<u>**Biochar -- Annotated Bibliography**</u>

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Abel, S., A. Peters, S. Trinks, H. Schonsky, M. Facklam, and G. Wessolek. 2013. Impact of biochar and hydrochar addition on water retention and water repellency of sandy soil. Geoderma 202–203:183–191.

Available water capacity; biochar; hydrochar; water repellency; water retention characteristics

German study looking at the effect of biochar and hydrochar on water retention and water repellency for different soils in packed soil columns and in the field. The soils used consist of a sand from a Arenic Regosol, a sand and loamy sand from an agricultural Haplic Luvisol, and a loamy sand from a former sewage farm site. The biochar feedstocks consisted of maize and beechwood, and the hydrochar was produced from maize silage. Both amendments increased available water capacity and decreased bulk density.

Adams, M.M., T.J. Benjamin, N.C. Emery, S.J. Brouder, and K.D. Gibson. 2013. The Effect of Biochar on Native and Invasive Prairie Plant Species. Invasive Plant Science and Management. 6:97–207.

Black carbon; carbon sequestration; competition; prairie restoration; replacement series

Greenhouse experiment growing big bluestem and sericea utilizing biochar produced from loblolly pine and switchgrass applied at four different rates, with or without Nitrogen fertilizer. Native prairie soils consist of a Mahalasville series (sandy loam, mixed, superactive, mesic Typic Argiaquolls) and a Sawabash series (fine silt clay loam, mixed, superactive, calcareous mesic Cumulic Endoaquolls). The study found that the biochar had more effect on vegetation growth in the sandy soil with increased growth on big bluestem, but no increase in the growth of sericea.

Ball, P. N., M.D. MacKenzie, T.H. DeLuca, and W.E. Holben. 2010. Wildfire and charcoal enhance nitrification and ammonium-oxidizing bacteria abundance in dry montane forest soils. Journal of Environmental Quality 39:1243-1253.

Ammonia-oxidizing bacteria; charcoal; Douglas-fir; nitrification; *Pinus ponderosa*; Ponderosa pine; *Pseudotsuga menziesii*; wildfire

Soil cores were taken in the Selway-Bitterroot Wilderness in northern Idaho from shallow, skeletal soils (Dystrocryepts) classified as fire maintained or fire excluded. Charcoal content in the soils was measured, as well as the amount and effect on ammonia-oxidizing bacteria. Recent wildfire was shown to result in increased charcoal and nitrification rates, while also influencing ammonia-oxidizing bacteria abundance and community structure.

Berglund, L.M., T.H. DeLuca, and O. Zackrisson. 2004. Activated carbon amendments to soil alters nitrification rates in Scots pine forests. Soil Biology and Biochemistry 36:2067–2073.

Activated carbon; birch litter; boreal forest; charcoal; fire; nitrification; nitrogen transformations; phenolic compounds

This study included replicated field sites in Scots pine forests in northern Sweden and supporting laboratory incubations. Researchers utilized two rates of activated carbon additions as a surrogate for wildfire produced charcoal, and two rates of glycine additions to measure net nitrification, N mineralization, and free phenol concentrations in sandy glacial soils classified as either Typic or Entic Haplocryods. Nitrification and ammonification rates increased with activated carbon additions in laboratory incubations, but results were not supported in field conditions. Phenolic accumulations were reduced by charcoal application.

Biederman, L.A., and W. Stanley Harpole. 2013. Biochar and its effects on plant productivity and nutrient cycling: A meta-analysis. GCB Bioenergy 5:202–214.
Carbon sequestration; charcoal; plant productivity; soil nutrients; soil organisms; pH

Meta-analysis conducted on 371 independent studies by searching databases for keywords 'biochar', 'char', 'black carbon', 'charcoal', and 'agchar'. Statistical analysis concluded that adding biochar to soils resulted in increased crop yield, aboveground productivity, rhizobia nodulation, plant K tissue concentration, soil P, soil N, soil K, and total soil C.

Braadbaart, F., and I. Poole. 2008. Morphological, chemical and physical changes during charcoalification of wood and its relevance to archaeological contexts. Journal of Archaeological Science 35:2434–2445
Wood; *Quercus*; oak; *Pinus*; pine; carbonization; charring; charcoal; reflectance; archaeobotany

The morphological (anatomy, degree of shrinkage), physical (reflectance), and chemical (elemental, molecular composition) properties of charcoal are characterized in this study. Charcoal was experimentally produced with a variation in temperature, time of exposure, heating rate, and wood type.

Briggs, C., J.M. Breiner, and R.C. Graham. 2012. Physical and Chemical Properties of Pinus ponderosa Charcoal. Soil Science 177:263–268.
char; cation exchange capacity; *Pinus ponderosa*; Ponderosa pine; soil color; water repellency; water-holding capacity

Comparison of pine (Pinus ponderosa) charcoal produced under controlled conditions to pine charcoal produced under wildfire conditions and field aged for 7 years. Laboratory produced charcoal had a more neutral pH, high C/N ratio, and low specific surface area while field aged charcoal was moderately acidic, reduced C/N ratio, and accumulated Calcium on exchange sites.

