Biochar as an adaptation strategy for climate change:
Mechanistic, social and systems understanding of biochar use for climate change adaptation and resource management in Indonesia.

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Biochar is the carbon-rich solid product that remains following the pyrolysis of organic agricultural waste. When mixed in to soil, biochar: 1) remains stable, and thus its carbon is sequestered (greenhouse gas (GHG) mitigation), 2) suppresses emissions of other GHGs, nitrous oxide and methane (GHG mitigation), 3) utilises agricultural waste and generates energy (climate change adaptation) 4) increases soil fertility of degraded tropical lands potentially increasing harvest yields (climate change adaptation and poverty reduction) and 5) is able to strongly sorb contaminants thus remediating soil.

In this project implementation and socio-economic issues of the application of biochar to degraded Indonesian soils was investigated. The mechanisms of how and whether biochar is able to improve crop yield were investigated using controlled field trials on a strongly acidic soil. A substantial increase in yield was observed for maize when two different biochars were amended at two different doses. A liming effect and a nutrient addition effect, mainly of potassium, were observed to be responsible for the increase in yield.

More basic fundamental biochar related research was carried out through several laboratory-based experiments. Several problematic organic and inorganic pollutants were chosen as model compounds in order to investigate binding to biochar. The sorption of the legacy pesticides hexachlorocyclohexanes (HCH) to several biochars was determined, with differences arising due to isomer stereochemistry and biochar type. Per- and polyfluoroalkyl substances (PFAS) and heavy metal contaminated soils were treated with designer biochars that were intended for use as remediation sorbents. Activation and iron enrichment had a large positive effect of remediation efficacy for the PFAS and heavy metal contaminated soils, respectively. Biochar amendment to soil in order to sequester PCBs and reduce bioavailability to passive samplers and plants was successfully demonstrated. Parallel experiments were carried out in order to investigate the sorption, bioavailability, bioaccessibility and ecotoxicity of pyrene, PCB 52, and p,p’-DDE in polluted soil. Biochar was able to reduce bioaccessibility and ecotoxicity through a strong sorption.

Social research identified the barriers and opportunities for implementation of biochar in Indonesia and a life cycle assessment comparing the use of biochar to conventional energy production and farming was carried out. Economic factors were addressed via a cost-benefit analysis to assess whether different biochar technologies are favourable compared to composting considering social benefits compared to costs.

The project was a successful collaboration between the Norwegian Geotechnical Institute (NGI), the Norwegian University of Life Sciences (NMBU), the Technical University Trondheim, Norway (NTNU), Menon Economics, the Danish Technical University (DTU), The United Nations development program (UNDP) and the Indonesian Soil Research Institute (ISRI).

Several spin-off projects resulted from the work. The first of which was an Indonesian contribution to the Biochar for Sustainable Soils project, where around thirty farmers were trained in biochar making in two districts on Java and Sumatra. The second was the use of biochar in Brazilian soils to improve pasture crop growth.
Project introduction

Biochar is the charcoal product obtained when agricultural waste is heated with limited access to oxygen (pyrolysis). In contrast to organic material, biochar is stable for thousands of years when mixed into soils, and thus represents carbon that is actively removed from the short-lived carbon cycle. Biochar was pointed out in the IPCC Fourth Assessment Report as a key technology for reaching low carbon dioxide atmospheric concentration targets. The first and second of the United Nations sustainable development goals are “End poverty in all its forms everywhere” and “No hunger”. Biochar can be added to soils in order to increase crop yields, thus positively contributing to achieving these goals.

According to the Economist in 2016, Indonesia had the largest economy in Southeast Asia and is one of the emerging market economies of the world. The country is classified as a low-middle-income country, with a per capita GDP of 3,500 US$. It is the sixteenth largest economy in the world by nominal Gross Domestic Product (GDP) and is the seventh largest in terms of GDP (on Purchase-Power Parity, PPP).

Indonesia’s total land area is 190 million hectares and the total area of acidic upland is approximately 103 million hectares. Of this area, about 56 million hectares is suitable for agricultural practice. It is this acidic upland that could benefit from the addition of biochar. The acidic upland soils have agricultural limitations primarily related to their acidic nature, high content of phyto-toxic metals such as aluminum, nutrient deficiencies and in some cases water limitations. Biochar can be rich in alkaline components (Ca, Mg, K) and can contribute to the neutralization of soil acidity and to a decrease in the solubility of aluminum. In addition to these benefits, biochar can hold and exchange nutrients (N, K, Ca) as well as contribute K.

