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Environmental hotspots in the life cycle of a biochar-soil system

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A B S T R A C T

A life cycle assessment was conducted to study the environmental effects of a biochar-soil system and to identify the main environmental hotspots. Six scenarios were evaluated, which included the production of biochar from agricultural and forestry residual biomass pyrolyzed at 300, 400, and 500 °C, using a functional unit of 1 t of produced biochar. Modeling of the system and evaluation of impacts were performed using SimaPro selecting impact categories of climate change, human toxicity, freshwater eutrophication, and fossil depletion. According to the results, the climate change impact category presented the greatest relative importance in the life cycle of biochar, with greenhouse gas emission reductions of up to 2.74 t CO_2 eq t^{-1} biochar when the biochar applied to soil is produced from forestry residual biomass at 500 °C.

In relation to hotspots in the life cycle of biochar, transportation was the only stage identified that contributes environmental loads to the system, in contrast, carbon storage, natural gas avoided and urea avoided generate environmental benefits. Carbon storage in biochar is the main hotspot in the system associated to climate change, while the avoided use of natural gas and urea have great influence on fossil depletion, freshwater eutrophication, and human toxicity categories. These categories are highly sensible to allocation methodology options and the assumptions associated to the system boundaries expansion. This finding requires a comprehensive justification and to guarantee the data quality when the system expansion is considered in a LCA study of a biochar-soil system, including energy balance and syngas use, as well as, avoided urea estimation. This study considered one agricultural season, and future works should consider biochar amounts used as soil amendment in each agricultural season for evaluating residual effects of biochar use regarding fertilizers savings.

1. Introduction

Biochar is a product rich in carbon consisting of organic, thermally stable material that ensures its storage and beneficial potential in soil. It is distinct from other solid products of thermochemical conversion such as charcoal or activated carbon in that the main purpose is long-term carbon storage rather than the creation of raw material for industrial processes or energy generation (Mašek et al., 2013). Biochar is produced by thermal decomposition of organic material under conditions with low oxygen (O_2) supply at relatively low temperatures (<700 °C) (Lehmann and Joseph, 2009), generating subproducts including gases (synthesis gas) and liquids (tars and oils) (Bridgwater and Peacocke, 2002) in a process known as pyrolysis. This process often mirrors the production of charcoal. However, it distinguishes itself from charcoal and similar materials that are discussed below by the fact that biochar is produced with the intent to be applied for improving soil productivity (Lehmann and Joseph, 2009). Bio-oil and syngas yields increase, whereas biochar yield decreases with increasing temperature of pyrolysis (Imam and Capareda, 2012). Typical yields of slow pyrolysis are: 30% liquid, 35% gas and 35% coal (Brown, 2009), where biochar is used as an energy source or soil amendment while tar and synthesis gas are sources of renewable

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energy. The latter use has generated greater interest due to limited energy supplies, fluctuations in the fossil fuel prices, and CO_2 emissions from combustion that cause global warming and climate change (Huang et al., 2013). Net CO_2 emissions from biofuel use are considered zero or negative due to the released CO_2 was previously recycled and captured during photosynthesis (Qian et al., 2015).

Lehmann and Joseph (2009) consider that there are four complementary, synergistic objectives that could provide an incentive for applying biochar to soil: waste management, energy generation, as a soil amendment, and to mitigate the effects of climate change. An improvement of soil fertility reduces fertilizer inputs and consequently the carbon emissions during fertilizer production, transport, and application. Land application of biochar could potentially reduce P losses to runoffs and minimize the adverse impact of waste application on aquatic environments (Wang et al., 2015). Biochar application to soil may also reduce emissions of other greenhouse gases such as CH_4 and N_2O (Qian et al., 2015). Biochar amendment to soil has been proposed as a method for increasing soil C storage and suppressing soil N_2O emissions on a global scale (Woolf et al., 2010). Recent studies have shown that biochar suppressed cumulative soil N_2O production by 91% in near-saturated, fertilized soils (Case et al., 2015). These researchers also found that cumulative denitrification was reduced by 37%, which accounted for 85–95% of soil N_2O emissions. The mechanisms for explaining how biochar amendment influences soil N_2O emissions are uncertain (Spokas et al., 2011), particularly whether N_2O emission reductions would persist after prolonged biochar incorporation in the field (Ameloot et al., 2016). In many studies where biochar has been shown to reduce N_2O fluxes, mechanisms have been proposed based mainly on prior knowledge of the requirements of nitrifiers and denitrifiers (Clough et al., 2013). One alternative mechanism for biochar N_2O suppression is a restriction in the availability of inorganic N to soil nitrifiers and denitrifiers via immobilisation in biochar-amended soil (Nelissen et al., 2014). Some studies have found no differences or even increases in cumulative N_2O emissions after biochar addition (Scheer et al., 2011). Many studies have evaluated the effects of biochar on N_2O emissions, but only few have evaluated its weight in impacts related to global warming over the life cycle of a biochar system.