DeLuca, T.H., and G.H. Aplet. 2008. Charcoal and carbon storage in forest soils of the Rocky Mountain West. Frontiers in Ecology and the Environment 6:18–24.
Boreal forest; carbon storage; charcoal; forest management; temperate forest; wildfire

Review paper on the formation of charcoal from wildfire as a passive form of carbon for soil systems. Charcoal is an important component of the soil organic matter pool in temperate grasslands and forests. The contributions in soil functioning is still being explored, but has benefits that range from increasing water holding capacity, ion exchange, and surface area and requires consideration in ecological assessment, C modeling, and forest management.

DeLuca, T.H., M.D. MacKenzie, M.J. Gundale, and W.E. Holben. 2006. Wildfire-Produced Charcoal Directly Influences Nitrogen Cycling in Ponderosa Pine Forests. Soil Science Society of America Journal 70:448-453.
Charcoal; nitrogen; *Pinus ponderosa*; Ponderosa pine

Soils collected from western Montana pine (Pinus ponderosa) forests classified as Typic Dystrocryepts and a grassland soil (Typic Haplocryolls) for comparison were mixed with charcoal, predominantly from ponderosa pine and Douglas-fir collected from a wildfire-exposed forest in Western Montana, and used for laboratory incubations. Soils had been subjected to various fire intervals from 2 to 130 years. Results showed that charcoal readily stimulates nitrification although the mechanism for the increase is not identified.

DeLuca, T.H., and A. Sala. 2006. Frequent fire alters nitrogen transformations in ponderosa pine stands of the inland northwest. Ecology 87:2511–2522.
Charcoal; Douglas-fir; fire frequency; Inland Northwest USA; nitrification; nitrogen mineralization; *Pinus ponderosa*; ponderosa pine; *Pseudotsuga menziesii*; wilderness

This study tries to determine how natural repeated fire over a 69-130 year period influences nutrient availability and N transformations in unlogged stands of Ponderosa pine/Douglas-fir forests of the Inland Northwest (Idaho and Montana). All soils sampled were characterized as shallow, skeletal Dystrocryepts. The work in this study clearly shows that repeated fires reduced soil N capital and increased net N nitrification in forest soils relative to stands unburned for almost seven decades.

Drake, J.A., A. Carrucan, W.R. Jackson, T.R. Cavagnaro, and A.F. Patti. 2015. Biochar application during reforestation alters species present and soil chemistry. Science of the Total Environment 514:359–365.
Afforestation; climate change mitigation; nitrogen; phosphorus; revegetation; soil carbon; species diversity

This study looks at an Australian forest utilizing biochar added at three different rates along with a direct seed forest species mix made up of indigenous trees and shrubs at three *different sites. The biochar was produced from Southern Blue Gum fines (Eucalyptus globulus) and soils were characterized by great group as Chromosol and Podzol based on the Australian soil classification. Biochar was found to increase total Carbon, and altered electrical conductivity, phosphorus, and nitrate- and ammonium-nitrogen. Biochar also increased the number of species present, but had species specific effects on stem counts.*

FAO. (1985). ‘‘Industrial Charcoal Making’’ FAO Forestry Department, Rome.
Charcoal; forests; industrial; manual

Food and Agriculture Organization of the United Nations manual on the industrial technologies for charcoal making as an aid to increase production of charcoal while also conserving forest resources by introducing more efficient means of production.

Gaskin, J.W., C. Steiner, K. Harris, K.S. Das, and B. Bibens. 2008. Effect of low-temperature pyrolysis conditions on biochar for agricultural use. Transactions of the American Society of Agricultural and Biological Engineers 51:2061–2069.
Agricultural residues; biochar; black carbon; carbon sequestration; charcoal; plant nutrition; pyrolysis; soil fertility; soil organic carbon

Study evaluating the agricultural potential of biochar produced from poultry litter, peanut hulls, and pine chips at two different temperatures, with or without steam. Researchers found that properties were strongly influenced by feedstock and temperature. The C content was higher in the pine feedstock, while nutrients such as P, K, Ca, and Mg were significantly higher in biochar produced at a higher temperature, and the cation exchange capacity was higher in the biochar produced at a lower temperature.

Gundale, M.J., and T.H. DeLuca. 2006. Temperature and source material influence ecological attributes of ponderosa pine and Douglas-fir charcoal. Forest Ecology and Management 231:86–93.
Allelopathy; catechin; charcoal; Douglas-fir; fire; N cycling; ponderosa pine

Charcoal was generated from the bark and wood of Douglas-fir (Pseudotsuga menziesii) and ponderosa pine (Pinus ponderosa) trees at two temperatures. The charcoal was then added to soil collected from the Lubrecht Experimental Forest in Montana which are characterized as a sandy-skeletal, mixed, frigid Typic Dystrustept. The soils amended with charcoal and a glycine additive were incubated and net ammonification, nitrification, pH, effectiveness of sorbing catechins, and other variables were measured. It was found that the greatest source of variability in measured variables was due to the pyrolization temperature.

