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Research article

The effects of straw or straw-derived gasification biochar applications on soil quality and crop productivity: A farm case study

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A B S T R A C T

Thermal gasification of straw is a highly efficient technology that produces bioenergy and gasification biochar that can be used as a soil amendment, thereby returning non-renewable nutrients and stable carbon, and securing soil quality and crop productivity.

A Danish on-farm field study investigated the impact of traditional straw incorporation *vs.* straw removal for thermal gasification bioenergy production and the application of straw gasification biochar (GB) on soil quality and crop production. Two rates of GB were applied over three successive years in which the field was cropped with winter wheat (*Triticum aestivum* L.), winter oilseed rape (*Brassica napus* L.) and winter wheat, respectively, to assess the potential effects on the soil carbon pool, soil microorganisms, earthworms, soil chemical properties and crop yields.

The application of GB did not increase the soil organic carbon content significantly and had no effect on crop yields. The application of straw and GB had a positive effect on the populations of bacteria and protists, but no effect on earthworms. The high rate of GB increased soil exchangeable potassium content and soil pH indicating its potassium bioavailability and liming properties.

These results suggest, that recycling GB into agricultural soils has the potential to be developed into a system combining bioenergy generation from agricultural residues and crop production, while maintaining soil quality. However, future studies should be undertaken to assess its long-term effects and to identify the optimum balance between straw removal and biochar application rate.

1. Introduction

In the face of challenges such as the growing human population and the impact of climate change, a sustainable food and energy supply is becoming increasingly important (Smith et al., 2015). The agricultural sector can contribute to climate change mitigation by decreasing greenhouse gas (GHG) emissions and reducing CO_2 in the atmosphere through soil carbon sequestration. Furthermore, new synergies between agriculture and energy production may have mitigation potentials by providing agricultural residues for bioenergy production to substitute fossil fuels (Smith and Olesen, 2010).

Thermal gasification efficiently produces bioenergy from a wide range of agricultural residues (Ahrenfeldt et al., 2013; Thomsen et al., 2015) and a valuable by-product, a carbon-rich material, biochar. Gasification biochar (GB) has been proven to be stable towards microbial degradation and therefore has a high carbon sequestration potential when it is incorporated into soil (Hansen et al., 2016). Furthermore, the positive effects of straw GB on soil cation exchange capacity, soil water retention and root development have been demonstrated (Bruun et al., 2014), in addition to a liming effect (Hansen et al., 2016) and fertiliser value (Müller-Stöver et al., 2012). Thus, the use of straw GB as a soil amelioration and carbon sequestration agent is a promising approach for combining the production of bioenergy and maintenance of soil quality (Hansen et al., 2015), but the concept has not yet been fully

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proven under field conditions.

Concerns have been raised in relation to an increased removal of crop residues for bioenergy since straw incorporation, for example, is regarded as an important tool in maintaining soil organic carbon (SOC) content and soil quality (Powlson et al., 2011). It also promotes the abundance of earthworms (Kennedy et al., 2012) that play an important role in soil functioning, including organic matter decomposition, plant nutrient cycling and soil structure improvement (Kladivko, 2001). Unfortunately, there is very little understanding about the effect of biochar on soil fauna, including earthworms (Lehmann et al., 2011). Both negative (Li et al., 2011) and positive effects (Busch et al., 2012) of biochar on earthworms have been reported. However, these results are from laboratory-based studies using the compost worm *Eisenia fetida*. Marks et al. (2016) found negative effects on soil fauna in the field after three years of successive application of gasification biochar at 12 and 50 t ha^{-1}, which was most likely due to the high content of polycyclic aromatic hydrocarbons (PAH). Thus, more research is needed into the effect of straw removal and biochar addition under field conditions, with particular attention paid to soil biota.

A field trial on a Danish farm was therefore established as a case study for the concept of combining bioenergy and agricultural production by low-temperature gasification of straw residues and then recycling the residual biochar product back into the soil. The trial was located on the Bregentved Estate, which is an agricultural and forestry business comprising 3.465 ha of agricultural land and 3.054 ha of forest on Zealand in eastern Denmark. Bregentved's business concept is based on establishing management strategies for both agricultural and forestry land with a focus on sustainability and the climate-friendly production of food and energy. The main crops are wheat, barley and winter oilseed rape (*ca.* one third each). Approximately 6% of the produced straw is baled and used to generate the heat needed by the estate in a local, estate-owned incineration facility. The rest of the straw is incorporated in the field in order to sequester carbon and thereby contribute to soil quality improvements and climate change mitigation. The Bregentved Estate has been practising conservation agriculture (minimum tillage) in combination with straw incorporation since 2005 in order to increase soil organic matter and biota such as earthworms. This has brought about 30% reduction in the consumption of fuel for field operations compared to the traditional ploughing system (A. Dolmer, pers.com.). Since 2011, controlled traffic farming (CTF, which includes GPS-assisted permanent driving tracks for all machinery operations) has also been implemented to minimise soil compaction and improve water retention and infiltration. However, according to the estate manager, there may be a potential to remove and use a higher proportion of the cereal straw to produce bioenergy, provided that straw removal will not impair soil fertility.

