Journal of Cleaner Production 158 (2017) 1–7

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

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

Edmundo Muñoz [a, b], Gustavo Curaqueo [c], Mara Cea [c, d], Leonardo Vera [a, b], Rodrigo Navia [c, d, e, *]

[a] School of Environmental Engineering, Universidad Andres Bello, República 440, Santiago, Chile
[b] Center for Sustainability Research, Universidad Andres Bello, República 440, Santiago, Chile
[c] Scientific and Technological Bioresources Nucleus, Universidad de La Frontera, Casilla 54-D, Temuco, Chile
[d] Department of Chemical Engineering, Universidad de La Frontera, Casilla 54-D, Temuco, Chile
[e] Centre for Biotechnology and Bioengineering (CeBiB), Universidad de La Frontera, Casilla 54-D, Temuco, Chile

A R T I C L E I N F O

Article history:
Received 15 September 2016
Received in revised form
28 April 2017
Accepted 28 April 2017
Available online 29 April 2017

Keywords:
Biochar
LCA
Residual biomass
Pyrolysis
Soil amendment

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

* Corresponding author. Scientific and Technological Bioresources Nucleus, Universidad de La Frontera, Casilla 54-D, Temuco, Chile.
E-mail address: rodrigo.navia@ufrontera.cl (R. Navia).

http://dx.doi.org/10.1016/j.jclepro.2017.04.163
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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.

(2013) and is considered the most useful because the main function of the system is biochar production.

The general scheme of system boundaries is shown in Fig. 1; this is used to propose different scenarios and scopes based on the operational conditions of the pyrolysis and the types of residual biomass. The system being modeled considered a system boundaries expansion, under the assumption that pyrolysis energy excess will generate a co-product which will avoid natural gas production and consumption. A second system boundary expansion was considered due to urea use avoidance because of biochar use, information estimated from field tests previously performed.

2.2. Life cycle inventory

The information used in this study includes in-situ data collection, laboratory tests, a pilot plant, field experiments, commercial databases, scientific and technical literature, and equipment operation manuals. The Ecoinvent database from the SimaPro 8 software was used to identify the environmental aspects associated with the use of diesel and natural gas.

The bulk densities of chipped and compacted residual biomass were 300 kg m^{-3} (Karlhager, 2008) and 700 kg m^{-3} (García and Sole, 2005). A Jenz Hem 561 chipping machine with a production capacity of 45 t h^{-1} (150 m^3 h^{-1}) and fuel consumption of 58 L h^{-1} was used for the chipping process, while a Trabisa packaging machine with a production capacity of 14 t h^{-1} and fuel consumption of 39 L h^{-1} was used for compaction. 0.21 kg wires were required to pack 1 t of forestry residual biomass, a forestry freighter with a capacity of 36 m^3 h^{-1} and fuel consumption of 7 L h^{-1} was employed to load the trucks and the chipping machine. Depending on the different densities, the transported mass per truck was 24 t for chipped biomass and 30 t for compacted biomass (Muñoz et al., 2015).

Biochar was produced from oat hulls (agricultural waste) and pine bark (forestry waste). A pilot-scale electric pyrolyzer with a maximum capacity to process 5 kg of raw material per batch was used to produce biochar. The pyrolyzer was purged with nitrogen gas (to displace air) before starting the process (Gonzalez et al., 2013). Carbonization temperatures used for both types of residual biomass were 300, 400 and 500 °C. Based on these pyrolysis processes, six biochar production scenarios were analyzed with LCA methodology (A1, A2 and A3 scenarios for oat hull biochar pyrolyzed at 300, 400 and 500 °C and B1, B2 and B3 scenarios for pine bark biochar pyrolyzed at the same operation temperatures); mass and energy balance data for the six scenarios evaluated are shown in Table 1. Biochar is highly stable and has an average lifetime greater than 1000 years at 10 °C (Roberts et al., 2010). According to Cheng et al. (2008) the residence time of biochar at 10 °C is 1335 years. However, the stability of biochar varies according to the type of biomass, the pyrolysis process, and environmental conditions. Given the importance of carbon stability on the global warming impact category, this evaluation considered that 80% of the carbon is stable and the remaining 20% is labile and released into the atmosphere during the first 100 years. This conservative criterion has already been proposed by Roberts et al. (2010).

