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Temperature and source material influence ecological attributes of ponderosa pine and Douglas-fir charcoal

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Abstract

Charcoal has numerous physical and chemical properties that allow it to influence a variety of ecological processes. The objective of this study was to evaluate how several ecological properties of charcoal vary as a function of formation temperature and the source of woody material from which it is formed in ponderosa pine/Douglas-fir (*Pinus ponderosa/Psuedotsuga menziesii*) ecosystems. We generated charcoal in the laboratory at two temperatures (350 and 800 °C) and from four source materials (bark and wood from mature Douglas-fir and ponderosa pine trees), collected in western Montana. In an incubation experiment, where soils were amended with charcoal and glycine, all charcoal types resulted in higher rates of net ammonification relative to the no-charcoal control, and all charcoal types (except 800 °C ponderosa pine bark) increased net nitrification rates relative to the control. All charcoal types were also effective at sorbing catechin (±), an allelochemical produced by the invasive species *Centaurea maculosa*; however, higher temperature charcoals had a higher sorption capacity. High temperature charcoals also demonstrated higher extractable NO_3^-, pH, electrical conductivity, total C content; whereas, soluble and total phenol concentrations, extractable PO_4^{3-} and NH_4^+, and density were lower in high temperature char relative to low-temperature charcoal. The species (ponderosa pine or Douglas-fir) and material (wood or bark) from which charcoal formed also resulted in variation in several properties; however, this variation was of minor importance relative to differences caused by temperature, and thus is likely a less significant source of variation in natural systems. These data suggest that charring temperature, which may be correlated with fire severity during fire events, is likely the greatest source of variability in these charcoal properties in the ponderosa pine/Douglas-fir ecosystem.
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Keywords: Ponderosa pine; Douglas-fir; Charcoal; Fire; N cycling; Allelopathy; Catechin

1. Introduction

Charcoal is a highly recalcitrant by-product of fire and has recently been shown to influence a variety of ecological processes and to enhance soil fertility. These effects include: sorption of dissolved organic matter from the soil solution (Zackrisson et al., 1996; Wardle et al., 1998; Glaser et al., 2002); sorbtion of allelochemicals resulting in reduced competitive dominance of some late successional species (Zackrisson et al., 1996; DeLuca et al., 2002; Berglund et al., 2004; Hille and den Ouden, 2005; Keech et al., 2005); enhanced N turnover (DeLuca et al., 2006); contribution of nutrients such as NH_4^+, NO_3^-, and PO_4^{3-} (Glaser et al., 2001, 2002); and modification of soil properties such as pH and cation exchange capacity that may increase nutrient availability in forest soils (Glaser et al., 2001, 2002; Belangér et al., 2004).

Charcoal is likely highly variable in natural ecosystems and may result in substantial variation in these ecological effects. Two factors that likely generate substantial variability in charcoal properties are formation temperature and the type of material from which charcoal is formed (Glaser et al., 2002; Keech et al., 2005). Temperature may affect charcoal by volatilizing certain elements and organic molecules, while concentrating those that remain, resulting in a different chemical composition in high and low-temperature charcoal. Source material may also influence properties of charcoal because lignified materials, such as wood and bark, likely have different chemistries and physical structures (Bold et al., 1987). For instance, a simple difference in tracheid diameter between the wood of two species may determine the surface area, and thus sorption

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capacity, of charcoal generated from these substrates (Keech et al., 2005).

Differences in charcoal properties caused by temperature and source material may have important ecological significance (Keeley et al., 1985; Jäger et al., 1996), although this has rarely been investigated. In the ponderosa pine/Douglas-fir ecosystem of the inland western United States, it is recognized that fire frequency and intensity has significantly changed following Euro-American settlement (Arno, 1980; Barrett and Arno, 1982; Arno et al., 1995; Fulé et al., 1997; Mast et al., 1999; Moore et al., 1999). Historically, fire return intervals were more frequent, less intense, and promoted dominance of large diameter ponderosa pine. This fire regime also prevented widespread dominance of low elevation Douglas-fir, a less fire tolerant species. Exclusion of fire from this system has led to increased stand densities, increased dominance of Douglas-fir, and an increased risk of high-intensity stand-replacing wildfire (Arno, 1980; Barrett and Arno, 1982; Arno et al., 1995; Fulé et al., 1997; Mast et al., 1999; Moore et al., 1999). These changes in fire intensity and forest species composition may correspond with a shift in physical and chemical properties of charcoal generated in the system. The objective of this study, therefore, was to evaluate whether (1) temperature and (2) source material would cause any differences in several charcoal properties that may influence soil fertility and various ecological processes.

