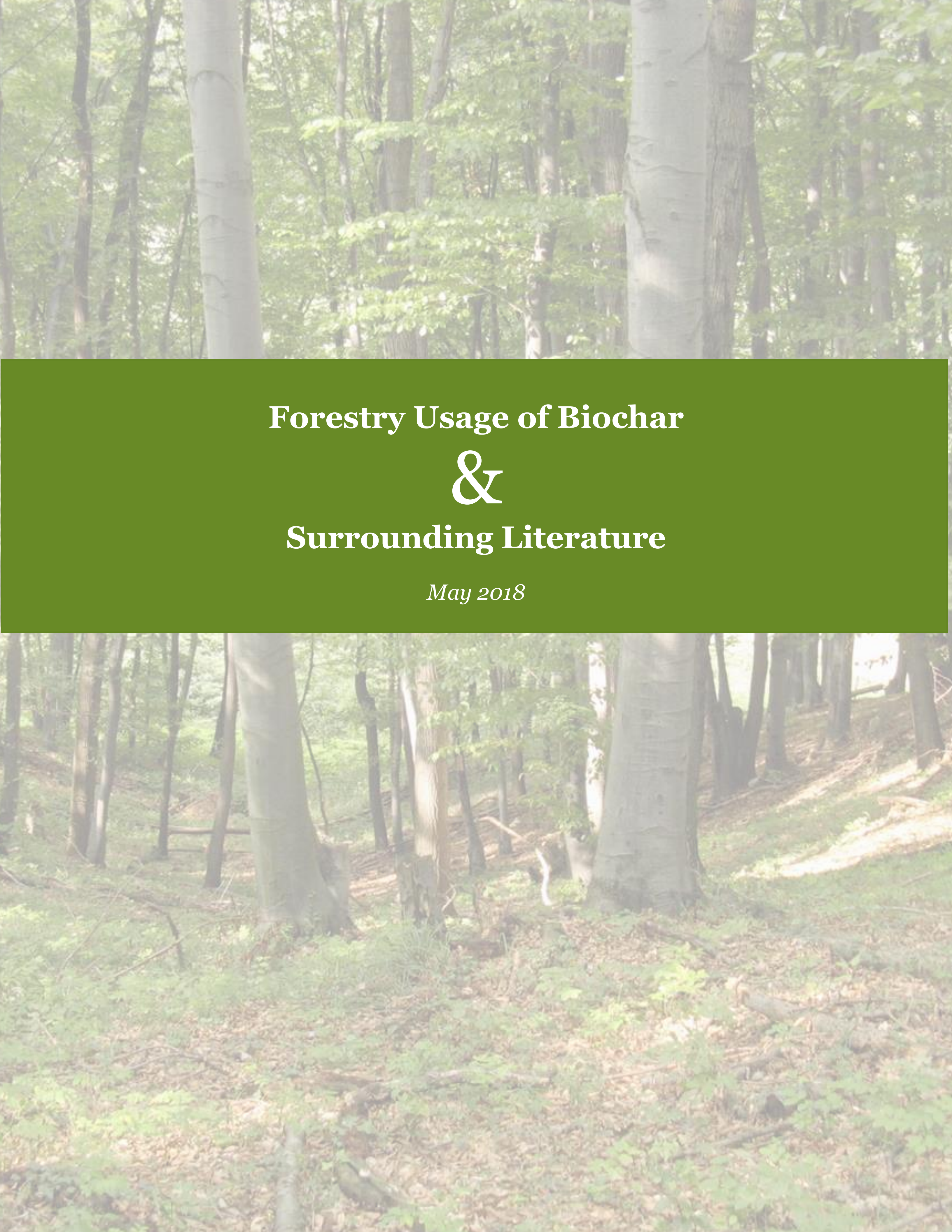


Forestry Usage of Biochar

&

Surrounding Literature

May 2018

Articles Pertaining to Forestry Usage of Biochar

1) Methods to Reduce Forest Residue Volume after Timber Harvesting and Produce Black Carbon
https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5362704/

Abstract
Forest restoration often includes thinning to reduce tree density and improve ecosystem processes and function while also reducing the risk of wildfire or insect and disease outbreaks. However, one drawback of these restoration treatments is that slash is often burned in piles that may damage the soil and require further restoration activities. Pile burning is currently used on many forest sites as the preferred method for residue disposal because piles can be burned at various times of the year and are usually more controlled than broadcast burns. In many cases, fire can be beneficial to site conditions and soil properties, but slash piles, with a large concentration of wood, needles, forest floor, and sometimes mineral soil, can cause long-term damage. We describe several alternative methods for reducing nonmerchantable forest residues that will help remove excess woody biomass, minimize detrimental soil impacts, and create charcoal for improving soil organic matter and carbon sequestration.

2) Understory vegetation response to thinning and burning restoration treatments in dry conifer forests of the eastern Cascades, USA.
http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.510.242&rep=rep1&type=pdf

Restoration/fuel reduction treatments are being widely used in fire-prone forests to modify stand structure, reduce risks of severe wildfire, and increase ecosystem resilience to natural disturbances. These treatments are designed to manipulate stand structure and fuels, but may also affect understory vegetation and biodiversity. In this study, we describe prescribed fire and thinning treatment effects on understory vegetation species richness, cover, and species composition in dry coniferous forests of central Washington State, U.S.A … Species composition varied within and among treatment units, but was not strongly or consistently affected by treatments. Our study shows that thinning and burning treatments had mostly neutral to beneficial effects on understory vegetation, with only minor increases in exotic species. However, the pre-treatment condition had strong effects on understory dynamics, and also modified some responses to treatments. The maximum benefit of restoration treatments appears to be where understory richness is low prior to treatment, suggesting restoration efforts might be focused on these areas.

3) Management of mixed-severity fire regime forests in Oregon, Washington, and Northern California
https://www.researchgate.net/publication/294423546_Tamm_Review_Management_of_mixed-severity_fire_regime_forests_in_Oregon_Washington_and_Northern_California

Abstract

Increasingly, objectives for forests with moderate- or mixed-severity fire regimes are to restore successionally diverse landscapes that are resistant and resilient to current and future stressors. Maintaining native species and characteristic processes requires this successional diversity, but methods to achieve it are poorly explained in the literature. In the Inland Pacific US, large, old, early seral trees were a key historical feature of many young and old forest successional patches, especially where fires frequently occurred. Large, old trees are naturally fire-tolerant, but today are often threatened by dense understory cohorts that create fuel ladders that alter likely post-fire successional pathways. Reducing these understories can contribute to resistance by creating conditions where canopy trees will survive disturbances and climatic stressors; these survivors are important seed sources, soil protectors, and critical habitat elements. Historical timber harvesting has skewed tree size and age class distributions, created hard edges, and altered native patch sizes. Manipulating these altered forests to promote development of larger patches of older, larger, and more widely-spaced trees with diverse understories will increase landscape resistance to severe fires, and enhance wildlife habitat for underrepresented conditions.