Gundale, M.J., M.-C. Nilsson, N. Pluchon, and D. A. Wardle. 2016. The effect of biochar management on soil and plant community properties in a boreal forest. GCB Bioenergy 8:777–789.

Biochar management; boreal forest; carbon sequestration; charcoal; forest regeneration; ground layer vegetation; humus; nitrogen mineralization; nutrients; soil carbon efflux

A large scale field experiment was conducted in northern Sweden to evaluate how soil and vegetation processes responded to biochar application and the disturbance associated with mixing biochar in the soil. Prior to treatment, the area that had previously consisted of Scots Pine (Pinus sylvestris), was clear felled and any remaining stumps were removed and biochar, primarily from P. sylvestris, was added utilizing an excavator. The soil at the treatment sites was classified as a fine sandy Typic Haplocryod. The site was then replanted with Scots Pine seedlings. Biochar was found to enhance net N mineralization and soil ammonium, but had no impact on nitrate or vegetation properties.

Hansen, V., H. Hauggaard-Nielsen, C.T. Petersen, T.N. Mikkelsen, and D. Müller-Stöver. 2016. Effects of gasification biochar on plant-available water capacity and plant growth in two contrasting soil types. Soil and Tillage Research 161:1–9.
Available water capacity; barley; coarse sand; gasification biochar; shoot and root growth; soil structure

Spring barley was grown in a pot experiment utilizing wood and straw gasification biochar to measure available water capacity and plant growth responses under two different watering regimes. Irrespective of soil type, the gasification biochars had a significant effect on the available water capacity with the highest increase in the coarse sand. The straw biochar caused an increase in shoot and root growth in the barley, whereas no response was seen with the wood biochar.

Hart, S., and N. Luckai. 2013 Charcoal function and management in boreal ecosystems. Journal of Applied Ecology 50:1197–1206.
Activated carbon; boreal forest; climate change; forest management; prescribed burn; soil carbon; wildfire

A review paper about the important role in soil function and carbon storage that charcoal plays in fire-prone ecosystems focusing on boreal forests. The paper details the formation of charcoal and its stability in soils, as well as the mechanisms for degradation. With changes in frequency and intensity of fire, boreal soil carbon stocks become more vulnerable. Management of boreal forest charcoal is suggested to maintain soil function and productivity.

Jeffery, S., F. Verheijen, M. van der Velde, and A. Bastos. 2011. A quantitative review of the effects of biochar application to soils on crop productivity using meta-analysis. Agriculture, Ecosystems and Environment 144:175–187.
Biochar; crop productivity; crop yield; effect size; meta-analysis; soil

A statistical meta-analysis to evaluate the relationship between biochar and crop productivity (either yield or above-ground biomass) and the mechanism that could be *behind the relationship. It was found that overall there was a statistically significant benefit of biochar, with the most positive effects seen in acidic and neutral soils, and coarse or medium texture soils. Poultry biochar had the greatest positive effect while biochar made from biosolids had the only significant negative effect. Researchers suggest that the mechanism behind positive effects was the greater water holding capacity and a liming effect that improved crop nutrient availability due to increased cation exchange capacity.*

Jeong, J., C. Gyu Jo, G. Won Baek, J.H. Park, H.S. Ma, B. Oh Yoo, and C. Kim. 2017. Soil and the foliage nutrient status following soil amendment applications in a Japanese cypress (*Chamaecyparis obtusa* Endlicher) plantation. Journal of Sustainable Forestry 36 (3):289-303.
Biochar; fertilization; forest disease; pine wilt disease; sawdust; vegetation restoration

This study was used to evaluate the response of biochar, sawdust, and fertilizers as soil amendments in a Japanese cypress (Chamaecyparis obtusa Endlicher) plantation established following clear-cutting in a pine-wilt-disease disturbed forest in Korea. The soil located in the plantation was classified as an Inceptisol, originating from sandstone or shale, with a loam or silty loam texture. Results showed that biochar in addition to a compound fertilizer can enhance extractable soil nutrients and foliar N and P in Japanese cypress restoration.

Keech, O., C. Caracaillet, and M.-C. Nilsson. 2005. Adsorption of allelopathic compounds by wood-derived charcoal: the role of wood porosity. Plant and Soil 272:291–300.
Adsorption; allelopathy; boreal forests; *Empetrum hermaphroditum*; germination; wood-derived charcoal anatomy

An examination of the effects of charcoal produced from eight boreal and one temperate woody plant species on adsorption of allelopathic compounds produced by the dwarf shrub (Empetrum hermaphroditum) that interferes with the regeneration of other boreal trees in Sweden. Results comparing the adsorption capacity of the various biochars produced showed that biochar from the deciduous species had a significantly higher adsorption capacity than the conifer and ericaceous species. Presence of macro-pores seemed to be the most important factor for biochars adsorption capacity.