Field trials were conducted at two volcanic soils located in the Araucanía Region in southern Chile. In both sites a barley crop (*Hordeum vulgare* L. cv. Sebastián) was established. In the first site the soil was inceptisol and at the second site the soil was ultisol. The biochar was applied at a rate equivalent to 20 t ha^{-1} through localized inter-row application on the surface soil of microplots (1.5 m × 3.5 m). A total of 70 kg N ha^{-1} was applied at sowing and 80 kg N ha^{-1} at the internode elongation growth stage in the inceptisol microplots, whereas the ultisol microplots received 60 kg N ha^{-1} at sowing and 70 kg N ha^{-1} at the internode elongation growth stage. Barley grain yield in the microplots increased significantly by 31.3% and 21.8% in the inceptisol and ultisol, relative to the control without biochar addition (Curaqueo et al., 2014). These results were used to calculate the fertilizer avoided by increased production. A decrease of 37.2 kg N ha^{-1} (80.8 kg urea ha^{-1}) for the same production level without biochar was calculated. This value was used to expand the system boundary for considering additional functions of biochar as established in ISO 14044 (2006).

The energy mix of the Chilean Central Interconnected System (Sistema Interconectado Central, or SIC) was modeled in SimaPro 8 to adapt international databases and processes to local conditions,

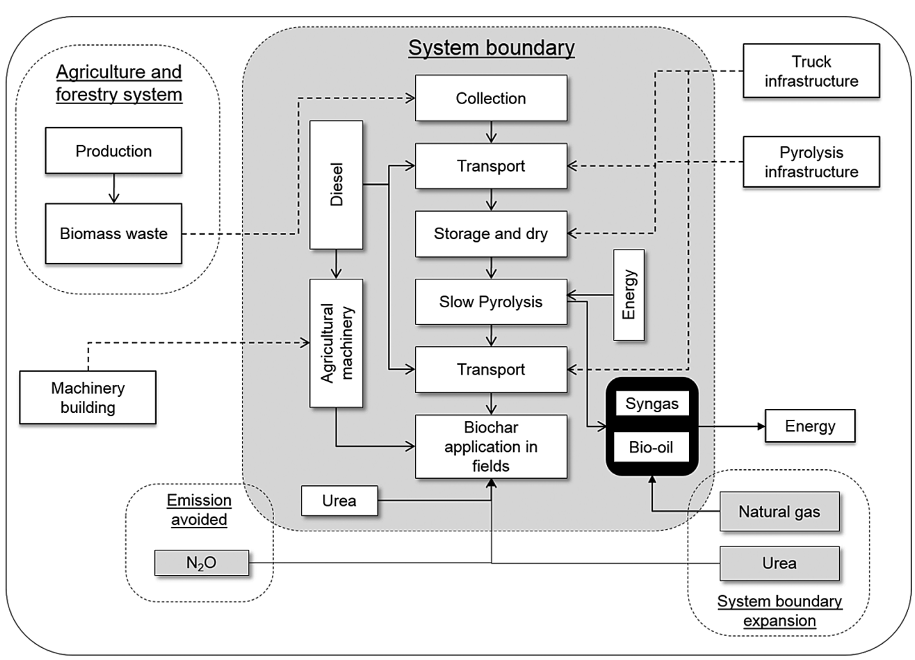

Fig. 1. System boundaries for LCA of a biochar-soil system.

Table 1
Mass and energy balance of the pyrolysis process for different residual biomass scenarios and operational conditions.