4) Biochar for Forest Restoration in the Western United States
http://greenyourhead.typepad.com/files/biochar_for_forest_restoration_wba_rev.pdf

Abstract

This paper examines the value of biochar for forest restoration in the western forests of the United States, and proposes some economically viable methods for producing it. Western forests have become degraded as a result of even-aged logging and suppression of natural fire regimes. Charcoal from historic wildfires is an important component of soil that has been depleted in forests where fire has been excluded. We review some of the literature reporting on the effects of biochar in forest soils and discuss some forest restoration activities that can replace soil charcoal, thereby increasing carbon sequestration in forest soils, and improving forest health. One important forest restoration activity is removal of small diameter trees and brush that may hamper the reintroduction of natural fire regimes. This material has limited economic value, but it can make good feedstock for biochar production. Biochar produced in the forest can be retained for forest soil improvement. Some fraction of the biochar produced in the forest can be exported for sale as a forest product that can help pay for the removal and treatment of problem biomass. We compare several systems for making biochar in the forest, including new ways to approach burn piles and broadcast burning for the purpose of maximizing charcoal production for use in place to help restore forest soil carbon. Finally, we introduce a new type of pyrolysis that is well suited for mobile biochar production in forest settings -- Flame Cap Pyrolysis -- and provide details of three different biochar production systems using these technologies.

5) Comprehensive Document Containing Cal Fire's Response to the Comments on the Draft Forest Carbon Plan Concept Paper
http://www.fire.ca.gov/fcat/downloads/FCAT_PublicComments_Compilation.pdf

Introduction

This Workshop provided an opportunity for the Forest Carbon Action Team (FCAT) to present a draft Concept Paper for the Forest Carbon Plan (Plan) and to solicit public feedback on their efforts. The Plan, anticipated to be completed by the end of 2016, will provide forest carbon targets and an array of strategies to promote healthy wildland and urban forests. The Concept Paper provides an overview of the proposed goals and strategies of the Plan. It is intended to serve as a discussion document to foster interaction with and feedback from the public as the FCAT continues to develop the Plan.

Presenters:
- Edie Chang, California Air Resources Board, Deputy Executive Officer
- Liz Berger, USDA Forest Service, Regional Forester’s Liaison in Sacramento
- Claire Jahns, California Natural Resources Agency, Assistant Secretary for Climate Issues
- Helge Eng, CAL FIRE, Deputy Director for Resource Management
- Ashley Conrad-Saydah, California Environmental Protection Agency, Deputy Secretary for Climate Policy
- Russ Henly, California Natural Resources Agency, Assistant Secretary of Forest Resources Management
- Klaus Scott, California Air Resources Board, Greenhouse Gas Inventory Branch

6) Towards a global assessment of pyrogenic carbon from vegetation fires.
https://www.ncbi.nlm.nih.gov/pubmed/26010729

Abstract
The production of pyrogenic carbon (PyC; a continuum of organic carbon (C) ranging from partially charred biomass and charcoal to soot) is a widely acknowledged C sink, with the latest estimates indicating that ~50% of the PyC produced by vegetation fires potentially sequesters C over centuries. Nevertheless, the quantitative importance of PyC in the global C balance remains contentious, and therefore, PyC is rarely considered in global C cycle and climate studies. Here we examine the robustness of existing evidence and identify the main research gaps in the production, fluxes and fate of PyC from vegetation fires. Much of the previous work on PyC production has focused on selected components of total PyC generated in vegetation fires, likely leading to underestimates. We suggest that global PyC production could be in the range of 116-385 Tg C yr(-1) , that is ~0.2-0.6% of the annual terrestrial net primary production. According to our estimations, atmospheric emissions of soot/black C might be a smaller fraction of total PyC (<2%) than previously reported. Research on the fate of PyC in the environment has mainly focused on its degradation pathways, and its accumulation and resilience either in situ (surface soils) or in ultimate sinks (marine sediments). Off-site transport, transformation and PyC storage in intermediate pools are often overlooked, which could explain the fate of a substantial fraction of the PyC mobilized annually. We propose new research directions addressing gaps in the global PyC cycle to fully understand the importance of the products of burning in global C cycle dynamics.

7) The global pyrogenic carbon cycle and its impact on the level of atmospheric CO2 over past and future centuries.
https://www.ncbi.nlm.nih.gov/pubmed/27992954

Abstract

The incomplete combustion of vegetation and dead organic matter by landscape fires creates recalcitrant pyrogenic carbon (PyC), which could be consequential for the global carbon budget if changes in fire regime, climate, and atmospheric CO2 were to substantially affect gains and losses of PyC on land and in oceans. Here, we included global PyC cycling in a coupled climate-carbon model to assess the role of PyC in historical and future simulations, accounting for uncertainties through five sets of parameter estimates. We obtained year-2000 global stocks of (Central estimate, likely uncertainty range in parentheses) 86 (11-154), 47 (2-64), and 1129 (90-5892) Pg C for terrestrial residual PyC (RPyC), marine dissolved PyC, and marine particulate PyC, respectively. PyC cycling decreased atmospheric CO2 only slightly between 1751 and 2000 (by 0.8 Pg C for the Central estimate) as PyC-related fluxes changed little over the period. For 2000 to 2300, we combined Representative Concentration Pathways (RCPs) 4.5 and 8.5 with stable or continuously increasing future fire frequencies. For the increasing future fire regime, the production of new RPyC generally outpaced the warming-induced accelerated loss of existing RPyC, so that PyC cycling decreased atmospheric CO2 between 2000 and 2300 for most estimates (by 4-8 Pg C for Central). For the stable fire regime, however, PyC cycling usually increased atmospheric CO2 (by 1-9 Pg C for Central), and only the most extreme choice of parameters maximizing PyC production and minimizing PyC decomposition led to atmospheric CO2 decreases under RCPs 4.5 and 8.5 (by 5-8 Pg C). Our results suggest that PyC cycling will likely reduce the future increase in atmospheric CO2 if landscape fires become much more frequent; however, in the absence of a substantial increase in fire frequency, PyC cycling might contribute to, rather than mitigate, the future increase in atmospheric CO2 .

8) Examining the Potential of Forest Residue-Based Amendments for Post-Wildfire Rehabilitation in Colorado, USA.
https://www.ncbi.nlm.nih.gov/pubmed/28321358

Abstract

Wildfire is a natural disturbance, though elemental losses and changes that occur during combustion and post-fire erosion can have long-term impacts on soil properties, ecosystem productivity, and watershed condition. Here we evaluate the potential of forest residue-based materials to rehabilitate burned soils. We compare soil nutrient and water availability, and plant recovery after application of 37 t ha^{-1} of wood mulch, 20 t ha^{-1} of biochar, and the combination of the two amendments with untreated, burned soils. We also conducted a greenhouse trial to examine how biochar influenced soil nutrient and water content under two wetting regimes. The effects of wood mulch on plant-available soil N and water content were significant and seasonally consistent during the three-year field study. Biochar applied alone had few effects under field conditions, but significantly increased soil pH, Ca, P, and water in the greenhouse. The mulched biochar treatment had the greatest effects on soil N and water availability and increased cover of the most abundant native plant. We found that rehabilitation treatments consisting of forest residue-based products have potential to enhance soil N and water dynamics and plant recovery following severe wildfire and may be justified where erosion risk or water supply protection are crucial.