2. Methods

The charcoals we evaluated were generated from ponderosa pine and Douglas-fir bark and wood. These substrates were selected because their relative input into the forest charcoal pool in ponderosa pine forest ecosystems of the northwestern United States has likely changed dramatically in the last century due to changes in forest composition. Additionally bark is commonly charred on trees during non-lethal low-intensity fire, whereas high-intensity fire often results in tree death and charring of wood. Thus, the relative contribution of wood as compared to bark charcoal may have changed as a result of a shift towards more intense fires currently observed in this system. Further, we compare the influence of temperature on charcoal by generating charcoal at two temperatures, 350 and 800 °C, which represent lower and upper thresholds for charcoal formation (Glaser et al., 2002). These temperatures may reflect differences in charcoal formation conditions during historical low-intensity wildfires and current high-intensity wildfires (Neary et al., 1999).

We collected wood and bark samples from five ponderosa pine and five Douglas-fir trees within a two ha area at the University of Montana, Lubrecht Experimental Forest, western Montana. Samples were cut from stumps of trees between 50 and 100 years of age that were harvested 2 years earlier. We generated charcoal in a muffle furnace (Barnstead Thermolyne 62730, Barnstead International, Dubuque, Iowa) by burying 2–3 cm^3 pieces of wood or bark in clean silicate sand and heating at 350 or 800 °C for 2 h.

2.1. Nitrogen mineralization and nitrification

The influence of charcoal samples on net ammonification and nitrification rates was estimated through a 14-day incubation experiment. Treatments were established by amending a western Montana forest soil with each type of charcoal. The forest soil was collected in October 2004 from the subsurface horizon (20–30 cm, B_w Horizon) of a forest soil associated with a low elevation (1100 m) ponderosa pine/Douglas-fir vegetation in western Montana. The soil is described as a sandy-skeletal, mixed, frigid Typic Dystrustept. This system is characterized by low annual rainfall (<35 cm annually) with approximately 50% falling as snow during the winter months. Soils were immediately returned to the lab, where they were sieved (4 mm) and homogenized. We then added one part sand to three parts field moist soil (by mass) to increase porosity and gas exchange, such that nitrification would not be limited by low O_2 availability. The sand fraction was obtained by purchasing filter grade silica sand (for pool filters), and was washed with 1 M HCl, followed by distilled water, prior to homogenization with field collected soil. This sand amended soil had a pH of 6.8, electrical conductance of 91.2 μS, and had a textural distribution of 71% sand, 21% silt and 8% clay (sandy loam). Treatments were established by adding two percent (by mass) charcoal that was ground to a fine powder to this soil, which represents a realistic charcoal concentration in forest ecosystems (Zackrisson et al., 1996). A no-charcoal control was also established to assess background levels of net ammonification and nitrification. We added 150 g of each soil treatment to 1 l mason jars ($n = 5$), and brought their water content to approximately 60% water holding capacity. Glycine was added to all mason jars during this water addition at a rate of 500 mg kg^{-1} soil to provide a large source of highly labile organic N that would stimulate rapid N turnover. Soils were incubated for 14 days at 25 °C, upon which samples were extracted in 2 M KCl. Amino N, NH_4^+, and NO_3^- were measured from these extracts using the ninhydrin method (Moore, 1968), the Berthelot reaction (Willis et al., 1993) and the cadmium reduction method (Willis and Gentry, 1987), respectively.

2.2. Sorption of an allelochemical

Sorption of catechin, a recently identified allelochemical in spotted knapweed (*Centaurea maculosa*) (Bais et al., 2003), was measured by placing 1 g of charcoal powder in a 50 ml solution of 200 ppm catechin (±) (Sigma Chemicals), delivering 10 mg catechin g^{-1} charcoal. This solution was shaken for 24 h, and filtered. Catechin concentration was measured on these extracts using the Prussian blue method with catchein (±) as a standard (Stern et al., 1996).

2.3. Charcoal chemical properties

Numerous physical and chemical analyses were conducted to determine variability among charcoal samples. With the exception of density, all analyses were conducted on charcoal samples that were crushed to a fine powder in a shatterbox. Charcoal pH was measured from a 4:1 slurry of deionized water

to charcoal. Electrical conductance (EC) was measured from charcoal paste (2:1 distilled water and charcoal). Cation exchange capacity (CEC) was estimated on charcoal samples using an NH_4^+ replacement method (Schollenberger and Simon, 1945), where 1 g of charcoal was rinsed twice with 25 ml of 1 M NH_4OAc (pH 7) to saturate exchange sites. Excess saturating solution was removed from charcoal samples with three consecutive washes with 25 ml of 95% ethyl alcohol. Sorbed NH_4^+ was then extracted with 25 ml of 2 M KCl and analyzed on a segmented flow analyzer (Auto Analyzer III, Bran Luebbe, Chicago, IL) using the Berthelot reaction (Mulvaney, 1996). Charcoal density was estimated by measuring dry mass of intact charcoal pieces (2–3 cm^3) and measuring volume displacement in deionized water.