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Biochar is also able to sequester organic pollutants due to its inherent physicochemical properties. Biochar is composed of rigid and planar stacks of highly disordered polyaromatic hydrocarbon sheets (graphene) with relatively few polar functionalities (ketone, ether, hydroxyl, quinoid, carboxyl and other functional groups) on its surface. Biochar has a high carbon content, a large microporous network and a high surface area. These are responsible for the high sorption strength of organic compounds to biochar.

This project mainly focused on the stabilization of soil pollutants, and soil fertility improvement and poverty reduction. Desk, laboratory and field work was carried out in Norway and Indonesia to answer real world and mechanistic questions.

FACTS

The use of biochar combines a number of important benefits:

1) carbon sequestration and reduction of other GHG gas emissions (N₂O and CH₄),
2) waste management and energy production,
3) stabilization of soil pollutants
4) soil fertility improvement and poverty reduction.
Project aims and objectives

The main aims of the research were to:

1. Elucidate the mechanisms of biochar’s potential to improve soil fertility in degraded Indonesian soils.
2. Investigate the remediation of organic pollutants by biochar in contaminated soils in order to reduce plant and biota toxicity and bioavailability.
3. Combine socio and economic data to obtain life-cycle analyses and cost-benefit analyses for a system understanding of optimal implementation strategies and economic consequences of biochar use.

PROJECT CONSORTIUM

The project consortium brought together lead researchers with environmental, social and economic backgrounds from Norway, Denmark and Indonesia. The project was led by the Norwegian Geotechnical Institute (NGI) in collaboration with the Norwegian University of Life Sciences (NMBU), the Technical University Trondheim, Norway (NTNU), Menon Economics, the Danish Technical University (DTU), The United Nations development program (UNDP) and the Indonesian Soil Research Institute (ISRI). Dr Sarah Hale from NGI was the project leader (sah@ngi.no).

Improving agricultural soil in Indonesia: Field trials

As discussed previously, there are several inherent properties of degraded acidic Indonesian soils which limit crop growth and can be overcome by the addition of biochar. These ultisols require significant liming or the addition of organic matter to remediate Al toxicity and since biochar contains a major ash component, which is alkaline in nature, it can be used with this goal in mind.

During the project, two extensive field trials at an experimental farm in the Lampung district, South Sumatra, were carried out to test this hypothesis. In the first field trial, two biochars made from cacao shell and rice husk were added to the soil at dosages of 0, 5 and 15 tons/ha in five replicate plots and the field trial carried out for 5 seasons. Prior to the amendment of biochar, the soil had high levels of exchangeable aluminium (Al; around 2 cmol, kg$^{-1}$) and a very low pH (3.6 in KCl). The Lampung district has high rainfall (1796 mm) and temperatures (30 °C) throughout the year, and thus a high soil leaching and weathering potential.

The hypotheses for this study were that:

- agronomic effects of biochar amendment could be explained by reduced soil acidity, as expressed by reduced exchangeable Al$^{3+}$ concentrations as well as increased pH, Ca/Al ratios, and base saturation.
- the biochar effectiveness on crop yield would decline over time, due to continued nutrient leaching and rapid depletion of the biochar alkalinity.

The cacao shell biochar exhibited a much higher acid neutralizing capacity than the rice husk biochar (ANC, 217 cmolc kg$^{-1}$ vs. 45 cmolc kg$^{-1}$, respectively), resulting in a much higher alkalinity and subsequent effect on maize yield. The amendment of 5 t/ha cacao shell biochar alleviated the deleterious effects of Al$^{3+}$ and improved maize emergence and grain yield. The 15 t/ha biochar dose had an even stronger positive effect on maize yield in all seasons except the first one.

The hypotheses for this study were that:

The maize yield obtained with the 15 t/ha cacao shell biochar peaked in season 2, continued to have a good
effect in seasons 3 and 4 and started to fade during season 5. For the 5 t/ha dose, this decline was already seen from season 3 onwards. This effect was attributed to leaching of the alkaline ashes in the humid tropical climate with high rainfall.

Results from the field trial support both of the hypotheses above. The primary cause of increased crop production in this Ultisol due to biochar addition was related to the biochars acid neutralizing capacity. When added to soil biochar exhibited a liming effect, causing a significant decline in toxic Al. The effect of biochar was reduced over time, showing that multiple biochar amendments are necessary if the effect is to be sustained.