9) The microbiomes and metagenomes of forest biochars.
https://www.ncbi.nlm.nih.gov/pubmed/27212657

Abstract

Biochar particles have been hypothesized to provide unique microhabitats for a portion of the soil microbial community, but few studies have systematically compared biochar communities to bulk soil communities. Here, we used a combination of sequencing techniques to assess the taxonomic and functional characteristics of microbial communities in four-year-old biochar particles and in adjacent soils across three forest environments. Though effects varied between sites, the microbial community living in and around the biochar particles had significantly lower prokaryotic diversity and higher eukaryotic diversity than the surrounding soil. In particular, the biochar bacterial community had proportionally lower abundance of Acidobacteria, Planctomycetes, and β-Proteobacteria taxa, compared to the soil, while the eukaryotic biochar community had an 11% higher contribution of protists belonging to the Aveolata superphylum. Additionally, we were unable to detect a consistent biochar effect on the genetic functional potential of these microbial communities for the subset of the genetic data for which we were able to assign functions through MG-RAST. Overall, these results show that while biochar particles did select for a unique subset of the biota found in adjacent soils, effects on the microbial genetic functional potential appeared to be specific to contrasting forest soil environments.

10) Biochar application during reforestation alters species present and soil chemistry.
https://www.ncbi.nlm.nih.gov/pubmed/25679816

Abstract

Reforestation of landscapes is being used as a method for tackling climate change through carbon sequestration and land restoration, as well as increasing biodiversity and improving the provision of ecosystem services. The success of reforestation activities can be reduced by adverse field conditions, including those that reduce germination and survival of plants. One method for improving success is biochar addition to soil, which is not only known to improve soil carbon sequestration, but is also known to improve growth, health, germination and survival of plants. In this study, biochar was applied to soil at rates of 0, 1, 3 and 6 t ha(-1) along with a direct-seed forest species mix at three sites in western Victoria, Australia. Changes in soil chemistry, including total carbon, and germination and survival of species were measured over an 18 month period. Biochar was found to significantly increase total carbon by up to 15.6% on soils low in carbon, as well as alter electrical conductivity, Colwell phosphorous and nitrate- and ammonium-nitrogen. Biochar also increased the number of species present, and stem counts of Eucalyptus species whilst decreasing stem counts of Acacia species. Biochar has the potential to positively benefit reforestation activities, but site specific and plant-soil-biochar responses require targeted research.

11) Carbon sequestration potential and physicochemical properties differ between wildfire charcoals and slow-pyrolysis biochars.
https://www.ncbi.nlm.nih.gov/pubmed/28894167

Abstract

Pyrogenic carbon (PyC), produced naturally (wildfire charcoal) and anthropogenically (biochar), is extensively studied due to its importance in several disciplines, including global climate dynamics, agronomy and paleosciences. Charcoal and biochar are commonly used as analogues for each other to infer respective carbon sequestration potentials, production conditions, and environmental roles and fates. The direct comparability of corresponding natural and anthropogenic PyC, however, has never been tested. Here we compared key physicochemical properties (elemental composition, δ13C and PAHs signatures, chemical recalcitrance, density and porosity) and carbon sequestration potentials of PyC materials formed from two identical feedstocks (pine forest floor and wood) under wildfire charring- and slow-pyrolysis conditions. Wildfire charcoals were formed under higher maximum temperatures and oxygen availabilities, but much shorter heating durations than slow-pyrolysis biochars, resulting in differing physicochemical properties. These differences are particularly relevant regarding their respective roles as carbon sinks, as even the wildfire charcoals formed at the highest temperatures had lower carbon sequestration potentials than most slow-pyrolysis biochars. Our results challenge the common notion that natural charcoal and biochar are well suited as proxies for each other, and suggest that biochar's environmental residence time may be underestimated when based on natural charcoal as a proxy, and vice versa.

12) Biochar influences on soil CO2 and CH4 fluxes in response to wetting and drying cycles for a forest soil.
https://www.ncbi.nlm.nih.gov/pubmed/28755008

Abstract

Biochar has been the focus of significant research efforts in agriculture, but little research has been conducted in forested ecosystems. Here, we assess CO2 and CH4 fluxes from a forest soil in response to biochar additions using a before-after-control-intervention experimental design. Soil CO2 and CH4 fluxes were measured over a series of wetting cycles by coupling soil mesocosms equipped with auto-chambers to a laser-based spectrometer for high-frequency measurements of gas fluxes and related soil processes. We found that soil CO2 fluxes were higher and CH4 fluxes were less negative (e.g. reduced CH4 uptake) for the biochar-amended soil compared to the no biochar condition. Furthermore, biochar improved soil infiltrability under wet conditions, and enhanced soil moisture levels under dry conditions. Biochar additions shifted the point of maximum soil respiration (i.e. soil CO2 efflux) to a slightly wetter soil moisture level. The point of maximum CH4 uptake was also shifted to a slightly wetter moisture level for soil with biochar. Overall differences in soil gas fluxes were found to be minor compared to the increase in soil carbon resulting from the biochar addition. Biochar may thus contribute to improved forest management through increases to soil carbon stocks and improved soil moisture levels.

13) Time-lapse effect of ancient plant coal biochar on some soil agrochemical parameters and soil characteristics.
https://www.ncbi.nlm.nih.gov/pubmed/28299568

Abstract

Biochar is a solid material obtained from reductive, oxygen-free processes, i.e. the thermo-chemical conversion of biomass in oxygen-limited environment. The obtained products have high carbon sequestration potential and strong nutrient-water absorption capacities because of the enlarged carbon surfaces. It is not yet clear how carbon stimulates agrochemical parameters in soil and how those characteristics are developing as time goes on a long-term basis. Samples of ancient (25, 35, 80 years old) plant coal-affected soils were collected in a temperate deciduous forest site located in the south part of the Bükk Mountains (in North Eastern Hungary). Physical-chemical soil characteristics, such as soil pH, cation exchange capacity (CEC), the organic and inorganic nitrogen (NH4+, NH3-) and the available nutrients (P2O5 and K2O), were estimated beside organic matter (SOM) content, measured by two different methods. Levels of polycyclic aromatic hydrocarbon (PAH) compounds in soil and in various biochar samples were assessed in relation with permissible limit values and potential toxicity. Positive correlation was found between the amount of available nutrients, total organic nitrogen content, cation exchange capacity and the age of plant coal-affected soils. The sample soils were exposed to continuous plant coal biochar effect for 25 years, during which macronutrients absorbed and accumulated in the plant coal surfaces. After this period, the degradation of carbon developed simultaneously with the reduction of the amount of available nutrients, till the end of the studied 80-year-affecting period. Measured CEC level indicated positive correlation with nutrient availability and the age of biochar-affected soils. Our results support the hypothesis that biochar in soil can improve its general agrochemical characteristics in relation with its persistence in a specific soil-plant system. Potential PAH content and toxicity of biochar products are key issues of developing proper application rates in sustainable agricultural practices.

