal hearth soil on tree growth we used a common garden experiment with three major Euro-Mediterranean forest trees with different traits and ecology, one evergreen (*Quercus ilex,* holm oak) and two deciduous (*Fagus sylvatica*, beech, and *Quercus cerris*, Turkey oak). These were sown on control and charcoal-enriched soil collected in forest hearths abandoned since decades. Seed germination, seedling growth, photosynthetic efficiency and mortality were measured over a period of two years. Some responses were species-specific, while others were possibly associated to key traits such as evergreen vs. deciduous habit. Although charcoal soil effects were mainly positive on growth rate (height increase), they were mostly negative on germination of beech seeds, survival of holm oak seedlings, and photosynthetic efficiency. Although total biomass was not significantly affected, the root:shoot ratio was increased as a possible effect of physiological drought on hearth soil. These results support field-based evidence that the long persistence of charcoal remains in the soil may be not a favourable condition for forest regeneration. Management implications concern the use of biochar practices to promote forest restoration, which should be further tested on a wide range of species in different life-stages before applications in the field, also considering its long-term consequences.

1. Introduction

Traditional forms of land use have shaped ecosystems since the times of the first civilizations and still affect present-day soil properties also in forest habitats (Glatzel, 1991; Verheyen et al., 1999; Dupouey et al., 2002; Baeten et al., 2010). Via their influence on soil characteristics, past land uses have also deeply affected plant diversity, composition and structure of woodlands, especially in the Mediterranean region (Arianoutsou, 2001; Lloret and Vilà, 2003; Blondel, 2006; Bartha et al., 2008; Kopecký et al., 2013; Nocentini and Coll, 2013). The production of wood charcoal is among the oldest forms of human use in these forests. This existed since the Neolithic and continued for millennia in different continents (Montanari et al., 2000; Ludemann, 2003, Ludemann, 2010; Deforce et al., 2013) to be almost completely abandoned in the 19th century due to the rapidly increasing use of coal (Deforce et al., 2013). As a legacy of this widespread practice, a very high number of spots of charcoal-enriched soil remains nowadays in most European forests (Ludemann, 2011), especially in the Mediterranean countries where the activity lasted until a few decades ago (Blondel, 2006; Nocentini and Coll, 2013; Carrari et al., 2017, Mastrolonardo et al., 2018). Such spots, the so-called "charcoal hearth sites" (or charcoal kilns and charcoal kiln sites), still appear today as

Abbreviations: SR14, survival rate at the first year (2014); SR15, survival rate at the second year (2015); Fv/Fm, maximum quantum yield for primary photochemistry of dark-adapted samples; RB, root biomass; SB, shoot biomass; RSR, root:shoot biomass ratio; CHS, charcoal hearth soil; COS, control soil; *QI*, *quercus ilex* L.; *QC*, *quercus cerris* L.; *FS*, *fagus sylvatica* L.

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small, ovoid terraces (30–45 m^2) with flat surface and black-colored soil (Ludemann, 2003; Hardy et al., 2016; Kerré et al., 2016; Raab et al., 2017).

Previous studies in broadleaf woodlands showed that these sites have long-lasting legacy effects on soil properties and vegetation characteristics (Mikan and Abrams, 1995, 1996; Young et al., 1996; Wittig et al., 1999; Borchard et al., 2014; Raab et al., 2015; Hardy et al., 2016). Regardless of the abandonment time the soil is usually characterized by a distinct "charcoal layer" 10–80 cm deep (Mastrolonardo et al., 2018). In this layer, charcoal fragments in German sites were on average 2.6 times thicker than in the adjacent forest (Raab et al., 2017). In most studies, soil properties resulted deeply altered mainly due to the high content of both black and organic carbon (Borchard et al., 2014; Hardy et al., 2016). Despite a higher C:N ratio, the total N was also usually increased (e.g. Carrari et al., 2016a; Criscuoli et al., 2014). Moreover, cation exchange capacity per unit of organic carbon was higher than in the natural forest soil, even in sites older than 150 years (Hardy et al., 2016). Soil reaction was found to depend on the time since abandonment, with higher pH values in sites < 150 years old (e.g. Mikan and Abrams, 1996; Criscuoli et al., 2014) and lower values where the activity ceased at least 150 years ago, as in the Wallonian area (Hardy et al., 2016).