Extractable NH_4^+ and NO_3^- were measured by placing 1 g of charcoal in 25 ml 2 M KCl, shaking for 30 min, and then filtering through Whatman #2 filters. The extracts were analyzed for NH_4^+-N using the berthelot reaction and NO_3^--N by the cadmium reduction method (Mulvaney, 1996) on a segmented flow analyzer (Auto Analyzer III, Bran Luebbe, Chicago, IL). Soluble PO_4^{3-} was measured by placing 1 g of charcoal in 25 ml of 0.01 M $CaCl_2$ for 30 min. Extracts were filtered through Whatman #42 filter paper and then analyzed on a segmented flow analyzer using the molybdate method as described by Kuo (1996).

Total C was measured via dry combustion on a Fissions Elemental Analyzer (EA 1100, Milano, Italy). Soluble and total phenols were measured by extracting 1 g of ground charcoal in 25 ml of deionized water and 50% methanol, respectively, and were analyzed using the Prussian blue method (Stern et al. 1996).

2.4. Statistical analysis

Most variables (11 of 14) did not meet assumptions of normality or heteroscadasticity, and could not be transformed to meet these assumptions, and thus were analyzed using a Kruskal–Wallis test. A few variables (3 of 14 variables) met these assumptions, and were compared using a one-factor ANOVA, followed by the Student–Newman–Keuls (SNK) post hoc procedure. Letters are used in figures to indicate pairwise differences identified through SNK analysis. All statistical comparisons were conducted using SPSS version 11.0.

3. Results and discussion

3.1. Nitrogen mineralization and nitrification

Several studies have shown that charcoal can significantly increase net N turnover, with particular emphasis on nitrification rates (Zackrisson et al., 1996; DeLuca et al., 2002, 2006; Berglund et al., 2004). Our data further supports these studies by demonstrating that all charcoal types resulted in increased net ammonification rates relative to the no-charcoal control, and all but one charcoal type (800 °C ponderosa pine bark) increased net nitrification rates relative to the control (Fig. 1). This suggests that charcoal formed under a variety of temperature conditions and from a variety of source materials may enhance soil N turnover in natural systems. There were no clear differences in net ammonification and nitrification rates between charcoal treatments that could be attributed to formation temperature or source material.

The specific mechanisms by which charcoal influences net ammonification and nitrification rates is not clear. Charcoal may sorb organic molecules with a high C:N ratio, leading to lower N immobilization rates and thus higher ammonification rates during decomposition. It is also possible that charcoal adsorbed residual allelopathic compounds present in the forest soil used in this incubation experiment. This soil was collected from beneath a ponderosa pine stand, a tree species known to produce litter rich in phenol and terpene based compounds with allelopathic properties (Lodhi and Killingbeck, 1980; White, 1991, 1994). Alternatively, the porous structure of charcoal could have provided safe sites in which soil heterotrophic and nitrifying bacteria were able to more safely operate.

3.2. Sorption of an allelochemical

Charcoal may influence belowground processes and plant-plant interactions by adsorbing compounds inhibitory to plants