14) Biochar and its potential in Canadian forestry
http://www.silviculturemagazine.com/articles/winter-2013/biochar-and-its-potential-canadian-forestry

Abstract

A number of processes contribute to post-fire regeneration and rejuvenation. Many tree species show adaptations to survive fire events (e.g., thick insulating bark, high belowground storage), or to regenerate by seed following fire (e.g., the serotinous cones of Jack Pine). In addition, nutrients previously stored in living parts of trees have been released into the system, and soil temperature is increased by a reduction in litter. However, something much less obvious also contributes to post-fire forest rejuvenation: namely, a phenomenon that has been termed the "charcoal effect". In experiments in the 1990s in Scandinavia, additions of charcoal to soils were shown to increase nitrogen

uptake and growth of some trees, and result in a proliferation of understory vegetation. Some fern species would only establish where charcoal was present. An initial hypothesis of the main mechanism responsible was the capacity of charcoal to absorb growth-inhibiting phenolic compounds associated with the leaf litter of certain understory species, in particular Ericaceous shrubs (blueberries and their kin).

15) Biochar and forest restoration: a review and meta-analysis of tree growth responses
https://www.researchgate.net/publication/279197938_Biochar_and_forest_restoration_a_review_and_meta-analysis_of_tree_growth_responses

Analysis

Biochar", or charcoal intended for use as a soil amendment, has received great attention in recent years as a means of enhancing carbon sequestration and soil properties in agricultural systems. Here we address the potential for biochar use in the context of forest restoration, reviewing relevant experimental studies on biochar use in forest ecosystems, the properties of chars generated from wood waste material, and available data on tree growth responses to biochar. To our knowledge the earliest mention of char use as a soil amendment is actually specifically in the context of forest restoration (in the 1820s in Scotland). Wood waste biochars have an unusual set of properties that suggest their applicability in a forest restoration context: namely, high recalcitrance promoting long-lasting effects, retention of cations, anions, and water, in the soil, sorptive properties that can reduce bioavailability of a wide range of toxic materials, and relative ease of production from locally available feedstocks. A meta-analysis of recent studies on biochar responses of woody plants indicates a potential for large tree growth responses to biochar additions, with a mean 41 % increase in biomass. Responses are especially pronounced at early growth stages, and appear to be higher in boreal and tropical than in temperate systems, and in angiosperms than conifers; however, there is high variability, and field studies are few. The properties of biochars also vary greatly depending on feedstock and pyrolysis conditions; while this complicates their use, it provides a means to design biochars for specific restoration situations and objectives. We conclude that there is great promise for biochar to play an important role in a wide variety of forest restoration efforts, specifically as a replacement product for other forms of organic matter and liming agents.

16) Soil and greenhouse gas responses to biochar additions in a temperate hardwood forest
https://onlinelibrary.wiley.com/doi/pdf/10.1111/gcbb.12211

Abstract

Biochar additions can improve soil fertility and sequester carbon, but biochar effects have been investigated primarily in agricultural systems. Biochar from spruce and maple sawdust feedstocks (with and without inorganic phosphorus in a factorial design) were added to plots in a commercially managed temperate hardwood forest stand in central Ontario, Canada; treatments were applied as a top-dressing immediately prior to fall leaf abscission in September 2011. Forests in this region have acidic, sandy soils, and due to nitrogen deposition may exhibit phosphorus, calcium, and magnesium limitation. To investigate short-term impacts of biochar application on soil nutrient supply and greenhouse gas fluxes as compared to phosphorus fertilization, data were collected over the first year after treatment application; linear mixed models were used to analyze data. Two to six weeks after treatment application, there were higher concentrations of potassium in spruce and maple biochar plots, and phosphorus in spruce biochar plots, as compared to the control treatment. There were higher concentrations of calcium, magnesium, and phosphorus in the phosphorus plots. In the following spring and summer (9–12 months after treatment application), there were higher soil calcium concentrations in maple biochar plots, and phosphorus plots still had higher soil phosphorus concentrations than control plots. No treatment effects on fluxes of carbon dioxide, methane, or nitrous oxide were detected in the field; however, laboratory incubations after 12 months showed higher microbial respiration in soils from maple biochar plots as compared to spruce biochar, despite no effect on microbial biomass. The results suggest that the most important short-term impact of biochar additions in this system is the increased supply of the limiting plant nutrients phosphorus and calcium. We expect that larger changes in mineral soil physical and chemical properties will occur when the surface-applied biochar becomes incorporated into the soil after a few years.

17) A Comparison of Producer Gas, Biochar, and Activated Carbon from Two Distributed Scale Thermochemical Conversion Systems Used to Process Forest Biomass
https://www.fs.fed.us/rm/pubs_other/rmrs_2013_anderson_n001.pdf

Abstract
Thermochemical biomass conversion systems have the potential to produce heat, power, fuels and other products from forest biomass at distributed scales that meet the needs of some forest industry facilities. However, many of these systems have not been deployed in this sector and the products they produce from forest biomass have not been adequately described or characterized with regards to chemical properties, possible uses, and markets. This paper characterizes the producer gas, biochar, and activated carbon of a 700 kg h^{-1} prototype gasification system and a 225 kg h^{-1} pyrolysis system used to process coniferous sawmill and forest residues. Producer gas from sawmill residues processed with the gasifier had higher energy content than gas from forest residues, with averages of 12.4 MJ m^{-3} and 9.8 MJ m^{-3} , respectively. Gases from the pyrolysis system averaged 1.3 MJ m^{-3} for mill residues and 2.5 MJ m^{-3} for forest residues. Biochars produced have OPEN ACCESS Energies 2013, 6 165 similar particle size distributions and bulk density, but vary in pH and carbon content. Biochars from both systems were successfully activated using steam activation, with resulting BET surface area in the range of commercial activated carbon. Results are discussed in the context of co-locating these systems with forest industry operations.

18) An Assessment of Forest-based Woody Biomass Supply and Use in Montana
http://www.bber.umt.edu/pubs/forest/biomass/MT_DNRC_Biomass_Report_B&W.pdf

Abstract

This report was prepared at the request of the Montana DNRC and quantifies the volumes of woody biomass supply and use in Montana. Four woody biomass sources were examined: live trees, standing dead trees, logging residue, and primary mill residue. Not all of the woody biomass supply described in this paper is or would be available to users because of various economic, logistic, and social factors. Estimates of the quantity potentially available from live and standing dead trees were made using the latest (2003 to 2007) Forest Inventory and Analysis (FIA) data. Estimates of logging residue and primary mill residue were made using the latest (2004) information in the FIA Timber Products Output (TPO) database.