In field trial two, a more mechanistic approach was taken in order to investigate which mechanisms caused the increase the yield of maize. More specifically, the field trial addressed whether an alleviation of soil acidity (liming mechanism), or an increase of nutrients (nutrient addition) could explain observed effects. A similar controlled field trial was carried out, this time over seven planting seasons using five different amendments; control, biochar, lime, washed biochar and ash. The postulated biochar liming mechanism was probed by comparing the amendment of biochar to lime (in plots with the same pH) and the postulated improvement in nutrient availability was probed by comparing the amendment of washed biochar (to remove the ash component) with pure ash produced from the same amount of feedstock.

Results from the field trial show that the control plot receiving just NPK fertilizer and urea had a very low, or no, yield. All treatments increased the yield and by an average of; seven times for the lime treatment, five times for the lime treatment, five times for the washed treatment and eight times for the ash treatment, over the seven planting seasons. In concurrence with the first field trial, the grain yield for the biochar, lime and washed biochar treatments decreased over time, while for the ash treatment it was sustained.

When comparing the biochar and the lime treatments, it was the lime treatment that resulted in the highest pH and the lowest Al³⁺ concentrations in soil. However, it was the biochar treatment that produced the highest maize yield. This result shows that while there is a liming effect at play, there are additional properties of the biochar that further improve the soil and result in a more conducive growth environment.

When comparing the ash treatment to the washed biochar treatment, it was the ash treatment that resulted in the highest maize yield. The water washing of the biochar removes the ash fraction which contains important macro and micro nutrients, which is all that remains in the ash treatment. It is the ash treatment contained the greatest concentrations of the most important nutrients; P, K, Ca and Mg. The base saturation showed a similar trend, and these combined provide direct evidence that the ash treatment is providing a nutrient addition effect, most likely by the addition of K, as well as its pH effect, resulting in the highest maize yield.

Shovelomics is a tool that allows differences in plant root systems to be visualized. Top photograph; control without any treatment, middle photograph; biochar treatment and bottom photograph; ash treatment.

For more information related to this work please refer to:

Cornelissen, G; Jubaedah; Nurida, NL; Hale, SE; Martinse, V; Silvani, L; Mulder, J (2018), "Fading positive effect of biochar on crop yield and soil acidity during five growth seasons in an Indonesian Ultisol". Science of the total environment, 634, 561-571
Fundamental biochar research:
The removal of hexachlorocyclohexanes from contaminated water via the addition of biochar

Hexachlorocyclohexanes (HCH) are halogenated compounds comprising 4 isomers: α-HCH, β-HCH, γ-HCH and δ-HCH, which differ in their tridimensional structure. HCH has been extensively used as a pesticide despite the fact that only γ-HCH (lindane) has insecticide properties. HCHs are toxic, carcinogenic, teratogenic and neurotoxic to humans and HCHs accumulate in the environment. Remediation techniques are needed that are cost effective and sustainable in order to address this worldwide problem.

The addition of biochar to an aqueous solution containing HCHs was tested in this work. Three biochars from different feedstocks; digestate (BCd), greenhouse tomato waste (BCgtw) and durian shell (BCds) were tested. The biochars had very diverse properties; with surface areas between 5.4 and 328.6 m² g⁻¹, pore volumes between 5.1 and 186.6 cm³ g⁻¹, pore dimension ranging from 1.05 to 5.85 Å, and were made at pyrolysis temperatures between 400 and 700 ºC.

Sorption was dictated by both biochar physicochemical properties and HCH isomer stereochemistry. Freundlich adsorption constants (Log KF) values ranged from 3.7 to 5.8 (µg kg⁻¹) (µg L⁻¹)n for the isomers and the three biochars. No competition was observed between α-, β-, γ- and δ-HCH for any of the biochars. Log KF values for α-, γ- and δ-HCH followed the order: BC digestate > BC greenhouse tomato waste > BC durian shell, in contrast to β-HCH which followed the order: BC durian shell > BC greenhouse tomato waste > BC digestate. Biochar surface area and iron content were the primary biochar physicochemical properties that affected sorption.

The production of biochar in Indonesia

The sorption of hexachlorocyclohexanes to biochar is dictated by HCH stereochemistry and biochar physicochemical properties.