Kloss, S., F. Zehetner, A. Dellantonio, R. Hamid, F. Ottner, V. Liedtke, M. Schwanninger, M.H. Gerzabek, and G. Soja. 2012. Characterization of slow pyrolysis biochars: effects of feedstocks and pyrolysis temperature on biochar properties. Journal of Environmental Quality 41:990–1000.
Biochar; characterization; composition; molecular; mineralogical composition

Biochars were produced from three different feedstocks, wheat straw, poplar wood, and spruce wood, which had been pyrolyzed at three different temperatures and two different lengths of time. The biochar was then characterized by looking at pH, electrical *conductivity, elemental composition, cation exchange capacity, and surface area. The different biochars were scanned by various methods to determine molecular characteristics and mineralogical composition. The results show that biochars are highly heterogeneous, composition and properties vary based on feedstock and treatment temperature.*

Kochanek, J., R.L. Long, A.T. Lisle, and G.R. Flematti. 2016. Karrikins Identified in Biochars Indicate Post- Fire Chemical Cues Can Influence Community Diversity and Plant Development PLoS ONE 11(8):1–19.
Arabidopsis; biochar; germination; karrikinolide; seedling; post-fire; smoke

Biochars were prepared by three distinct pyrolysis technologies using feedstocks of green waste (wood fragments and plant fibers), sugarcane trash, paper mill waste or woodchips. After production, the chemical properties of the biochars including karrikins (smoke-derived compounds) were measured and assays set up to measure the dose-response of karrikinolide on seed germination and growth using two plant species that require the chemical cues to break dormancy post-fire. The results showed that biochar contains the chemical karrikans that are able to stimulate seed germination, mimicking natural post-fire effects.

Kolb, S.E., K.J. Fermanich, and M.E. Dornbush. 2009. Effect of Charcoal Quantity on Microbial Biomass and Activity in Temperate Soils. Soil Science Society of America Journal 73:1173–1181.
Charcoal; extractable N; microbial biomass and activity; Wisconsin

Charcoal produced from pyrolyzed bull manure, dairy manure, and pine shavings was added to four soils collected around Wisconsin that represent a range of soil properties and land use histories, at five different application levels. The soils were characterized as Kewaunee soil series (Alfisol), Pence soil series (Spodosol), Plainfield soil series (Entisol), and Plano soil series (Mollisol). The results show that microbial biomass and activity increased with increasing charcoal application, while extractable N decreased, and differences in the magnitude of the microbial response appeared dependent on differences in nutrient availability among soils.

Laird, D.A., P. Fleming, D.D. Davis, R. Horton, B. Wang, and D.L. Karlen. 2010. Impact of biochar amendments on the quality of a typical Midwestern agricultural soil. Geoderma 158:443-449.
Biochar; black carbon; charcoal; manure; soil quality

Biochar made from mixed hardwood, mainly oak (Quercus spp.) and hickory (Carya spp.), were added at three different application rates was added to a Clarion series soil (Mesic Typic Hapludolls) collected from the upper layer in Boone County, Iowa. Soil columns were constructed and incubated for 500 days, and then analyzed for pH, cation exchange capacity, water retention, and plant available nutrients. Results showed that the biochar *additions decreased bulk density, increased water holding capacity, cation exchange capacity, specific surface area, pH, retention of P and several other plant nutrients.*

Laungani, R., K. Elgersma, K. McElligott, M. Juarez, and T. Kuhfahl. 2016. Biochar amendment of grassland soil may promote woody encroachment of Eastern Red Cedar. Journal of Soil Science and Plant Nutrition 16(4):941-954
Biochar; immobilization; invasion; litter; nitrogen; plant-soil feedback

This greenhouse experiment looked at the use of biochar, sawdust, and leaf litters as amendments on non-agricultural species, specifically to prevent the encroachment of invasive species. Biochar and litter amendments were produced from grass litter of Bromus inermis (an exotic grass species) and Schizachyrium scoparium (a dominant native grass) collected in Nebraska. Juniperus virginiana seedlings were grown in a Steinauer series soil classified as fine-loamy, mixed, superactive, calcareous, mesic Typic Udorthents with the various amendment types. Seedlings grown in biochar amended soil were found to have a 40% increase in size, and a 2 order of magnitude increase in available ammonium.