Items	Unit	Agriculture biomass waste			Forestry biomass waste		
		Scenario A1 (300 °C)	Scenario A2 (400 °C)	Scenario A3 (500 °C)	Scenario B1 (300 °C)	Scenario B2 (400 °C)	Scenario B3 (500 °C)
Biochar	%	50	32	31	60	54	46
Syngas	%	37	40	39	23	26	28
Bio-oil	%	13	28	30	17	20	26
Natural gas avoided[a]	MJ	1738	5847	6467	3366	4400	6715
Energy consumption[a]	MJ	1973	4169	4453	2362	2854	3888

[a] Calculation based on production of 1 t of biochar.

estimating an electricity generation for the 2014 period of 52,210 GWh. This generation was distributed as follows: 44.9% hydroelectric, 28.4% coal, 15.4% natural gas, 5.2% biomass, 3.1% petroleum, 2.3% wind, and 0.7% solar energy (CNE, 2015).

2.3. Impact assessment

The impact assessment was performed using SimaPro 8 software and specifically the ReCiPe midpoint methodology hierarchist version (Goedkoop et al., 2013). The impact categories analyzed were climate change (kg CO_2 eq), human toxicity (kg 1.4-DB eq), freshwater eutrophication (kg P eq), and fossil depletion (kg oil eq), since in a previous normalization those were the categories of greatest relative importance (Muñoz et al., 2015).

2.4. Sensitivity analysis

A sensitivity analysis was performed to assess the effect of the assumptions and the methodology used in the LCA. The variables evaluated were natural gas avoided and urea avoided by increased barley production. The range considered for natural gas avoided was between 0 and the total natural gas avoided obtained in this study, whereas the urea avoided was between 0 and 80.08 kg urea, corresponding to the value estimated in field trials.

3. Results and discussion

3.1. Life cycle assessment of biochar production

Comparing the agricultural and forestry waste scenarios from biochar production (Fig. 2), it is evident that forestry biomass generates greater environmental benefits in all impact categories and these benefits increase with an increase in pyrolysis temperature. Higher pyrolysis temperatures increase the percentage of syngas, which reduces biochar production (Table 1). This is important considering that the functional unit selected is expressed in terms of process output. To produce 1 t of biochar it is required greater quantities of raw material as the pyrolysis temperature is increased, varying from 2 to 3.2 t biomass t^{-1} biochar for agricultural waste and 1.7 to 2.2 t biomass t^{-1} biochar for forestry waste. In terms of the differences between agricultural and forestry waste, these are mainly due to the higher calorific value of syngas from forestry waste, which reaches 16,000 MJ kg^{-1} of biomass, compared to syngas from agricultural waste, which has values close to 9000 MJ kg^{-1}.

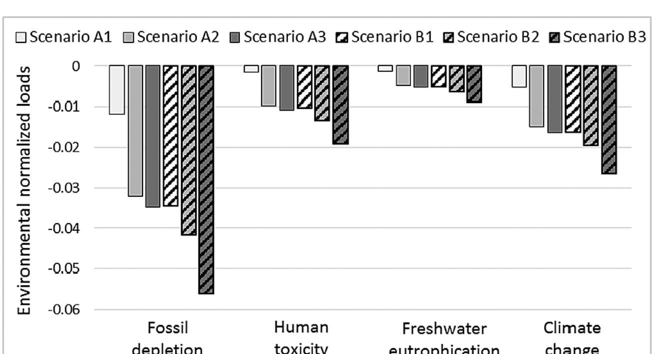

Fig. 2. Results normalized using the ReciPe Midpoint (H) methodology, from scenarios A and B, considering a scope from collection to the pyrolysis plant.

According to the findings, the most important environmental hotspots in biochar production were biomass densification, transportation and syngas production. Syngas production was found to be the most important, contributing to more than 90% of the environmental benefits in all evaluated impact categories. Fossil depletion is the impact category of greatest relative importance after results normalization, varying from −16 to −77 kg oil eq t^{-1} of biochar. Syngas production has a similar influence on climate change, with values between 36 and 183 kg CO_2 eq t^{-1} of biochar. These results are substantially different from values already published, which range from 0.8 t CO_2 eq (Roberts et al., 2010) to 1.25 t of CO_2 eq (Ibarrola et al., 2012) using 1 t of treated biomass as the calculation basis, or between 2.1 and 2.7 t CO_2 eq t^{-1} of biochar produced (Hammond et al., 2011). These differences are mainly due to the scope of this study, which did not consider the carbon stored in biochar, because carbon storage will be effective only if the biochar is applied to the soil.