For more information related to this work please refer to:
Silvani, L; Cornelissen, G; Hale, SE, 2019, “Sorption of alpha-, beta-, gamma- and delta-hexachlorocyclohexane isomers to three widely different biochars: Sorption mechanisms and application”, Chemosphere, 219, 1044-1051
Fundamental biochar research:
The remediation of per- and polyfluorinated alkyl substances and heavy metal contaminated soils

Per- and polyfluorinated alkyl substances (PFAS) are hydrophobic, fluorine alkylated, saturated carbon chain compounds with a hydrophilic sulfonate or carboxylate head attached at a terminal end. PFAS are mobile in the environment and have even been found in remote areas like the Arctic and Antarctic. These compounds have begun to attract a great deal of regulatory attention and some of the class of compounds have been placed on the REACH list of substances of very high concern. Shooting range soils often contain high levels of lead (Pb) and antimony (Sb) that arise from the weathering of spent bullets. The highest Pb and Sb concentrations are usually found near bullet traps, however, due to weathering of spent bullets and metal mobility, the pollution can become highly diffuse and persist for hundreds of years. Both types of pollutants result in a large problem with respect to the contamination of soils.

In this research, designer biochars were used in order to test whether they could remediate PFAS and heavy metal polluted soils with varying total organic carbon contents (either low TOC moraine soil or high TOC peat soil). For the PFAS contaminated soil a waste timber biochar (BC) and an activated coconut shell biochar (aBC) were tested. The activation process resulted in a biochar with a high surface area, and thus “designed” for remediation of PFAS contaminated soils. For the heavy metal contaminated soils, the waste timber biochar and a wood shrub iron enriched biochar (Fe-BC) were used. Enrichment with iron resulted in a biochar that was “designed” for the remediation of heavy metal soils. The biochars were added to the soils at doses varying from 1 to 20 weight %.

Amending 20% BC to the low TOC soil led to reductions in leachate concentrations of 86% for PFOS. For the same soil, the amendment of 1% aBC resulted in a reduction of greater than 99.7% for PFOS. BC significantly reduced the concentration of Pb and Sb compared to the unamended control. Amending 20% BC to the low TOC soil led to reductions of 61 and 12% for Pb and Sb concentrations. In contrast, amending 20% of Fe-BC, reduced Pb concentrations by 98% and Sb concentrations by 47%.

For the high TOC soil contaminated with PFAS, the amendment of BC did not lead to any significant reduction of PFOS leachate concentrations. However, for the aBC, the amendment of 1% resulted in a reduction of 96% for PFOS and increasing the amendment dose to 20% resulted in a reduction of ≥ 99%. With regard to the heavy metals in the high TOC soil, the amendment of 20% BC resulted in the removal of 40% and 90% Pb and Sb. In contrast to this, the amendment of 20% Fe-BC led to an improved effect for Pb (reduction of 75%), but a lower effect for Sb (60% reduction).

The sorption of PFOS, PFHxS, PFOA or PFHxA to biochar and activated biochar in the low TOC soil (top panels). The sorption of Pb and Sb to biochar and iron enriched biochar in the low TOC soil (bottom panels). The data are plotted as the ratio between the concentration in the leachate water after and before biochar amendment. The smaller this number, the greater the effect of biochar remediation.
Fundamental biochar research: Waste timber pyrolysis in a medium-scale unit

During the pyrolysis process to make biochar, carbon-containing gases are emitted, mainly volatile organic carbon species, carbon monoxide and aerosols. In modern pyrolysis units, gases are after-combusted, which reduces emissions substantially. However, emission data for industrial-scale pyrolysis units are scarce, both with regard to gases, aerosols, heavy metals and polycyclic aromatic hydrocarbons (PAH). Thus, the environmental impact of this process is not fully known.

Making biochar from waste timber (WT) provides a promising method for waste handling as it results in the potential valorisation of such residues as it provides a material that can be utilized further. For this process to be sustainable, emissions during the process need to be low and the resulting biochar of sufficient quality for its use, be it for sorbent amendment or to improve degraded soils. To investigate this, three batches of WT and one reference batch of clean wood and leaves were pyrolyzed in a representative medium-scale pyrolysis unit (called a Pyreg-500) with after-combustion of the pyrolysis gases. During pyrolysis the gas, aerosol, metal and PAH emissions were measured and emissions factors were calculated. The emissions factor provides a measure of how much gas is emitted in the process relative to carbon monoxide, on a weight basis. The biochar produced was then characterised and quantified for levels of contamination that remained, both in terms of total concentrations and also leachable concentrations.