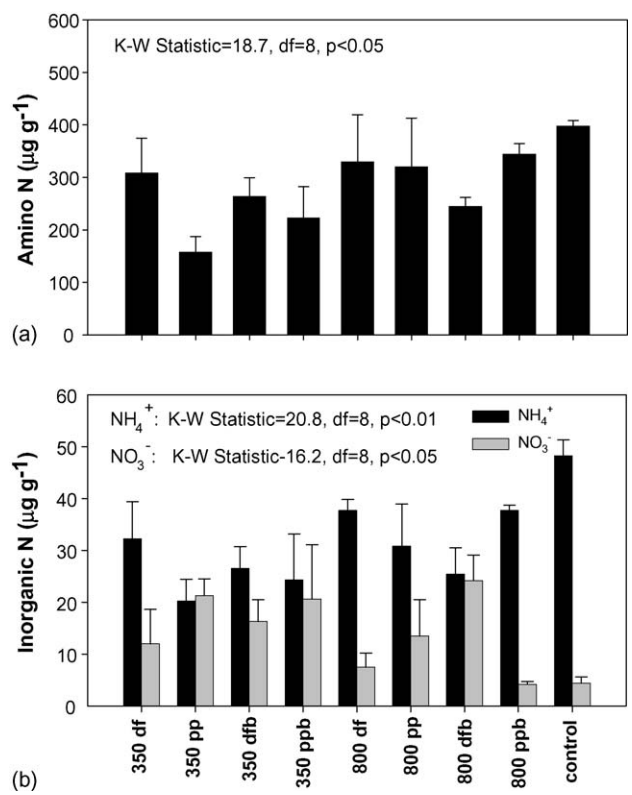

Fig. 1. Mean (S.E.) (a) amino N (b) and inorganic N (NH_4^+ and NO_3^-) following a 14-day incubation experiment where glycine was added as a labile organic N source. Soils were amended with charcoal made from Douglas-fir and ponderosa pine wood and bark (Douglas-fir wood, Douglas-fir bark, ponderosa pine wood, and ponderosa pine bark, respectively) at low (350 °C) and high (800 °C) temperatures. The control soil received no-charcoal amendment. Data meeting assumptions of normality were compared using a one-way ANOVA, followed by the Student–Neuman–Kuels post hoc procedure, where letters indicate pairwise differences. Non-normal data were compared using the Kruskal–Wallis test.

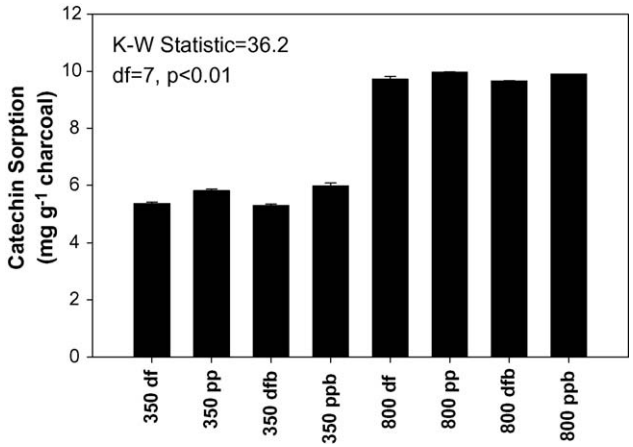

Fig. 2. Mean (S.E.) catechin (±) sorption of charcoal made from Douglas-fir and ponderosa pine wood and bark (Douglas-fir wood, Douglas-fir bark, ponderosa pine wood, and ponderosa pine bark, respectively) at low (350 °C) and high (800 °C) temperatures. Catechin (±) was prepared as a 200 ppm solution, and a total of 10 mg was shaken with 1 g of charcoal. Data were compared using the Kruskal–Wallis test.

or microorganisms. These allelochemicals may have entered the soil solution from throughfall, litter leachate, or root exudation, and are likely most biologically active when dissolved in the soil solution. This effect has been observed in both greenhouse (Callaway and Aschehoug, 2000; Hille and den Ouden, 2005; Keech et al., 2005) and field experiments (Nilsson et al., 2000). Catechin, a biphenol molecule, is a root exudate identified in many plant species. The negative isomer of catechin has been identified as a root exudate of spotted knapweed (*C. maculosa*) (Bais et al., 2003), an invasive species in the western United States, and has been shown to have strong allelopathic effects on several native western plant species. Our data indicate that all charcoals types had a high capacity to adsorb catechin (±) from solution (>5 mg catechin g^{-1} charcoal); however, high temperature charcoals demonstrated a higher sorption capacity compared to low-temperature charcoals (Fig. 2). Ponderosa pine wood and ponderosa pine bark charcoal also had a higher capacity to sorb catechin (±) than Douglas-fir wood and Douglas-fir bark at both temperatures, but these differences were minor compared to those caused by temperature. Higher sorptivity of ponderosa pine charcoal may be caused by its larger tracheid diameter than Douglas-fir (Piñol and Sala, 2000), which likely equates to a higher surface area charcoal with greater sorption capacity.

Hille and den Ouden (2005) recently proposed that the ability of natural charcoal to sorb allelochemicals has likely been overstated because several studies that have demonstrated this effect have used activated carbon rather than natural charcoal. In support of their hypothesis, Hille and den Ouden (2005) demonstrated a much higher capacity of activated carbon to alleviate allelopathic inhibition of Scotch pine (*Pinus sylvestris*) seeds compared to a low-temperature (450 °C) ''natural'' charcoal. Our data, however, suggest that there is likely a high degree of variation in the sorptivity of natural charcoal in forest ecosystems, and that charcoals formed at temperatures higher than 450 °C, as used by Hille and den Ouden (2005), are likely to be more effective in sorbing