Lehmann, J. 2007 Bio-energy in the black. Frontiers in Ecology and the Environment 5:381-387.
Biochar; concept; overview

This concept and overview paper details the benefits of capturing the off-gases from the production of biochar for energy use. As a by-product from the pyrolization of various feedstocks, biochar also has beneficial uses in agriculture and can complement the use of fertilizers or replace fertilizers all together. Research is needed to maximize the favorable attributes of biochar and to fully evaluate the environmental risks, but the technology has potential to provide an important carbon sink and reduce environmental pollution by fertilizers.

Lehmann, J., and S. Joseph. 2009. Biochar for environmental management: an introduction. In: Lehmann, J., Joseph, S. (Eds.), Biochar for Environmental Management. Earthscan, London, pp. 1e12.
Biochar; management; research; terminology

This introduction chapter for the book Biochar for Environmental Management, briefly examines what biochar is, the terminology, and basis of biochar in management. This includes utilizing biochar as a soil amendment, for managing wastes, energy production, and for climate change mitigation.

Licata, C., and R. Sanford. 2012. Charcoal and Total Carbon in Soils from Foothills Shrublands to Subalpine Forests in the Colorado Front Range. Forests 3:944–958.
Black carbon; charcoal; fire; fire regime; forests; Rocky Mountains; soil organic carbon

Long-term soil charcoal leaves a legacy in the temperate forests of the Colorado Front Range. In order to measure the soil charcoal pools, researchers collected surface soil *samples from all the major fire regimes and vegetation types in the mountains west of Denver. Soil types were classified as Cryolls, Cryalfs, and Cryepts based on aspect and elevation. Results show that the most important factors in the amount of soil charcoal are fire regime and available biomass source. More research is needed to determine the ecological and biological importance of these results.*

MacKenzie, M.D., E.J.B. McIntire, S.a. Quideau, and R.C. Graham. 2008. Charcoal Distribution Affects Carbon and Nitrogen Contents in Forest Soils of California. Soil Science Society of America Journal 72:1774-1785.
Charcoal; distribution; fire exclusion

This study examines one representative site with three different vegetation types, oak woodland, mixed conifer, and red fir ecosystems across two elevation transects on the western slopes of the Sierra Nevada in California to quantify soil charcoal quantities. The sites had not experienced fire or management activities for an extended amount of time and soils have been classified as Inceptisols with some Alfisols. Forest floor and soil samples were taken randomly. Results showed that charcoal content increased with increasing elevation.

Michelotti, L., and J. Miesel. 2015. Source Material and Concentration of Wildfire-Produced Pyrogenic Carbon Influence Post-Fire Soil Nutrient Dynamics. Forests 6:1325–1342.
Black carbon; N mineralization; nitrogen; *Pinus banksiana*; pyrogenic carbon; soil respiration; wildfire

Focusing on the jack pine forests of Michigan, the researchers collected wildfire produced pyrogenic carbon in the forms of charred bark, charred pine cones, and charred woody debris. Soil samples were also collected that were characterized as a Grayling series (Typic Udipsamments) and Graycalm series (Lamellic Udipsamments). The collected soils and pyrogenic carbon were used for incubations at two concentration levels, and evaluated at four different time steps for CO_2 concentration, changes in ammonium and nitrate, total inorganic N concentrations, and mineralization rates. Results showed differences in pyrogenic carbon source material on post-fire soil dynamics and nutrients. More work needs to be done to elucidate the differences.

Nguyen, T.T.N., C. Xu, I. Tahmasbian, R. Che, Z. Xu, X. Zhou, H.M. Wallace, and S. Hosseini. 2017. Effects of biochar on soil available inorganic nitrogen: A review and meta-analysis. Geoderma 288:79–96.
Biochar; boosted regression tree; charcoal; fertilizer; nitrogen; systematic review

A meta-analysis to investigate biochar properties, and the interaction among biochar, soil, and fertilization on inorganic nitrogen. This study used 56 studies with 1080 experimental cases published between 2010-2015, and found that biochar (the majority of feedstock used was wood) reduced soil inorganic nitrogen regardless of experimental conditions. Soil *organic nitrogen was most affected by residence time of biochar in the soil, pyrolysis temperature, application rate, fertilizer type, and soil pH.*

Novak, J.M., I. Lima, B. Xing, J.W. Gaskin, C. Steiner, K.C. Das, M. Ahmedna, D. Rehrah, D.W. Watts, and W.J. Busscher. 2009. Characterization of designer biochar produced at different temperatures and their effects on a loamy sand. Annals of Environmental Science 3:195–206.
Designer biochar; feedstock; GRACEnet; pyrolysis; soil improvement

This study produced biochar from peanut hulls, pecan shells, poultry litter, and swichgrass at various temperatures which were mixed with a Norfolk series soil (fine-loamy, kaolinitic, thermic, Typic Kandiudults) and incubated to examine changes in soil properties. Biochar produced at higher temperatures were found to have a lower mass recovery, greater surface area, increased ash content, minimal total surface charge, higher pH and Carbon, with lower Hydrogen and Oxygen contents. Different feedstocks and pyrolysis temperatures influence soil physical and chemical properties in different ways.