19) Biochar Amendments To Forest Soils: Effects On Soil Properties and Tree Growth
https://forest.moscowfsl.wsu.edu/smp/solo/documents/GTs/McElligott-Kristin_Thesis.pdf

Results

The results indicate that biochar contributes to notable short-term soil chemical alterations associated with blending the properties of biochar with those of various soil types, but the nature and scope of the alterations vary by soil type and application method. The soil nutrient alterations do not appear to affect tree growth in the short-term, as biochar had a neutral main effect on poplar growth. These results suggest that biochar produced from bioenergy production could be returned to forest soils to replenish soil nutrient stocks and enhance C storage, with little to no effect on tree growth in the short-term. Results from these studies provided a basic understanding of the potential for biochar in our region, and offer several primary implications for biochar management that could contribute to a comprehensive plan for continuing forest bioenergy production systems.

20) Impact of biochar on earthworm populations: A review.
https://pdfs.semanticscholar.org/26a2/ef1f4cefeb32e6a4a59cb957cfc381d05823.pdf

Abstract

Despite the overwhelming importance of earthworm activity in the soil system, there are a limited number of studies that have examined the impact resulting from biochar addition to soil. Biochar is part of the black carbon continuum of chemo-thermal converted biomass. This review summarizes existing data pertaining to earthworms where biochar and other black carbon substances, including slash-and-burn charcoals and wood ash, have been applied. After analyzing existing studies on black carbon, we identified these additions have a range from short-term negative impacts to long-term null effects on earthworm population density and total biomass. Documented cases of mortality were found with certain biochar-soil combinations; the cause is not fully understood, but hypothesized to be related to pH, whether the black carbon is pre-moistened, effects on feeding behaviors, or other unknown factors. With wood ashes, negative impacts were overcome with addition of other carbon substrates. Given that field data is limited, soils amended with biochar did not appear to cause significant long-

term impacts. However, this may indicate that the magnitude of short-term negative impacts on earthworm
populations can be reduced with time.

21) Forest treatment residues for thermal energy compared with disposal by onsite burning: Emissions and energy return
https://www.fs.fed.us/rm/pubs_other/rmrs_2010_jones_g001.pdf

Abstract
Mill residues from forest industries are the source for most of the current wood-based energy in the US, approximately 2.1% of the nation's energy use in 2007. Forest residues from silvicultural treatments, which include limbs, tops, and small non-commercial trees removed for various forest management objectives, represent an additional source of woody biomass for energy. We spatially analyzed collecting, grinding, and hauling forest residue biomass on a 515,900 ha area in western Montana, US, to compare the total emissions of burning forest residues in a boiler for thermal energy with the alternatives of onsite disposal by pile-burning and using either natural gas or #2 distillate oil to produce the equivalent amount of useable energy. When compared to the pile-burn/fossil fuel alternatives, carbon dioxide emissions from the bioenergy alternative were approximately 60%, methane emissions were approximately 3%, and particulate emissions less than 10 mm were 11% and 41%, respectively, for emission control and no-control boilers. Emissions from diesel consumption for collecting, grinding, and hauling biomass represented less than 5% of the total bioenergy emissions at an average haul distance of 136 km. Across the study area, an average 21 units of bioenergy were produced for each unit of diesel energy used to collect, grind, and haul biomass. Fossil fuel energy saved by the bioenergy alternative relative to the pile-burn/fossil fuel alternatives averaged 14.7–15.2 GJ t1 of biomass.

Articles Pertaining to Prescribed Burns

22) A review of prescribed burning effectiveness in fire hazard reduction.
https://www.fs.fed.us/rm/pubs/rmrs_gtr292/2003_fernandes.pdf

Abstract
Mill residues from forest industries are the source for most of the current wood-based energy in the US, approximately 2.1% of the nation's energy use in 2007. Forest residues from silvicultural treatments, which include limbs, tops, and small non-commercial trees removed for various forest management objectives, represent an additional source of woody biomass for energy. We spatially analyzed collecting, grinding, and hauling forest residue biomass on a 515,900 ha area in western Montana, US, to compare the total emissions of burning forest residues in a boiler for thermal energy with the alternatives of onsite disposal by pile-burning and using either natural gas or #2 distillate oil to produce the equivalent amount of useable energy. When compared to the pile-burn/fossil fuel alternatives, carbon dioxide emissions from the bioenergy alternative were approximately 60%, methane emissions were approximately 3%, and particulate emissions less than 10 mm were 11% and 41%, respectively, for emission control and no-control boilers.

Emissions from diesel consumption for collecting, grinding, and hauling biomass represented less than 5% of the total bioenergy emissions at an average haul distance of 136 km. Across the study area, an average 21 units of bioenergy were produced for each unit of diesel energy used to collect, grind, and haul biomass. Fossil fuel energy saved by the bioenergy alternative relative to the pile-burn/fossil fuel alternatives averaged 14.7–15.2 GJ t1 of biomass.

23) Previous burns and topology limit and reinforce fire severity in a large wildfire. NB. This study was conducted in the Sierra Nevada region, thereby making it more relevant to Del Norte County
https://esajournals.onlinelibrary.wiley.com/doi/full/10.1002/ecs2.2019

Abstract

In fire-prone forests, self-reinforcing fire behavior may generate a mosaic of vegetation types and structures. In forests long subject to fire exclusion, such feedbacks may result in forest loss when surface and canopy fuel accumulations lead to unusually severe fires. We examined drivers of fire severity in one large (>1000 km2) wildfire in the western United States, the Rim Fire in the Sierra Nevada, California, and how it was influenced by severity of 21 previous fires to examine the influences on (1) the severity of the first fire since 1984 and (2) reburn severity. The random forest machine-learning statistical model was used to predict satellite-derived fire severity classes from geospatial datasets of fire history, topographic setting, weather, and vegetation type. Topography and inferred weather were the most important variables influencing the previous burn. Previous fire severity was the most important factor influencing reburn severity, and areas tended to reburn at the same severity class as the previous burn. However, areas reburned in <15 yr burned at lower severity than expected. Previous fire severity and Rim Fire severity were higher on ridges, at intermediate elevations (~750–1250 m), and on slopes <30°, indicating a consistent effect of topography on fire severity patterns in these forests. Areas burned with low severity prescribed fires burned at low severity again in the Rim Fire, and areas with long fire-free periods burned at higher severity. This fire history effect suggests that prescribed burning was an effective management tool, leading to lower fire severity in the previous burns and the subsequent reburn. Our results show that self-reinforcing fire behavior results mainly from effects of vegetation structure and fuels on fire severity and that this behavior is mediated by topographic setting and the time since last fire.

24) Fire disturbance and forest structure in old-growth mixed conifer forests in the northern Sierra Nevada.
https://onlinelibrary.wiley.com/doi/pdf/10.1111/j.1654-1103.2007.tb02604.x

Abstract

Question: This study evaluates how fire regimes influence stand structure and dynamics in old-growth mixed conifer forests across a range of environmental settings.

Location: A 2000-ha area of mixed conifer forest on the west shore of Lake Tahoe in the northern Sierra Nevada, California.

Methods: We quantified the age, size, and spatial structure of trees in 12 mixed conifer stands distributed across major topographic gradients. Fire history was reconstructed in each stand using fire scar dendrochronology. The influence of fire on stand structure was assessed by comparing the fire history with the age, size, and spatial structure of trees in a stand.