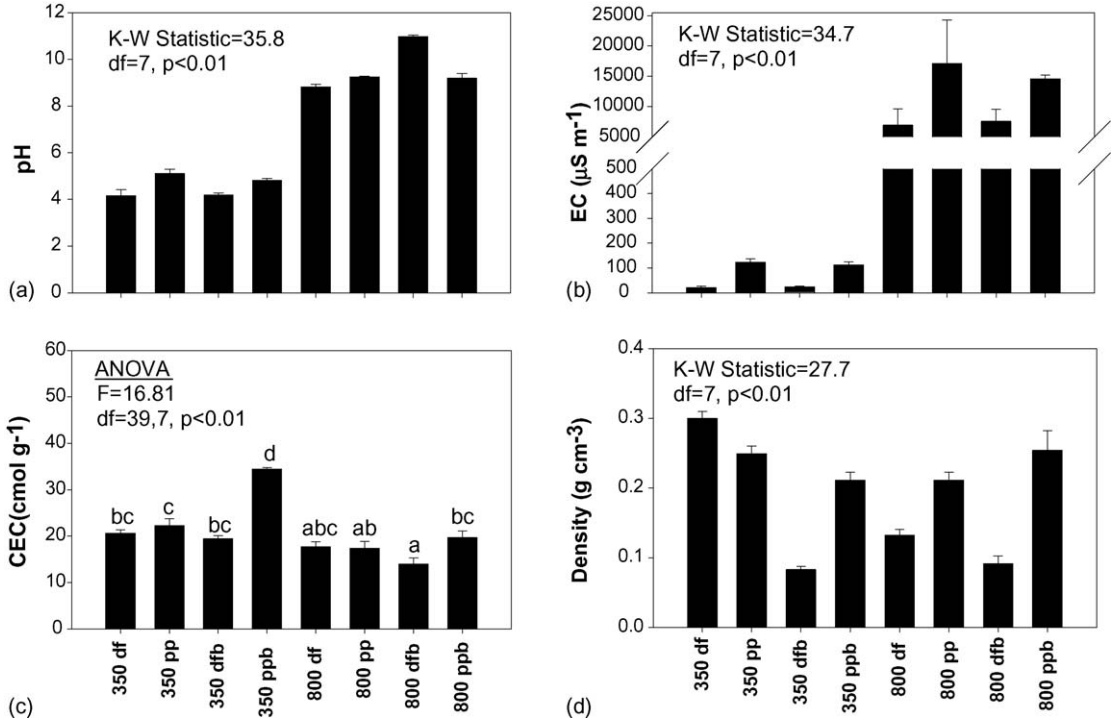

Fig. 3. Mean (S.E.) (a) pH (b) electrical conductivity (c) cation exchange capacity (d) and density of charcoal made from Douglas-fir and ponderosa pine wood and bark (Douglas-fir wood, Douglas-fir bark, ponderosa pine wood, and ponderosa pine bark, respectively) at low (350 °C) and high (800 °C) temperatures. Data meeting assumptions of normality were compared with one-way ANOVA, followed by the Student–Neuman–Kuels post hoc procedure, where letters indicate pairwise differences. Non-normal data were compared using the Kruskal–Wallis test.

allelochemicals. A high capacity of natural charcoals to sorb allelochemicals may contribute to a high degree of biodiversity observed in some fire maintained ecosystems or charcoal amended agroecosystems (Glaser et al., 2001) by diminishing the competitive dominance of allelopathic species. This effect may occur for years or decades, and then diminish as the sorption capacity of charcoal becomes saturated (Zackrisson et al., 1996).

3.3. Charcoal chemical properties

High temperature (800 °C) charcoal demonstrated higher pH, electrical conductivity, total C, and extractable NO_3^- relative to low-temperature (350 °C) charcoal; whereas, density, extractable PO_4^{3-}, NH_4^+, and soluble and total phenols were lower in high temperature charcoals relative to low-temperature charcoals (Figs. 3–5). Several variables also demonstrated clear differences that could be attributed to either species (ponderosa pine or Douglas-fir) or material (wood or bark), including EC, density, extractable PO_4^{3-}, NH_4^+, and NO_3^-, and soluble phenols; however, these differences were minor relative to differences caused by temperature for nearly every variable.

Many of the differences described above are likely a function of volatilization temperatures of different elements present in wood and bark or tissue composition differences between the source materials. Nitrogen, P, S, C, O, and H are elements that begin to volatilize at temperatures below 800 °C (Wright and Bailey, 1982; Neary et al., 1999), and likely account for a substantial portion of lost mass (i.e. lower density) from wood and bark during charring (Fig. 1). In contrast, alkaline metals (Ca^{2+}, K^+ and Mg^{2+}) volatilize at much higher temperatures than 800 °C and are thus likely to become more concentrated in high temperature charcoals (Belangér et al., 2004). The relative concentration and molecular speciation of these elements during heating can explain many of the differences caused by charring temperature.