Page-Dumroese, D.S., M.D. Busse, J.G. Archuleta, D. Mcavoy, and E. Roussel. 2017. Methods to Reduce Forest Residue Volume after Timber Harvesting and Produce Black Carbon. Scientifica:1–8.
Charcoal; kiln; pile burn; restoration; slash piles

Review paper detailing alternative methods for utilizing non-merchantable forest residues from forest thinning to create charcoal for improving soil organic matter and carbon sequestration. Slash piles are currently the favorite method for residue disposal, but there are long-term soil consequences that are unfavorable. By using portable pyrolization units or kilns, charcoal produced from the process can then be used for restoration purposes on site.

Pingree, M., E. Deluca, and T.H. Deluca. 2016. Adsorption capacity of wildfire-produced charcoal from Pacific Northwest forests. Geoderma 283:68–77.
Adsorption; black carbon; charcoal; Douglas-fir; mixed-severity fire regimes; *Pseudotsuga menziesii*; pyrogenic carbon; wildfire

Wildfire produced charcoal was collected from the forest floor from nine fire chronosequences (ranging from historic, intermediate, and recent fires) in the eastern Olympic Peninsula, Washington. Charcoal was also produced from Douglas-fir branches collected at the same sites, and heated at three different temperatures in a muffle furnace in the laboratory. All charcoals were evaluated for the adsorption of phenolic compounds, which are prevalent in forest systems. Results demonstrated that higher charcoal formation temperatures allowed greater phenol adsorption.

Pluchon, N., S.C. Casetou, P. Kardol, M.J. Gundale, M.-C. Nilsson, and D.A. Wardle. 2015. Influence of species identity and charring conditions on fire-derived charcoal traits. Canadian Journal of Botany 45:1669–1675.
Black carbon; boreal forest; charcoal trait; fire; pyrogenic carbon; pyrolysis

Charcoal was produced from three common boreal species under six charring conditions representing those encountered during boreal fires such as those in northern Sweden. The structural and chemical traits of the various charcoals were analyzed. Results showed that structural traits such as density and microporosity varied among tree species, and density decreased with increasing temperature. Chemical traits, such as electrical conductivity, total nitrogen and phosphorus contents differed among species, whereas pH, total N content and ammonium concentration responded to charring conditions. Overall, the traits of charcoal are driven by a combination of fire behavior and tree species.

Pluchon, N., M.J. Gundale, M.-C. Nilsson, P. Kardol, and D.A. Wardle. 2014. Stimulation of boreal tree seedling growth by wood-derived charcoal: effects of charcoal properties, seedling species and soil fertility. Functional Ecology 28:766–775.
Black carbon; boreal forest; feedback; fire; phosphorus; pyrogenic carbon; succession; wood traits

This study involved amending two forest soils with wood-derived charcoals from nine plant species common in boreal forests in northern Sweden. The two soils selected for collection were chosen based on the differing chemical properties. A greenhouse experiment was set up with factors consisting of two soil types and ten charcoal treatments (nine charcoal types and a charcoal-free control) and seedlings of four tree species. Charcoal additions had either positive or neutral effects on seedling growth, with angiosperms on average stimulated more than gymnosperm seedlings. Charcoal with higher phosphorus had a stronger positive effect on seedling growth, and charcoal from angiosperm tree species favors growth of angiosperm seedlings indicating a possible “after-life” effect.

Pluchon, N., A.G. Vincent, M.J. Gundale, M.-C. Nilsson, P. Kardol, and D.A. Wardle. 2016. The impact of charcoal and soil mixtures on decomposition and soil microbial communities in boreal forest. Applied Soil Ecology 99:40–50.
Black carbon; charcoal trait; CP-MAS ^{13}C NMR; fire; PLFA; priming effect

In this study six contrasting boreal forest soils were mixed with nine charcoal types (each from different woody plant species) and incubated for 9.5 months. The soils used were characterized as leptosol, gleyic podzol, and podzol, that were collected from different tree dominated forests. After the incubation, the soils were analyzed for mass loss, microbial properties, and composition of C compounds. Results showed that mixing of charcoal and soil did not influence key decomposer microbial groups, but there was a loss of C (primarily arising from a mass loss of soil organic matter) across all soil and charcoal types. This could indicate legacy effects of charcoal on forest processes that contribute to ecosystem C balance and ecosystem functioning.

Preston, C.M., and M.W.I. Schmidt. 2006. Black (pyrogenic) carbon: a synthesis of current knowledge and uncertainties with special consideration of boreal regions. Biogeosciences 33:397–420.

Boreal; pyrogenic carbon; review

A review paper detailing the characteristics and life cycle of pyrogenic carbon. The carbon cycle in boreal regions is strongly influenced by fire, converting biomass to gaseous forms and pyrogenic carbon. Pyrogenic carbon is largely resistant to decomposition, and can contribute to stable pools of C as well as influencing soil processes. The role and influences of pyrogenic carbon have not been defined for boreal regions, and developing standardized methods to elucidate this information would be important in the future.