Although the majority of biochar studies present environmental benefits of biochar application in soil, several investigations have reported negative impacts associated to the use of biochar in soil. Some of these studies indicate that the application of biochar to soil can induce a radiative forcing by changing the surface albedo (Genesio et al., 2012). An average mean annual albedo reduction of 0.05 was calculated for applying 30–32 Mg ha^{-1} biochar (Meyer et al., 2012). This resulted in a reduction of the overall climate mitigation benefit of biochar systems by 13–22% due to the albedo (Meyer et al., 2012). Dittmar et al. (2012) show that dissolved black carbon (DBC) continues to be mobilized from the watershed each year in the rainy season, estimating that the river exports 2700 t of DBC to the ocean each year from Atlantic forest in Brazil. They suggest that an increase in black carbon production on land could increase the size of the refractory pool of dissolved organic carbon in the deep ocean. A recent study quantified dissolution products of charcoal in a wide range of rivers worldwide and showed that globally, a major portion of the annual charcoal production is lost from soils via dissolution and subsequent transport to the ocean (Jaffé et al., 2013). They estimated that the global flux of soluble charcoal accounts to 26.5 ± 1.8 Mt y^{-1}, which is ~10% of the global riverine flux of dissolved organic carbon (DOC). The environmental consequences of this phenomenon are presently unknown, but may be reflected in the reduction of DOC bioavailability and associated effects on microbial loop dynamics and aquatic food webs. The mobilization of DBC from biochar-amended soils to wetlands and riparian areas could provide a source of DBC to ground and surface waters. It is also possible that DBC production is a major loss process for biochar-amended soils, reducing biochar's climate mitigation potential (Spokas et al., 2014). Spokas et al. (2014) estimated that biochar mass losses because of physical dissolution were in the range between 1 and 47%, depending on the type of raw material and pyrolysis temperature. However, the environmental consequences and biochar behavior in aquatic medium (stabilization and mineralization) were not discussed.

The inputs and outputs of materials and energy in each stage of biochar production can directly or indirectly cause environmental impacts. The environmental benefits and impacts must be evaluated throughout the entire production chain (Huang et al., 2013). Currently, the most widely used methodology is the life cycle assessment (LCA).

Roberts et al. (2010), using the LCA methodology, estimated the energy and climate change impacts and the economics of biochar systems. They estimated greenhouse gas (GHG) reductions were in the order of 0.8 t CO_2 eq t^{-1} per t of dry waste. Reductions from carbon sequestration in the biochar were the most important, with 66% of the total, and a positive net energy in the system, estimated at 4899 MJ t^{-1} dry waste. Hammond et al. (2011) evaluated biochar production using slow pyrolysis in the U.K. through LCA, establishing that these systems appear to offer greater carbon reduction than other bioenergy systems. Carbon reductions between 2.1 and 2.7 t CO_2 eq t^{-1} of biochar produced were found. They calculated energy generation between 1.08 and 2.16 MJ t^{-1} of dry raw material. Using LCA and considering 10 biodegradable waste types from the UK, Ibarrola et al. (2012) evaluated biochar production and bioenergy with three thermal treatment configurations: slow pyrolysis, fast pyrolysis, and gasification. They determined that slow pyrolysis is the best choice for carbon reduction, reaching values between 0.07 and 1.25 t of CO_2 eq t^{-1} of treated raw material. These values are close to those found by Hammond et al. (2011) where carbon reductions were reached on the order of 0.7–1.3 t of CO_2 eq $t^{-1}$of raw material processed.

Few LCA studies on biochar discuss the impact categories chosen and frequently use the impact evaluation methods provided by LCA software (Harsono et al., 2013) (CML 2000, Eco-Indicator 99, ReCiPe, etc.); energy (MJ) (Roberts et al., 2010) and global warming (kg CO_2 eq) (Hammond et al., 2011) are the impact categories typically evaluated. This study analyzes the life cycle of biochar produced from residual biomass using slow pyrolysis and applied as soil amendment in volcanic soil in the Araucanía Region of Southern Chile, with a strong emphasis on hotspots in the life cycle of biochar.

2. Methodology

2.1. Goal and scope

The objective of this study was to evaluate the environmental effects of biochar production and use in volcanic soils of Southern Chile in order to determine the environmental benefits of managing solid waste from agriculture and forestry in the Araucanía Region and the principal hotspots in the biochar life cycle. Hotspots identification implies the identification of elements within the system that contribute to a certain impact category (Thomassen et al., 2008), being recently used in LCA studies to identify the main environmental hotspots of peach production systems (Ingrao et al., 2015), offset paper production (Silva et al., 2015) and control systems (landfill and incineration) of municipal solid waste (Woon and Lo, 2014).

In this study, the functional unit was defined as 1 t of produced biochar. This functional unit has been employed by Harsono et al.