How changes in soil conditions influence forest vegetation in terms of composition, diversity and productivity is still not well understood. Regeneration of woody species on old charcoal sites was recently found to be affected in different forest types of the Mediterranean region (Carrari et al., 2016a,b), while contrasting results were found in Germany (Krause and Möseler, 1993; Wittig et al., 1999; Borchard et al., 2014) and North America (Mikan and Abrams, 1995; Young et al., 1996; Hart et al., 2008), possibly due to different soil types (Borchard et al., 2014). In the Mediterranean, positive or neutral effects were observed on the species richness and composition of young seedlings in the understorey (plant height < 1.30 m), depending on the forest type, while a strong decline of older individuals in the "established regeneration" layer (tree height of 1.3–4 m) was evident in all forest types (Carrari et al., 2016b). A similar detrimental influence on woody species was found in the old platforms of mixed oak-beech forests in eastern North America (Mikan and Abrams, 1995; Young et al., 1996). Overall, it appeared that the local conditions of charcoal sites severely hinder the recolonization processes that usually occur in forest gaps caused by natural events or other forms of human disturbance. However, the observational nature of these previous investigations did not allow to understand whether the causes for this blocked forest dynamics are connected to the soil conditions or other factors. At present, the only experiments about plant growth on soils enriched with charred wood remains were focused on the effects of biochar practices. Despite a large variability of responses, biochar is globally known to have mainly positive effects on plant growth due to improved chemical and physical characteristics of the soil (Baronti et al., 2010; Sohi et al., 2010; Vaccari et al., 2011). In agricultural systems, biochar treatments were found to increase water availability and ameliorate structure and formation of soil aggregates (Lehmann and Joseph, 2009) enhancing nitrogen availability (Rondon et al., 2007; DeLuca, 2009; Nelissen et al., 2012, 2015) and slowing down the release of nutrients (Yanai et al., 2007, Kammann et al., 2015), due to the organic coating formation (Hagemman et al., 2017).

Largely positive effects were also observed in forest biochar experiments, in which woody plants responded with a mean biomass increase of 41% (Thomas and Gale, 2015). However, these are in contrast with the mostly negative effect of charcoal sites on the establishment and growth of trees observed in the field in Italy (Carrari et al., 2016a,b) and North America (Mikan and Abrams, 1995, 1996). Such discrepancy may also point to factors associated with other properties of the charcoal hearth soil, rather than the accumulation of pyrogenic charcoal *per se*. These include the cascading effects of repeated slash pile and wood burning on the soil structure and chemical properties (Oswald et al., 1998) with consequent negative impact on the arbuscular mycorrhizal fungi (Korb et al., 2004) and microbial communities (Jiménez Esquilín et al., 2007), or the presence of potentially harmful soluble salts that may cause physiological drought (Mikan and Abrams, 1995). In addition, other "external" factors may contribute to the difficult establishment of woody species on charcoal platforms, such as heavy ungulate pressure that use these as preferential resting and grazing sites, or human disturbance as they are often located along old forest tracks (Carrari et al., 2017).

To understand the effect of hearth soil on the early stages of tree growth separately from those of the potential confounding factors above, we performed an ex-situ common garden experiment based on the two-years cultivation of three major forest species on hearth and control soil from their respective forest sites. Hence, this work aims at better understanding whether the hearth soil by itself acts as stress factor for tree regeneration at the early stages of growth, which is relevant before investigating the specific chemical, physical or biological properties of this substrate that cause the observed effects. Specifically, we examined the effect on the following processes: i) seed germination, ii) seedling mortality, iii) growth of seedlings in terms of height and above and below-ground biomass, and iv) photosynthetic efficiency of the seedlings.

2. Material and methods

2.1. Study species

We selected the most representative tree species of the three main forest types historically used in Tuscany for charcoal production: (1) the holm oak (*Quercus ilex* L. – *QI*) for evergreen sclerophyll forests of the Mediterranean coastal belt, (2) the Turkey oak (*Quercus cerris* L. – *QC*) for thermophilous deciduous forests of the internal hill belt, and (3) the beech (*Fagus sylvatica* L. – *FS*) for the montane belt forests. The sampling sites were located in the northern Apennines and in the area of Colline Metallifere in central Tuscany; main geographical and environmental features of the sites are given in Table 1. For each species, around 1000 healthy seeds were collected in autumn 2013 under two mother trees growing in close proximity of a charcoal hearth in the respective forest type.

2.2. Common garden set-up

In the same spot of seed collection, a representative and well preserved charcoal hearth platform repeatedly used until 50–60 years ago for wood charcoal production (supposedly at time intervals of 10–20 years) was selected in each forest type for collection of soil

Table 1
Main geographical and environmental variables of the sampling sites in Tuscany; *Quercus ilex* (*QI*), *Quercus cerris* (*QC*), *Fagus sylvatica* (*FS*).

	Geographic area	Locality	Forest type	Lat	Long	Altitude m a.s.L.	Parent rock material	Soil type
QI	Colline Metallifere	Val di Farma	evergreen sclerophyll	43° 4′21.54″N	11°16′43.20″E	508	Quarzitic sandstone	*Cambisol*
QC	Colline Metallifere	Val di Farma	thermophilous deciduous	43° 4′21.60″N	11°16′17.64″E	484	Quarzitic sandstone	*Cambisol*
FS	N Apennines	Colla di Casaglia	beech forests	44° 3′5.46″N	11°26′18.54″E	989	Siltitic sandstone	*Cambisol*