Prober, S. M., J. Stol, M. Piper, V.V.S.R. Gupta, and S.A. Cunningham. 2014. Enhancing soil biophysical condition for climate-resilient restoration in mesic woodlands. Ecological Engineering 71:246–255.

Biochar; climate change; collembolan; grasslands; mulch; soil amendments

Three experimental sites were established in native pastures originally dominated by grassy woodlands located in NSW, Australia that consisted of soils characterized as Red to Yellow Dermosols and Red Chromosols. Treatments applied to the study sites included biochar, P fertilizer, native grass seeding, and surface mulching. Biochar and mulching was produced form whole tree green waste from local eucalyptus. Two years after establishment, soils were analyzed for total C and N, available P, ammonium and nitrate N, and pH, as well as soil physical characteristics such as bulk density, compaction, infiltration, and volumetric soil moisture. Results showed that biochar and mulch decreased bulk density, creating softer soil surfaces, occasionally higher soil moisture, and better persistence of native grass seeding. Biochar also led to improved water infiltration, and increased total C.

Rhoades, C.C., K.L. Minatre, D.N. Pierson, T.S. Fegel, M.F. Cotrufo, and E F. Kelly. 2017. Examining the Potential of Forest Residue-Based Amendments for Post-Wildfire Rehabilitation in Colorado, USA. Scientifica 2017.

Biochar; mulch; *Pinus contorta*; post-fire rehabilitation; Rocky Mountains

This study evaluates the potential of forest-residue based materials to rehabilitate soils after fire. Biochar and mulch produced from local beetle kill lodgepole pine were added to plots established within the Church's Park burn area that had been characterized as gravelly, sandy-loam Alfisols on steep slopes experiencing considerable post-fire erosion. A complementary greenhouse study was set up with soils collected from the burn site, and identical treatments, for growing lodgepole pine seedlings. For three years following establishment, soil samples were analyzed for ammonium and nitrate N, cation exchange capacity, pH, and available water. Results showed that wood mulch increased total N, C, pH, and water consistently while biochar alone had few effects under field conditions.

Robertson, S., P. Rutherford, J. Lopez-Gutierrez, and H. Massicotte. 2012. Biochar enhances seedling growth and alters root symbioses and properties of sub-boreal forest soils. Canadian Journal of Soil Science:329–340.

Actinorhiza; *Alnus viridis* ssp. *sinuate*; black carbon; ectomycorrhizas; N fixation; *Pinus contorta*

This study consisted of a pot study that combined forest soils collected from central British Columbia, characterized as Gray Luvisols, with biochar produced from softwood chips (mainly lodgepole pine) at two different application levels, with and without urea fertilizer. Lodgepole pine (Pinus contorta) and sitka alder (Alnus viridis ssp. sinuate) were then planted in the pots and harvested 4 months after planting. Results showed that biochar raised soil pH, exchangeable cations, and cation exchange capacity of both soils. Pine seedlings had a greater biomass in the biochar with fertilizer treatment, which corresponded to an increase in ectomycorrhizas.

Santín, C., S.H. Doerr, E.S. Kane, C.A. Masiello, M. Ohison, J. M. de la Rosa, C.M Preston, and T. Dittmar. 2016. Towards a global assessment of pyrogenic carbon from vegetation fires. Global Change Biology 22:76–91.

Biochar; black carbon; carbon accounting; carbon emissions; carbon sequestration; charcoal; dissolved organic carbon; erosion; pyrogenic organic matter; wildfire

A review paper that examines the robustness of existing evidence on pyrogenic carbon and its lack of consideration in the global C cycle and climate studies, and to identify the main research gaps in the production, fluxes and fate of pyrogenic carbon from vegetation fires. Past research on the fate of pyrogenic carbon has focused on its degradation pathways, and its accumulation in and resilience in surface soils or as a sink in marine sediments. Off-site transport, transformation, and pyrogenic carbon storage in intermediate pools is often overlooked. The researchers propose new research directions to address the gaps in the global pyrogenic carbon cycle to understand the importance of the products of burning in global C dynamics.

Santín C., S.H. Doerr, R.A. Shakesby, R. Bryant, G.J. Sheridan, P.N.J. Lane, H.G. Smith, and T.L. Bell. 2012. Carbon loads, forms and sequestration potential within ash deposits produced by wildfire: new insights from the 2009 'Black Saturday' fires, Australia. European Journal of Forest Research 131:1245–1253.