Results: There was significant variation in species composition among stands, but not in the size, age and spatial patterning of trees. Stands had multiple size and age classes with clusters of similar aged trees occurring at scales of 113 - 254 m2. The frequency and severity of fires was also similar, and stands burned with low to moderate severity in the dormant season on average every 9–17 years. Most fires were not synchronized among stands except in very dry years. No fires have burned since ca. 1880.

Conclusions: Fire and forest structure interact to perpetuate similar stand characteristics across a range of environmental settings. Fire occurrence is controlled primarily by spatial variation in fuel mosaics (e.g. patterns of abundance, fuel moisture, forest structure), but regional drought synchronizes fire in some years. Fire exclusion over the last 120 years has caused compositional and structural shifts in these mixed conifer forests.

25) Can low-severity reverse composition change in montane forests of the Sierra Nevada, California, USA?
https://esajournals.onlinelibrary.wiley.com/doi/full/10.1002/ecs2.1484

Abstract

Throughout the Sierra Nevada, nearly a century of fire suppression has altered the tree species composition, forest structure, and fire regimes that were previously characteristic of montane forests. Species composition is fundamentally important because species differ in their tolerances to fire and environmental stressors, and these differences dictate future forest structure and influence fire regime attributes. In some lower montane stands, shade-tolerant, fire-sensitive species have driven a threefold increase in tree density that may intensify the risk of high-severity fire.

26) The Effect of Fire on Soil Properties
https://forest.moscowfsl.wsu.edu/smp/solo/documents/GTRs/INT_280/DeBano_INT-280.php

Abstract

Fire affects nutrient cycling and the physical, chemical, and biological properties of soils occupied by western-montane forests. Combustion of litter and soil organic matter (OM) increases the availability of some nutrients, although others are volatilized (for example, N, P, S). Soil OM loss also affects cation exchange capacity, organic chelation, aggregate stability, macro pore space, infiltration, and soil microorganisms. Nitrogen replenishment must be emphasized when prescribed burning programs are planned or during rehabilitation following wildfires.

27) Biochar: A better, greener way to fight forest fires
https://sustainabletechnologyforum.com/biochar-a-better-greener-way-to-fight-forest-fires_11949.html

Sample

Decades of suppressing naturally occurring forest fires, combined with continuous years of drought and millions of beetle-killed trees have caused forests to become overloaded with dried slash and standing deadwood, which has created massive tonnage of forest-fire fuel known as forest biomass. In 2009, the US Forest Service allocated $279 million for preventative measures, or "hazardous fuel reduction," over a 1.5 million-acre area. This represents less than 1 per cent of the high-risk WUI acreage, the land needing protection, as it totals 600 million acres, endangering 40 per cent of all US homes and 140 million people.

28) Restoring and managing low-severity fire in dry-forest landscapes of the Western USA
https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5310858/

Abridged Abstract

Low-severity fires that killed few canopy trees played a significant historical role in dry forests of the western USA and warrant restoration and management, but historical rates of burning remain uncertain. Past reconstructions focused on on dating fire years, not measuring historical rates of burning. Past statistics, including mean composite fire interval (mean CFI) and individual-tree fire interval (mean ITFI) have biases and inaccuracies if used as estimators of rates. In this study, I used regression, with a calibration dataset of 96 cases, to test whether these statistics could accurately predict two equivalent historical rates, population mean fire interval (PMFI) and fire rotation (FR)… Historical fuels (e.g., understory shrubs and small trees) could fully recover between multidecadal fires, allowing some denser forests and some ecosystem processes and wildlife habitat to be less limited by fire. Lower historical rates mean less restoration treatment is needed before beginning managed fire for resource benefits, where feasible. Mimicking patterns of variability in historical low-severity fire regimes would likely benefit biological diversity and ecosystem functioning.

29) The role of fire as a mineralizing agent in a Sierran coniferous forest
https://link.springer.com/article/10.1007/BF00345032

Abstract

The role of fire as an agent for mineralizing forest floor organic matter was investigated in a Sierra Nevada sequoia-mixed conifer forest. Soil chemical properties were determined in a series of small paired plots on and adjacent to burns done by the National Park Service in their control burn program. Total nitrogen, carbon, and cation exchange capacity were found to be significantly lower on burned plots, and phosphorus, calcium, magnesium, potassium, and pH were significantly higher on burned plots. The seasonal course of certain soil chemical properties was determined in a single set of larger plots.

Total nitrogen, nitrate, ammonium, phosphorus, and pH were shown to increase in the spring. It is concluded that fire is an effective but not a conservative mineralizing agent.

Studies Involving Kilns

30) Biochar from "Kon Tiki" flame curtain and other kilns: Effects of nutrient enrichment and kiln type on crop yield and soil chemistry.
https://www.ncbi.nlm.nih.gov/pubmed/28448621

Abstract

Biochar application to soils has been investigated as a means of improving soil fertility and mitigating climate change through soil carbon sequestration. In the present work, the invasive shrub "Eupatorium adenophorum" was utilized as a sustainable feedstock for making biochar under different pyrolysis conditions in Nepal. Biochar was produced using several different types of kilns; four sub types of flame curtain kilns (deep-cone metal kiln, steel shielded soil pit, conical soil pit and steel small cone), brick-made traditional kiln, traditional earth-mound kiln and top lift up draft (TLUD). The resultant biochars showed consistent pH (9.1 ± 0.3), cation exchange capacities (133 ± 37 cmolc kg-1), organic carbon contents (73.9 ± 6.4%) and surface areas (35 to 215 m2/g) for all kiln types. A pot trial with maize was carried out to investigate the effect on maize biomass production of the biochars made with various kilns, applied at 1% and 4% dosages. Biochars were either pretreated with hot or cold mineral nutrient enrichment (mixing with a nutrient solution before or after cooling down, respectively), or added separately from the same nutrient dosages to the soil. Significantly higher CEC ($P < 0.05$), lower Al/Ca ratios ($P < 0.05$), and high OC% ($P < 0.001$) were observed for both dosages of biochar as compared to non-amended control soils. Importantly, the study showed that biochar made by flame curtain kilns resulted in the same agronomic effect as biochar made by the other kilns ($P > 0.05$). At a dosage of 1% biochar, the hot nutrient-enriched biochar led to significant increases of 153% in above ground biomass production compared to cold nutrient-enriched biochar and 209% compared to biochar added separately from the nutrients. Liquid nutrient enhancement of biochar thus improved fertilizer effectiveness compared to separate application of biochar and fertilizer.

31) Production of Biochar for Soil Application: A Comparative Study of Three Kiln Models
https://www.sciencedirect.com/science/article/pii/S1002016015300503

Abridged Abstract

Biochar has potentials for soil fertility improvement, climate change mitigation and environmental reclamation, and charred biomass can be deliberately incorporated into soil for long-term carbon stabilization and soil amendment. Many different methods have been used for biochar production ranging from laboratory to industrial scales. However, in countryside of developing countries, biomass is generally used for cooking but not charred. Biochar production techniques at farmer scale have remained poorly developed… Quality of biochar was found to be mainly related to pyrolysis time. The costs for the biochar stove and pit kiln were US$ 65–77, while it was US$ 154 for the large size steel kiln.