The present study was conducted in a farmer-controlled field following common practice and crop rotation. The aim of the study was to assess the agronomical and environmental consequences of a system combining bioenergy production and recycling of gasification biochar. Over a three-year trial period, the objectives were to investigate the effect of cereal straw and straw GB application on: (1) soil organic carbon, (2) microorganisms and earthworms, (3) soil chemical properties and (4) crop yield.

2. Materials and methods

2.1. Biochar production and characterisation

A straw gasification biochar produced in a Low Temperature Circulating Fluidized Bed gasifier (LT-CFB) was used in this study. The LT-CFB gasifier applied (Ahrenfeldt et al., 2013) is designed to gasify biomass resources with a high content of low melting ash compounds (*e.g.* straw, manure or sewage sludge) that have proven difficult to convert in other thermal processes. The process is based on separate fast-pyrolysis and gasification fluid bed reactors with a circulating heating medium to transfer the heat from the gasification process to the pyrolysis. The process temperature is kept below the melting point of the ash components, *i.e.* maximum process temperatures of around 700–750 °C. In this way, sintering of the ash and subsequent fouling (*e.g.* from potassium) or corrosion (*e.g.* from chlorine) of the plant unit operations are avoided, as these compounds leave the process in solid form as ash particles (Ahrenfeldt et al., 2013). The straw used for biochar production originated from winter wheat (*Triticum aestivum* L.) grown on Zealand, Denmark. Wheat straw was chopped prior to LT-CFB gasification for optimal gasifier operation. The biochar characteristics is given in Table 1. Nine different polycyclic aromatic hydrocarbons (PAHs, acenaphthene, fluorene, phenanthrene, fluoranthene, pyrene, benzo(bjk)fluoranthene, benzo(*a*)pyrene, indeno(1,2,3-*cd*)pyrene and benzo(ghi)perylene) were quantified after a Soxhlet extraction of 2 g samples with toluene for 48 h by Eurofins GfA (Hamburg, Germany). More details about the production process and further characteristics of the GB can be found in a study by Hansen et al. (2015).

2.2. Experimental design

The field trial was established in a conventional agricultural field on the Bregentved Estate, Zealand, Denmark (55° 22′ N, 12° 05′ E) in August 2012 and was carried out for three successive growing seasons at the same site with permanent treatments. The climate is temperate and the long term annual average for 1961–1990 is a rainfall of 550 mm and a temperature of 9.1 °C. In the experimental period the annual rainfall was 463, 501, 683 and 591 mm and the average annual temperature was 8.4, 8.6, 10.2 and 9.4 °C in 2012, 2013, 2014 and 2015, respectively. The soil is a sandy loam and contains 14% clay (<0.002 mm), 14% silt (0.002–0.02 mm), 47%fine sand (0.02–0.2) and 24% coarse sand (0.2–2 mm). The total C content was 19.8 g kg^{-1} and total N 1.8 g kg^{-1}. This field trial followed a three-year crop sequence, typical of many crop farms in Denmark, consisting of winter wheat (*Triticum aestivum* L. cv. Jensen) sown in 2012, winter oilseed rape (*Brassica napus* L. cv. Explicit) sown in 2013 and winter wheat (*Triticum aestivum* L. cv. Dacanto) sown in 2014. The preceding crop in 2012 was spring barley (*Hordeum vulgare* L.).

The field trial was established in a randomized block design with four replicates. The experimental plots were 12 × 100 m. The trial involved six treatments: (1) control without cereal straw incorporation (Control), (2) control with cereal straw incorporation (Straw), (3) application of GB at a rate according to the amount of potassium (K) recommended for the crop (Low GB), (4) application of GB at a rate according to the phosphorus (P) recommended for the crop (High GB), (5) without any application of

Table 1
Chemical characteristics of the straw gasification biochar for each year of the field trial, n.d. = not determined.

	Year 1	Year 2	Year 3
C (%)	34.8	32.08	32
K (%)	5.8	5.69	5
P (%)	0.36	0.54	0.41
Mg (%)	n.d.	0.43	0.48
pH (water)	n.d.	10.5	n.d.
ΣPAH[a] (mg kg^{-1})	n.d.	2.5	2.2

[a] Sum af acenaphthene, fluorene, phenanthrene, fluoranthene, pyrene, benzo(bjk)fluoranthene, benzo(*a*)pyrene, indeno(1,2,3-*cd*)pyrene and benzo(ghi) perylene.

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