Black carbon; charcoal; mixed-species eucalypt forest; pyrogenic carbon; temperate rainforest

In this study, researchers sampled ash from three sites characterized as burned under "extreme fire severity" as well as five sites classified as moderate to high severity from the Black Saturday fires in eucalypt forests of Victoria, Australia. The ash was then analyzed for types of C including total, inorganic, water-soluble, and particulate organic fractions. Results showed that most C contained in the ash was organic and its pyrogenic nature infers increased resistance to degradation. The researchers felt this highlighted the *potential importance of the potential importance of the pyrogenic C pool in freshly deposited ash.*

Sika, M.P., and A.G. Hardie. 2014. Effect of pine wood biochar on ammonium nitrate leaching and availability in a South African sandy soil. European Journal of Soil Science 65:113–119.
Ammonium; biochar; fertilizer; leaching; nitrate

This study examined the potential of biochar to prevent leaching of ammonium nitrate fertilizer. Collected soils from a fallow field in South Africa, characterized as a leached, acidic, sandy soil (Haplic Stagnasol (Albic)) were mixed in columns with biochar produced from pine (Pinus radiata L.) at three different application rates. Columns were leached periodically over a period of 6 weeks and then analyzed for ammonium and nitrate leaching and exchangeable ammonium and nitrate. Results showed that biochar reduced the amount of ammonium and nitrate leached, but the soils contained only small amounts of exchangeable ammonium and nitrate. This result causes concern as this seems to reduce the amount of N that would be able available to vegetation.

Thomas, S.C., and N. Gale. 2015. Biochar and forest restoration: a review and meta-analysis of tree growth responses. New Forests 46:931–946.
Biochar; charcoal; feedstock; forest restoration; pyrolysis; soil carbon

Meta-analysis and review paper focusing on more fully developing the argument regarding the potential of biochar for forest restoration. The researchers searched peer-reviewed literature published through 2014 to locate studies presenting growth responses (aboveground biomass, or for both height and stem diameter) of trees from boreal, temperate, and tropical regions with the addition of biochar. Results of the meta-analysis concluded that there is strong evidence for positive effects of biochar additions on the growth for woody plants, with observed responses that appear to be generally larger than those observed in agricultural systems. There is high heterogeneity in responses among tree species and ecological systems, and it is not possible to unambiguously distinguish this heterogeneity from differences in soil and chars using the existing data.

Tryon, E.H. 1948. Effect of charcoal on certain physical, chemical, and biological properties of forest soils. Ecological Monographs 18:81–115.
Charcoal; mycorrhizae

In this study, three forest soils were collected of different textural grades, all characterized as belonging to a brown podsolic group, which included a Berlin clay loam, a Maltby sand loam, and a Merrimac sand. Charcoal was produced from pine and oak sieved into two different size classes, and then mixed with soils at 4 different application levels including a control. Soils were then analyzed for physical, chemical and biological properties, such as available moisture, hygroscopic water, and wilting percentage, effects on acidity, base exchange properties, nutrients, as well as effects on mycorrhizae, bacteria, and white pine seedlings. Results showed that in general charcoal had a tendency to improve the physical *and chemical properties of soil but that charcoal should never be added to soils in large amounts as the pH and soluble salt increase can have significant effects on vegetation.*

Wardle, D., O. Zackrisson, and M. Nilsson. 1998. The charcoal effect in Boreal Forests: mechanisms and ecological consequences. Oecologia 115:419–426.
Activated charcoal; boreal forest charcoal; ericaceous shrubs; wildfire

This study evaluated the short-term ecological effects of charcoal on the boreal forest plant-soil system. This was accomplished by a greenhouse pot study that combined boreal forest substrates of either ericaceous or herbaceous origin of differing levels of productivity, with or without charcoal, with or without forest litter, and with or without Pinus sylvestris or Betula pendula Roth. seedlings. Results showed that the charcoal addition enhanced seedling shoot to root ratios of both tree species, but only in the ericaceous substrate. Biochar stimulated the growth of Betula pendula Roth, but growth was retarded by the litter addition in the ericaceous substrate, while Pinus sylvestris was less sensitive to substrate origin. The researchers felt that the results provided clear evidence that immediately after wildfire fresh charcoal can have important effects in boreal forest systems.

Zackrisson, O., M.-C. Nilsson, and D.A. Wardle. 1996. Key ecological function of charcoal from wildfire in the Boreal forest. Oikos 77:10–19.
Boreal; charcoal; chronosequence; phenolic compounds

This study investigated the sorbtive properties of charcoal by a variety of activities. The first activity was to perform a chronosequence across twelve forest sites in northern Sweden to quantify the mass of charcoal located in the soils and the levels appeared to be sufficient enough to have important ecological effects. The ability of charcoal to adsorb phytotoxic active phenolic compounds was evaluated by measuring its ability to remove them from an aqueous solution produced from leaves of E. hermaphroditum. Vegetation measurements were also made at 32 sites used for previous sampling. The results indicate that charcoal has an important effect in enhancing site fertility in early post-fire forest successions and that this effect diminishes as succession proceeds.