Economics of Biochar

32) Use of mobile fast pyrolysis plants to densify biomass and reduce biomass handling costs - a preliminary assessment.

Abstract

ROI BioOil plants can be made modular and transportable, allowing them to be located close to the source of biomass and the subsequent transportation of high energy density BioOil to a central plant. Conversely, one central BioOil plant could supply several energy users in distributed locations, or several plants could supply numerous end-users, just as in the petroleum industry. Renewable Oil International® LLC (ROI) is one of several developers of fast pyrolysis technology. The production of BioOil can convert raw biomass into a low-viscosity liquid that, depending on the moisture content of the feedstock, increases the energy density of biomass by a factor of 6 to 7 times over green wood chips. The increase in energy density increases the amount of energy that can be hauled by standard tanker trucks versus a chip trailer van by a factor of two. Capital costs, exclusive of land costs, are comparable for a 50 MWe biomass handling system at the power plant. Land area requirements for fuel storage and handling are reduced roughly half for BioOil systems versus solid fuel handling systems. No analysis was made of operating and maintenance costs.

Biochar for Restoration

33) A review of biochars' potential role in the remediation, revegetation and restoration of contaminated soils.
https://www.ncbi.nlm.nih.gov/pubmed/21855187

Abstract

Biochars are biological residues combusted under low oxygen conditions, resulting in a porous, low density carbon rich material. Their large surface areas and cation exchange capacities, determined to a large extent by source materials and pyrolysis temperatures, enables enhanced sorption of both organic and inorganic contaminants to their surfaces, reducing pollutant mobility when amending contaminated soils. Liming effects or release of carbon into soil solution may increase arsenic mobility, whilst low capital but enhanced retention of plant nutrients can restrict revegetation on degraded soils amended only with biochars; the combination of composts, manures and other amendments with biochars could be their most effective deployment to soils requiring stabilisation by revegetation. Specific mechanisms of contaminant-biochar retention and release over time and the environmental impact of biochar amendments on soil organisms remain somewhat unclear but must be investigated to ensure that the management of environmental pollution coincides with ecological sustainability.

34) Biochar for Forest Restoration in Western States
https://forestry.usu.edu/files-ou/UFF34May2017.pdf

Abstract
Forest restoration projects in the western United States, including thinning for hazardous fuel reduction, leave behind a significant amount of wood waste or biomass, which include small-diameter logs, tree tops, and branches, as well as needles, leaves, and sometimes roots. These materials, also called forest residue or slash, are usually gathered into large piles and burned or left to decompose (Sue et al. 2016). This biomass almost always goes unused due to the wide price gap between high harvesting and transportation costs and low market values. However, a product called biochar is giving new hope for forest restoration in the West.

35) Characteristics of biochar and its application in remediation of contaminated soil.
https://www.ncbi.nlm.nih.gov/pubmed/23810668

Abstract
Biochar is produced by thermal decomposition of biomass under oxygen-limited conditions (pyrolysis), and it has received attention in soil remediation and waste disposal in recent years. The characteristics of biochar are influenced mainly by the preparation temperature and biomass. Higher pyrolysis temperature often results in the increased surface area and carbonized fraction of biochar leading to high sorption capability for pollutants. Biochars derived from various source materials show different properties of surface area, porosity and the amount of functional groups which are important concerning on the effect of biochar. Biochar has been proved to be effective in improving soil properties and increasing crop biomass. It has also been suggested that it can even enhance crop resistance to disease. Biochar has recently been used to remediate soil with both heavy metal and organic pollutants. The mechanism is electrostatic interaction and precipitation in the case of heavy metal, and the surface adsorption, partition and sequestration in the case of organic contaminants. However, application of biochar in soil has been shown to result in decreased efficacy of pesticides, which indicates a trade-off between the potentially promising effect of biochar on pesticide remediation and its negative effect on pesticide efficacy. While arguments on the effectiveness of biochar appear sound, further research is needed prior to widespread application of biochar in soil remediation.

36) Reduced plant uptake of pesticides with biochar additions to soil.
https://www.ncbi.nlm.nih.gov/pubmed/19419749

Abstract
We investigated the effectiveness of two types of biochars in reducing the bioavailability of two soil-applied insecticides (chlorpyrifos and carbofuran) to Spring onion (Allium cepa). The biochars prepared from the pyrolysis of Eucalyptus spp. wood chips at 450 and 850 degrees C (BC850) were thoroughly mixed into the soil to achieve 0%, 0.1%, 0.5% and 1% by soil weight. A spring onion crop was grown for 5 wk in the biochar-amended soils spiked with 50 mgkg(-1) of each pesticide. The loss of both pesticides due to degradation and or sequestration in soils decreased significantly with increasing amounts of biochars in soil. Over 35 d, 86-88% of the pesticides were lost from the

control soil, whereas it was only 51% of carbofuran and 44% of chlorpyrifos from the soil amended with 1.0% BC850. Despite greater persistence of the pesticide residues in biochar-amended soils, the plant uptake of pesticides decreased markedly with increasing biochar content of the soil. With 1% of BC850 soil amendment, the total plant residues for chlorpyrifos and carbofuran decreased to 10% and 25% of that in the control treatment, respectively. The BC850 was particularly effective in reducing phytoavailability of both pesticides from soil, due to its high affinity for and ability to sequester pesticide residues.

37) The effects of short term, long term and reapplication of biochar on soil bacteria.
https://www.ncbi.nlm.nih.gov/pubmed/29704711

Abstract

Biochar has been shown to affect soil microbial diversity and abundance. Soil microbes play a key role in soil nutrient cycling, but there is still a dearth of knowledge on the responses of soil microbes to biochar amendments, particularly for longer-term or repeated applications. We sampled soil from a field trial to determine the individual and combined effects of newly applied (1 year ago), re-applied (1 year ago into aged biochar) and aged (9 years ago) biochar amendments on soil bacterial communities, with the aim of identifying the potential underlying mechanisms or consequences of these effects. Soil bacterial diversity and community composition were analysed by sequencing of 16S rRNA using a Miseq platform. This investigation showed that biochar in soil after 1 year significantly increased bacterial diversity and the relative abundance of nitrifiers and bacteria consuming pyrogenic carbon (C). We also found that the reapplication of biochar had no significant effects on soil bacterial communities. Mantel correlation between bacterial diversity and soil chemical properties for four treatments showed that the changes in soil microbial community composition were well explained by soil pH, electrical conductivity (EC), extractable organic C and total extractable nitrogen (N). These results suggested that the effects of biochar amendment on soil bacterial communities were highly time-dependent. Our study highlighted the acclimation of soil bacteria on receiving repeated biochar amendment, leading to similar bacterial diversity and community structure among 9-years old applied biochar, repeated biochar treatments and control.