There were no significant differences in emission factors between the pyrolysis of WT and the clean wood/leaves reference, respectively, except for PM10, NMVOC, and PAH-16, which were significantly lower for WT than for the clean wood/leaves. Mean emission factors for the WT were (g kg⁻¹ biochar): CO = 7 ± 2, non-methane volatile organic compounds (NMVOC) = 0.86 ± 0.14, CH₄ = 0, aerosols (PM10) = 0.6 ± 0.3, total products of incomplete combustion (PIC) = 9 ± 3, PAH-16 = (2.0 ± 0.2) × 10⁻⁵, As (most abundant of metals) = (2.3 ± 1.9) x 10⁻³ and NOₓ = 0.65 ± 0.10.

The WT biochar did not satisfy premium or basic European Biochar Certificate criteria due to high levels of zinc and PAH. However, leachable metal contents at liquid-to-solid ratio of 10 were < 0.1% of total contents. Based on these results, the use of the WT biochar without further improvement or investigation would be limited to ex situ use, and would not be permitted for the use of improving soil fertility or in situ remediation.

For more information related to this work please refer to:
Fundamental biochar research: PCB sequestration, bioavailability and ecotoxicity following biochar amendment to soil

PCBs are ubiquitous in the environment, are persistent, bioaccumulative and toxic chemicals and as such are heavily regulated. Legacy soil, sediment and water pollution is a worldwide, high cost problem, and as for HCHs, PFAS and heavy metals, remediation methods are needed. In order to investigate whether biochar could be a promising alternative for the remediation of PCB contaminated soils, a pot experiment was conducted using aged spiked PCB polluted agricultural soil that was amended with two different biochar types; mixed wood shavings biochar and rice husk biochar at two different doses 1% and 4%. The uptake of PCBs to two plants; ryegrass (Lolium perenne) and turnip (Brassica rapa ssp. rapa), to the earthworm species Eisenia fetida and passive samplers (polyethylene, PE) was assayed with and without biochar amendment.

The main findings from the work can be summarised as follows.

- The earthworms showed a preference for the presence of biochar and did not seem to be affected by the presence of PCBs.
- PCB uptake to earthworms was both dependant on PCB congener and biochar type. Rice husk biochar reduced PCB uptake and thus ecotoxicity to a greater degree than mixed wood biochar.
- Both biochars sorbed PCBs, rice husk biochar performed best and there was no effect of biochar dose.
- Ryegrass yield increased when biochar was added to the contaminated soil.
- Plant uptake of PCBs was generally not affected by either type or dose of biochar, and ecotoxicity to plants was thus not reduced by biochar amendment.
- Biochar reduced the uptake of PCBs to PE passive samplers, thus reducing bioavailability however there were no real effects of biochar type or dose.
- There was a correlation between the uptake of PCBs by PE passive samplers and by earthworms. However, there was no correlation between the uptake of PCBs by PE passive samplers and by plants. This suggests that the accumulation of PCBs in PE passive samplers is a good proxy for the accumulation of PCBs in earthworms.

FACTS

**Passive sampling for organic pollutants**

Passive sampling is a technique in which a small plastic strip is placed in contaminated soil, sediment or water which allows the determination of freely dissolved pollutant concentrations. When a passive sampler is exposed to polluted water it accumulates contaminants that diffuse through a steric layer of water into well defined openings in its outer membrane until equilibrium is established. The pollutants that are accumulated are those that are freely dissolved and not those associated with aqueous particles or dissolved organic matter.

Equilibrium samplers establish a thermodynamic equilibrium between themselves and the water phase, and through the use of the concentration of pollutants accumulated by the passive sampler and compound specific device-water partitioning coefficients, freely dissolved bioavailable concentrations can be determined. Passive samplers are low cost, easy to deploy in laboratory and field settings, have minimal handling and analytical needs, can detect and concentrate very low aqueous pollutant concentrations and do not depurate or metabolise accumulated compounds. There are a plethora of materials that can be used as equilibrium passive samplers, the most common being polyethylene, polysiloxane, silicone rubber and polydimethylsiloxane.