High temperature charcoals consistently demonstrated a higher pH compared to lower temperature charcoals (Fig. 3). This higher pH is likely the result of the accumulation of oxides of alkaline metals. It is unlikely that the alkalinity associated with high temperature charcoal has a significant effect on the pH of forest soils because of their relatively small input relative to the large buffering capacity of most forest soils. A much greater source of alkalinity associated with forest fire is the white ash residue that is created when organic materials are more completely oxidized during combustion. Charcoal, however, may create high pH microsites within its porous structure that enhance processes such as nitrification, which are known to be inhibited under low pH conditions (Alexander, 1991).

As with pH, EC was several orders of magnitude higher in the high temperature charcoal than in the low-temperature charcoal. This further indicates that an ash residue containing soluble salts accumulates in the pore spaces of high temperature charcoal. Electrical conductivity of ponderosa pine charcoal was consistently higher than Douglas-fir for both substrates and

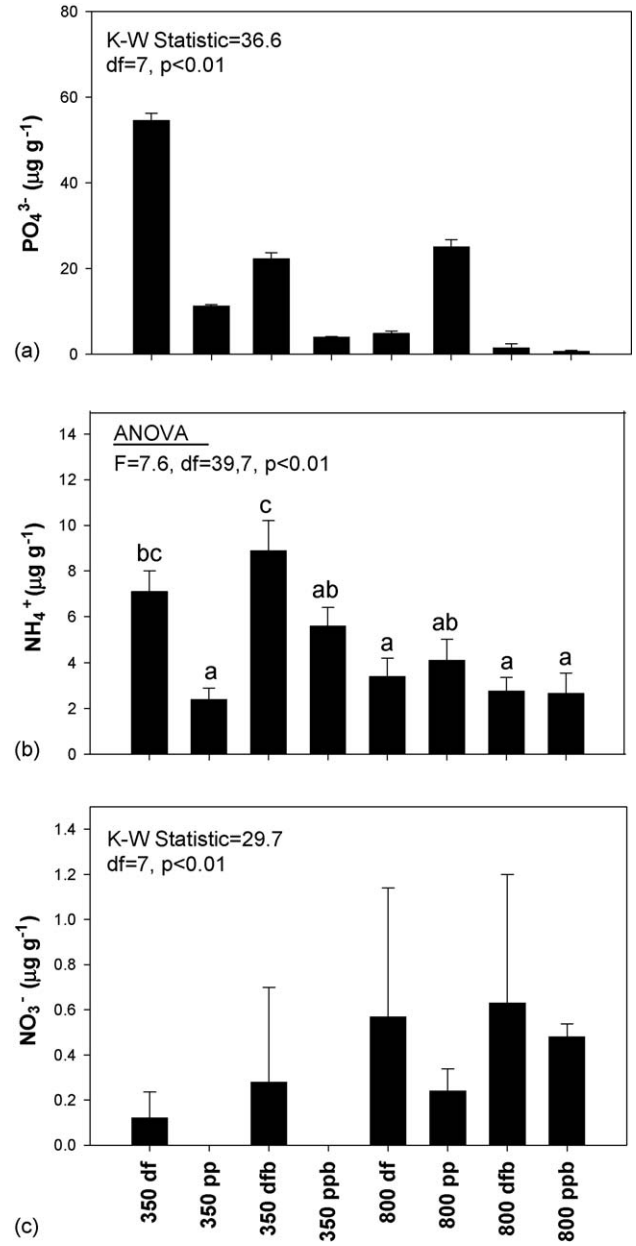

Fig. 4. Mean (S.E.) (a) extractable PO_4^{3-} (b) extractable NH_4^+ (c) and extractable NO_3^- of charcoal made from Douglas-fir and ponderosa pine wood and bark (Douglas-fir wood, Douglas-fir bark, ponderosa pine wood, and ponderosa pine bark, respectively) at low (350 °C) and high (800 °C) temperatures. Data were compared using the Kruskal–Wallis test.

temperatures (Fig. 3). This is likely a function of higher soluble salt accumulation in ponderosa pine charcoal that may occur as a function of differences in tissue composition between the species.