Potential Biochar Risks and Guidelines

38) Selected dark sides of biomass-derived biochars as environmental amendments.
https://www.ncbi.nlm.nih.gov/pubmed/28391921

Abstract

With the rapid increase in the application of biochars as amendments, studies are needed to clarify the possible environmental risks derived from biochars to use safely the biomass resources. This work reported selected dark sides of maize straw- and swine manure-derived biochars pyrolyzed at 300 and 500°C. During the pyrolysis processes, total heavy metals in the biochars were enriched greatly accompanying with considerable emission of the heavy metals into atmosphere and the trends became increasingly obvious with pyrolysis temperature. Meanwhile, the biochars showed distinctly decreased available heavy metals compared with raw feedstocks, which could be mainly attributed to the sorption by the inorganics in the biochars. The water- and acid-washing treatments significantly increased the releasing risks of heavy metals from biochars into the environments. Electron paramagnetic resonance analysis indicated that persistent free radicals, emerged strongly in the biochars as a function of the aromatization of biomass feedstocks, were free from the influence of water-, acid-, or organic-washing of the biochars and could remain stable even after aged in soils for 30days. Dissolved biochars, highly produced during pyrolysis processes, showed distinct properties including lower molecular weight distribution while higher aromaticity compared with soil dissolved organic carbon. The results of this study provide important perspectives on the safe usage of biochars as agricultural/environmental amendments.

39) Biochar as a Geoengineering Climate Solution: Hazard Identification and Risk Management – Doctoral Thesis of Adriana Downie
https://www.researchgate.net/file.PostFileLoader.html?id=56fe3ffdcbd5c2fea60f23c1&assetKey=AS:345995234824195@1459503101615

Abstract
This thesis makes a significant contribution to the field of biochar production and use in developing several aspects of its physical characterization, environmental sustainability, risks, and opportunities. The investigation builds the evidence and methods

40) Agronomic and remedial benefits and risks of applying biochar to soil: Current knowledge and future research directions
https://www.sciencedirect.com/science/article/pii/S0160412015300842

Abstract
'Biochar' represents an emerging technology that is increasingly being recognized for its potential role in carbon sequestration, reducing greenhouse gas emissions, waste management, renewable energy, soil improvement, crop productivity enhancement and environmental remediation. Published reviews have so far focused mainly on the above listed agronomic and environmental benefits of applying biochar, yet paid little or no attention to its harmful effects on the ecological system. This review highlights a balanced overview of the advantages and disadvantages of the pyrolysis process of biochar production, end-product quality and the benefits versus drawbacks of biochar on: (a) soil geochemistry and albedo, (b) microflora and fauna, (c) agrochemicals, (d) greenhouse gas efflux, (e) nutrients, (f) crop yield, and (g) contaminants (organic and inorganic). Future research should focus more on the unintended long-term consequences of biochar on biological organisms and their processes in the soil.

41) Biochar as a Geoengineering Climate Solution: Hazard Identification and Risk Management
https://www.tandfonline.com/doi/abs/10.1080/10643389.2010.507980

Abstract

Biochar technology has been proposed as a geoengineering solution that has potential to actively reduce the atmospheric concentrations of greenhouse gases and enhance the sustainability of agriculture. The magnitude of the technologies' net benefit must be considered in relation to the associated risks. Hazards posed by biochar technology need to be managed to a level that the resulting risks are deemed acceptable by society; identification of hazards is an essential first step. Effectively implemented risk management and sustainability guidelines, driven by informed policy directives, will result in biochar technology being an important tool for environmental and atmospheric greenhouse gas management.

42) Guidelines for the Development and Testing of Pyrolysis Plants to Produce Biochar
http://www.biochar-international.org/sites/default/files/IBI_Pyrolysis_Plant_Guidelines.pdf

Abstract

This document was produced to assist in the development and testing of small pyrolysis plants and provides advice on equipment design and testing as well as the specification and testing of the biochar product. The International Biochar Initiative encourages innovation and development of biochar production technologies at all scales. Because there are personal and environmental health and safety risks inherent in producing biochar, IBI has developed these Guidelines to assist in the safe and effective development and testing of biochar production technologies. The top concerns are to:

- Ensure the safety of equipment operators and the general public
- Minimise emissions of atmospheric contaminants
- Produce biochar that is suitable for soil application (refer to documentation of International Biochar Initiative's Characterisation Workgroup for parameters).

IBI seeks to promote biochar for environmental management and biochar production methods which are safe and beneficial for people and the environment.

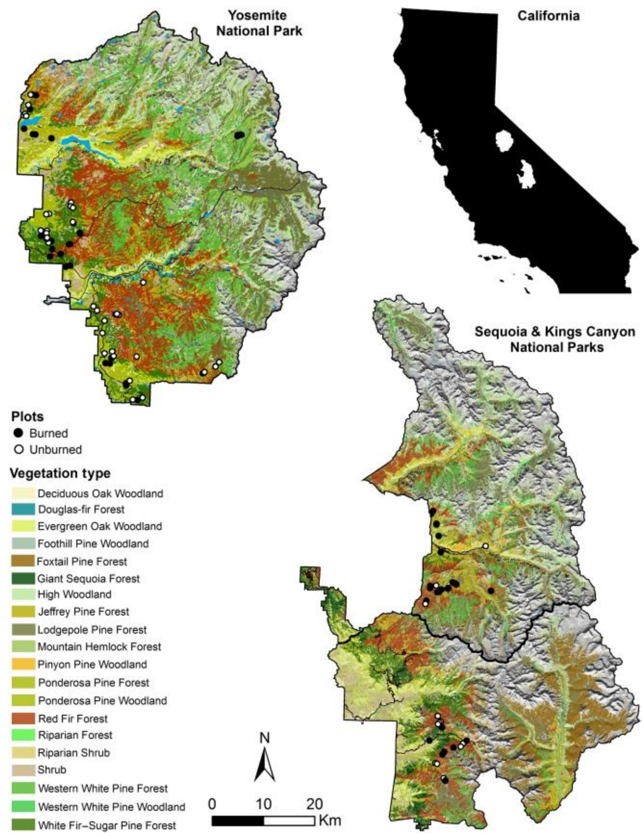
43) The 1978 National Fire-Danger Rating System- USDA Forest Service
https://www.fs.usda.gov/treesearch/pubs/27298

Abstract

Updating the National Fire-Danger Rating System (NFDRS) was completed in 1977, and operational use of it was begun the next year. The System provides a guide to wildfire control and suppression by its indexes that measure the relative potential of initiating fires. Such fires do not behave erratically–they spread without spotting through continuous ground fuels. Estimates of fire potential have a basis in the mathematical models used for fire behavior. The fire manager must select the fuel model that best represents the fuels in the protection area. Among the 20 fuel models available, not more than two or three are appropriate for any one area. This documentation of the 20 fuel models and their equations supplements previous reports on the System. The equations are presented in the coded format of FORTRAN and BASIC computer languages.

Miscellaneous Supporting Images

Map of Vegetation Types in California (Taken from https://esajournals.onlinelibrary.wiley.com/doi/full/10.1002/ecs2.1484)



Source: https://wol-prod-cdn.literatumonline.com/cms/attachment/d54b7145-1ddb-4c4d-a8b7-e875c88b22bd/ecs21484-fig-0001-m.jpg