For more information related to this work please refer to:

Fundamental biochar research:
Organic pollutant sorption, bioavailability, bioaccessibility and ecotoxicity in biochar amended field and spiked soils

A previous collaboration between NGI and RECETOX, a leading ecotoxicity research institute in Brno, Czech Republic, was strengthened via laboratory work looking at the effect of biochar amendment to soil on pollutant sorption, bioavailability, bioaccessibility and ecotoxicity of pyrene, PCB 52, and p,p’-DDE. Laboratory work was carried out in both countries and a joint publication produced.

The organic pollutants investigated in this work were chosen as they have varying hydrophobicities and are representative persistent, toxic and widely occurring soil pollutants. Sorption, bioavailability and ecotoxic effects of both the pollutants and the biochars were determined for both contaminated and non-contaminated soils. spiked and historically contaminated soils were used in order to investigate the fate and ecotoxicity of the pollutants following biochar amendment. Sorption and bioavailability were assessed using polyethylene (PE) passive samplers and an XAD extraction method and ecotoxicity was determined following the ISO standardized \textit{F. candida} toxicity test.

A distinction between positive primary amendment effects caused by reduced toxicity resulting from contaminant sorption, and negative secondary amendment effects of the biochars themselves was seen. The rice husk and wood based biochars used above had similar sorption capacities for pyrene, PCB 52 and p,p’-DDE, both when single compounds were used, when the compounds were mixed and in the presence and absence of soil.

p,p’-DDE natively contaminated and spiked soils were amended with between 1 and 10 weight % of both biochars. When 10 % biochar was added, bioavailability and bioaccessibility decreased by greater than 37% and greater than 41%, respectively, compared to unamended soils. Mortality of \textit{F. candida} was not observed at any biochar dose, while reproductive effects were dose dependent. \textit{F. candida} benefited from the reduction of p,p’-DDE bioavailability upon 1% and 5% biochar addition to contaminated soils while at 10% dose, these positive effects were nullified by biochar-induced toxicity. p,p’-DDE toxicity corrected for secondary effects caused by the amendment of biochar was predicted well by both PE uptake and XAD extraction.

The photographs show the methods that were used in the work: PE passive samplers to measure bioavailability, \textit{Folsomia candida} used to assess acute and chronic toxicity and XAD polymeric resin to determine bioaccessibility.

For more information related to this work please refer to:
The following publications have also been supported by this project:


The first piece of work is the result of the master thesis by Andreas Smebye in which the effect of biochar on the dissolved organic matter (DOM) in soils was investigated. A laboratory batch experiment was carried out in which a ferralsol was mixed with 10% of biochar produced in Indonesia. The result was an increase in pH from 4.9 up to 8.7 along with a release of dissolved organic carbon (DOC) of up to 0.7 g/kg soil. The background release of DOC from the unamended soil was 0.03 g/kg indicating the huge potential biochar has to mobilise DOM. The most likely explanation for this was the increase in pH which subsequently causes higher DOM solubility and desorption of DOM from mineral sites.

The second publication presents a review of the sorption capacity different biochars have for neutral organic compounds. Based on a literature study carried out at the time, 29 studies with 507 individual Freundlich sorption coefficients were compiled that covered the sorption strength of 107 organic contaminants.

These sorption coefficients were converted into biochar-water distribution coefficients ($K_D$) and ranged from 0.38 to 8.25 across all data. Variation was observed within the following compound classes; pesticides, herbicides and insecticides, PAHs, phthalates, halogenated organics, small organics, alcohols and PCBs. In order to ascertain whether sorption to biochar could be predicted based on biochar physicochemical properties, five commonly reported variables; production temperature temperature ($T$), surface area ($SA$), H/C and O/C ratios and organic compound octanol-water partitioning coefficient, were plotted against $K_D$ values using single and multiple-parameter linear regressions.

The correlation between $log K_D$ measured and $log K_D$ predicted for the complete data set

The sorption of a neutral organic pollutant can be described by:

$$log K_F = (0.17±0.06) log K_{OW} + (4.17±1.19) log T + (0.91±0.15) log SA + (1.41±0.27) log OC + (-0.35±0.11) log HC + (-9.02±3.11)$$

$R^2 = 0.59$, root mean squared error = 0.97, n = 151
Biochar seen in a life cycle perspective

The development of spatially differentiated life cycle impact assessment (LCIA) methods, which take into consideration local conditions and sensitivities of receiving ecosystems, has intensified in the past few years. Their application in life cycle assessment (LCA) studies has, however, lagged behind. In contrast to generic methods, which should be valid on a global scale (at the expense of higher spatial uncertainty), spatially differentiated LCIA methods are more accurate as they operate at either regional or local scales, corresponding to site-specific and site-dependent assessments, respectively. It is clear that spatial differentiation leads to more accurate and realistic estimations of environmental impacts.