The cation exchange capacity of all charcoals appeared to be high relative to the CEC reported for many forest soils (Fisher and Binkley, 2000), suggesting that charcoal has the potential to contribute a significant amount of exchange capacity to forest soils (Fig. 3). This finding is supported by Glaser et al. (2002), who reported high CEC of charcoals made at a variety of temperatures and from a variety of materials. Although there were numerous significant differences in CEC among the

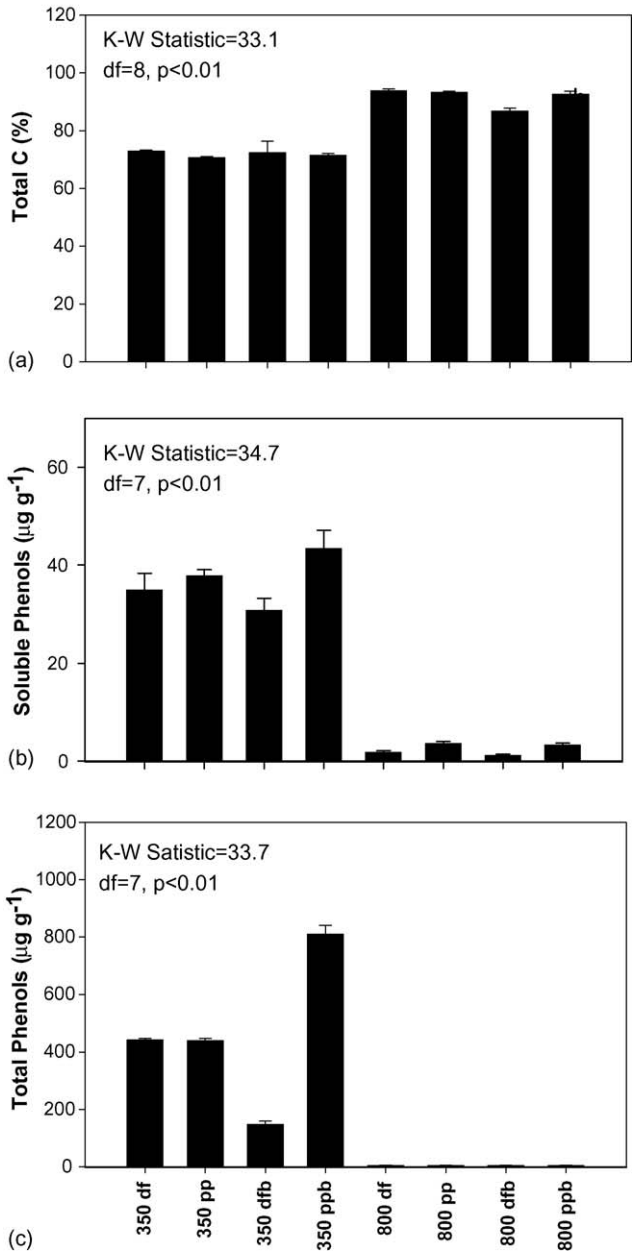

Fig. 5. Mean (S.E.) (a) total C (b) soluble phenols (c) total phenols of charcoal made from Douglas-fir and ponderosa pine wood and bark (Douglas-fir wood, Douglas-fir bark, ponderosa pine wood, and ponderosa pine bark, respectively) at low (350 °C) and high (800 °C) temperatures. Data meeting assumptions of normality were compared with one-way ANOVA, followed by the Student–Neuman–Kuels post hoc procedure, where letters indicate pairwise differences. Non-normal data were compared using the Kruskal–Wallis test.

charcoal samples, there were no clear differences that could be attributed to temperature, species, or source material (bark or wood).

Density of ponderosa pine wood and ponderosa pine bark charcoal was higher than Douglas-fir wood and Douglas-fir bark charcoal at both temperatures, except for 350 °C wood charcoal, where Douglas-fir was denser (Fig. 3). The noticeably lower density of Douglas-fir bark compared to ponderosa pine bark charcoal did not appear to be a function of oxidation or volatilization, but rather an abrupt swelling of Douglas-fir bark that occurred upon heating. This bark swelling could be an evolutionary adaptation of Douglas-fir to avoid thermal damage to its cambial tissue during fire events. It is unclear whether density differences between charcoal types has any ecological significance; however, low density charcoals may have a higher surface area per unit volume on which chemical and biological reactions can occur.

The low concentration of PO_4^{3-} and NH_4^+ in high temperature charcoal was also likely a function of their volatilization temperatures (Fig. 4). Amine bonds begin cleaving at relatively low temperatures (Neary et al., 1999), resulting in free NH_4^+ molecules on the surface of charcoal. At least some of this NH_4^+ appears to oxidize into NO_3^- (and NO_x gasses not measured), as suggested by the higher NO_3^- concentrations on high temperature charcoals. Phosphorous begins to volatilize around 600 °C (Prichett and Fisher, 1987). It appears that for most charcoal types, there is very little soluble P remaining after heating to 800 °C, as suggested by the low PO_4^{3-} concentrations extracted from high temperature charcoals. These data suggest that lower temperature charring results in less nutrient loss, and higher nutrient availability relative to high temperature charcoal.