The aim of life cycle aspect of the project was to assess the implications of using spatially differentiated LCIA methods on management recommendations for the implementation of biochar technology in Indonesia. Generic and regionalized impacts were calculated using a suite of relatively recent LCIA methods, which offer spatially differentiated characterization factors at the damage level, and compared to each other. The effect of spatial differentiation for use in decision-support was investigated. The influence on an absolute scale, i.e. whether the conversion of biomass residues to biochar and its subsequent use in agriculture provides has net positive effect compared to the current situation (no treatment of biomass residues), was investigated. All comparisons were made between four communities living on different Indonesian islands (Sulawesi, Sumba, Sumatra, and Java), three biochar production techniques (Kon-Tiki steel kiln, Adam retort, and earth-mound kiln) and two types of fertilizer (inorganic fertilizer and compost), giving a total of 24 scenarios.

Results showed that irrespective of the scenario and type of damage considered (human health or ecosystem quality), implementing biochar technology in Indonesia is expected to bring environmental benefits. These benefits were driven by the crop productivity increases when biochar was amended to the degraded Indonesian soils, which reduced the need for fertilizers and water for irrigation. Differences in productivity increase, combined with differences in inherent yield of crops without biochar addition explained differences in the ranking of the four communities living on the different Indonesian islands. Amendment of biochar to improve agriculture was particularly beneficial in cases where high productivity increase was combined with high inherent yield (seen in Sumba or Sumatra). With regards to the biochar production technology used, a general picture emerged in which the Kon-Tiki and Adam retort kilns performed better than the earth-mound kilns.

For more information related to this work please refer to:


An additional publication by the same authors is in preparation in which LCA is combined with cost-benefit analysis to investigate the use of biochar in the six countries from the B4SS project mentioned further on.

Generic and spatially differentiated damage to human health (a) and ecosystems (b) from biochar production using flame curtain kiln and its use for improving agriculture in Indonesia, as influenced by geographic location and fertilizer type.
Biochar for sustainable soils (B4SS)

The Biochar for Sustainable Soils project aimed to demonstrate and promote the adoption of sustainable land management practices through the use of biochar based soil amendments to improve productivity, climate resilience, support rural livelihoods, and contribute to watershed management. There were six countries involved in the project: Ethiopia, Indonesia, Kenya, China, Peru and Vietnam. More information about the project can be found here: https://biochar.international/

The Indonesian component of B4SS was led by NGI and involved biochar implementation with 20 farmers; 10 in Lampung, Sumatra, and 10 in Lamongan, East Java. The farmers were followed through their biochar journey and an initial baseline study was compared to a final survey in order to assess the agronomic and socio-economic effects of biochar implementation and acceptance of the production technology, after one (Lamongan) or two (Lampung) seasons of biochar use. The farmers were trained on how to produce biochar using the flame-curtain (Kon Tiki) kiln, how to enrich the biochar with mineral fertilizer and how to apply the biochar to the soil. This technology combines the simplicity of the traditional kiln with the cleanliness of improved methods, through the combustion of pyrolysis gases in the flame curtain (similar to retort kilns). With benefits such as high quality biochar, low toxic gas emissions, no need for start-up fuel, fast pyrolysis time (hours instead of days) and, importantly, easy and cheap construction and operation, the flame curtain technology represents a promising possibility for sustainable rural biochar production. The resulting effects of biochar amendment on crop production were monitored.

The main outcomes of the farmer implementation can be summarized as follows:
- The effect of biochar was modest with around an increase in yield of 8% in Lampung, and 5-10% in Lamongan
- Almost all farmers (90%) reported the wet climate to be a challenge for biochar preparation.
- Despite the limited observed increases in crop yield, in the final survey farmers reported better crop yield in 100% (Lampung) and 80% (Lamongan) of cases
- A surprisingly high number of farmers (75%) saw no disadvantages of biochar.
- An important result was that farmers were motivated to apply biochar in the future, but only in Lampung (100%), where all farmers found biochar fitting for their farming practice. In Lamongan the richer farmers were not motivated enough to do the extra work of biochar preparation.
- Making biochar from flame curtain kilns was observed to be environmentally neutral in a lifecycle perspective, as the production emissions were compensated for by carbon sequestration.

The project spin off: in collaboration with the International Institute for Sustainability (IIS), Brazil

LAND NEUTRAL AGRICULTURAL EXPANSION AND ECOLOGICAL RESTORATION IN BRAZIL

The overall aim of the project was to implement a novel integrated approach aimed at scaling up sustainable land-use solutions to conciliate agricultural expansion and environmental conservation. The International Institute for Sustainability is based in Rio de Janeiro and is dedicated to researching, designing and implementing sustainability solutions, with a main focus on sustainable land-use. The project was funded by Norad with a value of 29,557,500 NOK with the following partners; Fundación Solidaridad Latinoamericana (FSLA), IIS, Instituto Centro de Vida (ICV) and Embrapa Agrobioologia.

Currently the world’s second-largest agricultural producer, Brazil has the largest forecasted increases in agricultural output over the next four decades of any country worldwide. At the same time, Brazil is the world leader in deforestation, the nation richest in forest carbon and the most biodiverse country on the planet. Despite a recent reduction in deforestation rates, the heated forest-code debate is a reminder that strong tensions between the agricultural and environmental communities remain. The lack of integrated land-use planning, and policies further exacerbates this view. Three-quarters of Brazilian agricultural lands are occupied by pasturelands and these areas have a low average productivity and use just 32-34% of their sustainable carrying capacity.

NGI was involved in a small component of the project entitled “The use of biochar to improve soil quality and for sustainable intensification of agriculture in Brazilian Atlantic Forest biome”. The goal of this sub project was to regenerate degraded lands and improve soil quality to increase agricultural productivity, and to liberate land for large scale restoration. In order to address this, pot and field experiments were carried out and coupled to a cost benefit analysis for the effect of biochar amendment on two crops; Brachiaria and Panicum.

Results showed a 21% average increase in Brachiaria production over two years but no significant effects of amendment on Panicum yield. The positive effect for
Brachiaria were ascribed to an increase in the content of soil macronutrients, pH and CEC. As for the soils in Indonesia, one of the main problems with the degraded Brazilian soils is their high acidity and aluminium toxicity. This can be overcome by the amendment of biochar. This is the first work to show the potential biochar has to improve yields of pasture land.

Based on the cost-benefit analysis, the following points were evident. Each hectare amended with biochar saved 91 tonnes of CO2eq through land sparing effect, 13 tonnes of CO2eq sequestered in the soil, equating to US$455 in carbon payments. However, the costs of biochar production for smallholder farmers, outweighed the potential benefits of its use. Biochar is 67% more expensive than common fertilizers used in Brazil and thus the financial viability of producing and apply biochar on a small to medium size farmland remains a great challenge.

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For more information related to this work please refer to:

- Castro, A; Batista, ND; Latawiec, AE; Rodrigues, A; Strassburg, B; Silva, D; Araujo, E; de Moraes, LFD; Guerra, Jo; Galvao, G; Alves-Pinto, H; Mendes, M; dos Santos, JS; Rangel, MC; Figueredo, M; Cornilissen, G; Hale, S E (2018) "The Effects of Gliricidia-Derived Biochar on Sequential Maize and Bean Farming", Sustainability, 10, 3, 578

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Masters theses connected to this project:

- Remediation of PCB polluted soil using biochar: the uptake of PCBs in earthworms, plants and passive samplers, Sigurbjörn Hjartardóttir, Department of Chemistry, Faculty of Mathematics and Natural Sciences, University of Oslo

- The effect of biochar on dissolved organic matter in soil: A laboratory study of release and sorption of dissolved organic matter, Andreas Smebye, Department of Chemistry, Faculty of Mathematics and Natural Sciences, University of Oslo

- Postdoctoral stipend connected to this project: Ludovica Silvani, 2018-2019, Fundamental biochar research, field assistance in Indonesia


- B. Botnen Smebye, Department of Chemistry, Faculty of Mathematics and Natural Sciences, University of Oslo
- Sigurbjörn Hjartardóttir, Department of Chemistry, Faculty of Mathematics and Natural Sciences, University of Oslo
- Ludovica Silvani, 2018-2019, Fundamental biochar research, field assistance in Indonesia
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