A substantial amount of variation in extractable PO_4^{3-}, NH_4^+, and NO_3^- that existed among charcoal types also appeared to be a function of the species from which charcoal was made. Douglas-fir wood and Douglas-fir bark charcoal yielded more extractable PO_4^{3-}, NH_4^+, and NO_3^- at 350 °C (Fig. 4) than ponderosa pine wood or ponderosa pine bark; however, these differences disappeared at higher temperatures. This likely reflects a higher N and P content in Douglas-fir tissues relative to ponderosa pine, a difference which disappears due to volatilization of N and P at higher temperatures.

In addition to directly adding nutrients to soils, the C content, quality, and availability in charcoal may indirectly influence nutrient availability in natural systems by stimulating nutrient immobilization or by having a toxic effect on microbes or plant roots (Fritze et al., 1998; Villar et al., 1998). Our data clearly show that the total C content of higher temperature charcoals was consistently higher than lower temperature charcoals, suggesting that as temperature increases, N, P, S, H, and O volatilization increases disproportionately to C volatilization (Fig. 5), thus increasing the total C concentration in charcoal. The increased C content of charcoal with increasing temperature is likely a function of the low O_2 conditions under which charcoal formed, preventing complete C oxidation.

Lignin is a component of wood and bark that is resistant to decomposition in natural systems (Fisher and Binkley, 2000). Because lignin is highly recalcitrant, the concentration of phenol (a monomer of lignin) extracted from charcoal is indicative of lignin breakdown. Because other components of wood, such as cellulose and hemi-cellulose are more easily degraded than lignin (Fisher and Binkley, 2000), the phenol concentration of charcoal also likely reflects the majority of bio-available carbon left in the material after heating. Our results clearly show that higher temperatures reduce both soluble and total phenol C content (Fig. 5), suggesting that the

higher C content in high temperature charcoal is primarily in a highly recalcitrant form that is not readily bio-available. The data also show a relatively minor species effect, where ponderosa pine wood and ponderosa pine bark had a higher soluble phenol content at both temperatures than Douglas-fir wood or Douglas-fir bark. This species effect did not exist for the total phenol content of each charcoal.

The higher phenol concentration of low-temperature charcoals may have several ecological implications. Phenolic compounds, which are not readily available and resistant to decay in wood or bark prior to charring, may act as a high C:N carbon source for soil microbes, and thus stimulate N immobilization (Schimel et al., 1996). Although, this effect is likely to be minor compared to uncharred wood or bark, where lignin and cellulose are highly abundant and the C:N is clearly in a range that would cause net immobilization of soil inorganic N. The high concentration of soluble phenols on low-temperature charcoal may also be toxic to plant roots and some microbes (Fritze et al., 1998; Villar et al., 1998), and thus might reduce nutrient uptake by plants.

4. Conclusions

The results of this study clearly demonstrate that the physical and chemical properties of charcoal, and the potential influence of charcoal on the soil environment, are directly linked to the temperature under which the charcoal was formed and to a lesser degree, the origin of the charred material. The incubation experiment, where soils were amended with charcoal and glycine, demonstrated that charcoal has the capacity to increase net soil N transformations. This supports previous studies and further demonstrates that increased net N transformations occur in the presence of all charcoal types studied in this experiment. Because charcoal is highly recalcitrant, its positive influence on N cycling may delay the gradual slowing of N transformations frequently reported in the ponderosa pine ecosystems. All charcoals, especially high temperature charcoals, were also found to be highly effective at sorbing an organic compound with allelopathic properties. This also supports previous studies and suggests that the accumulation of charcoal in forest soils may reduce the competitive advantage of some allelopathic species by providing safe rooting space for species vulnerable to allelopathic interference. Our results also demonstrate that charcoal is a source of extractable nutrients (NH_4^+, NO_3^-, and PO_4^{3-}), bio-available carbon, cation exhchange capacity, and further, may influence the pH and electrical conductivity of forest soils. Assuming a frequently reported concentration of 2000 kg ha^{-1} of charcoal in forest soils (Zackrisson et al., 1996; DeLuca et al., 2006), this is not likely a substantial nutrient contribution to forest soil nutrient pools. However, charcoal may create microsites in forest soils with high nutrient content, nutrient turnover, and biological activity, which may persist on the scale of years to decades following fire (Zackrisson et al., 1996). Variation in almost all chemical properties of charcoal appeared to be much greater as a result of temperature of charcoal formation rather than source material. This suggests that high-intensity fire may generate charcoal with an array of chemical properties that are different from charcoal formed during low-intensity fire. Further studies are required to determine whether this degree of variation exists naturally, and whether variation in these charcoal properties lead to corresponding variation in soil processes and plant communities.

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