3.2. Life cycle assessment of biochar use

Comparing the life cycle of application of agricultural and forestry waste biochar in volcanic soils, a similar trend was observed for both biochar types: There are greater environmental benefits in all impact categories when the biochar is generated from pyrolysis at 500 °C, as shown in Fig. 3.

The fossil depletion impact category is strongly influenced by the biochar production stage, such that the environmental benefits increase with a rise in syngas generation. Regarding to the climate change impact category, the use of biochar provides environmental benefits in all scenarios evaluated (Fig. 4). This is mainly due to the stability of biochar and to a lesser extent to the natural gas avoided. Between 85 and 93% of greenhouse gas emissions avoided are associated with stabilized carbon in biochar applied to soil, and the remaining 7–13% are associated with generation of synthesis gas. These environmental benefits are always close to the range indicated as long as the biochar is applied to the soil, as its use as a source of energy will release the biogenic carbon stored, reducing the benefits associated with climate change.

The biochar produced from agricultural waste can reduce GHG emissions from 2.59 t CO_2 eq t^{-1} biochar to 2.70 t CO_2 eq t^{-1} biochar when the pyrolysis process is conducted at 300 °C and 500 °C. In the case of forestry waste the range is slightly greater, reaching reductions on the order of 2.67–2.74 t CO_2 eq t^{-1} biochar when the

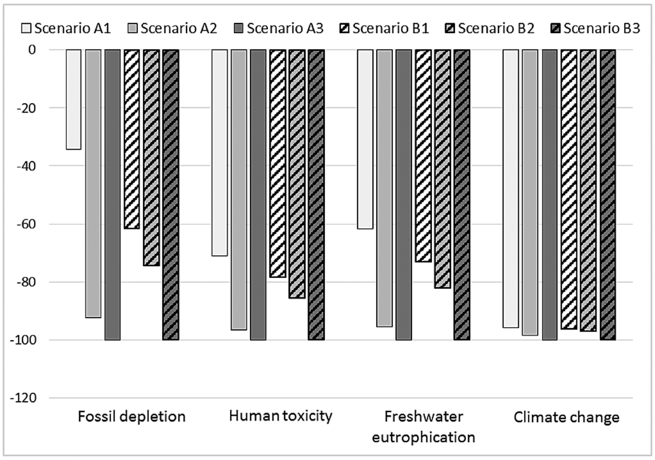

Fig. 3. Result of characterizations of life cycle impact categories for biochar-soil system, using RéciPe Midpoint (H) methodology.

biochar is produced at 300 °C and 500 °C. These values are close to those reported by Hammond et al. (2011): between 2.1 and 2.7 t CO_2. Table 2 presents the impact results for all categories evaluated. It is evident that human toxicity, freshwater eutrophication and fossil depletion show tendencies similar to the climate change category; i.e., the environmental benefits increased with higher pyrolysis temperature. Biochar produced from forestry waste has better environmental performance than biochar generated from agricultural biomass. The negative values (positive impacts) of the human toxicity, freshwater eutrophication and fossil depletion impact categories are generated because of the avoided products use during biochar production and use in soil. In the case of human toxicity, the main environmental benefits are related to the emissions associated to the avoided urea production. In the case of freshwater eutrophication, the environmental benefits are associated almost in an equivalent weight from avoided urea and natural gas use. The avoided eutrophication substances from both products are responsible for the impacts of this category. In the case of fossil depletion, the impacts are directly related to the avoided natural gas use due to syngas generation.

Currently, many studies have focused the discussion of the use of biochar in soil (Qian et al., 2015), and its effect on the nitrogen cycle (Clough et al., 2013), both from the perspective of application of nitrogen fertilizers (Spokas et al., 2011) and reduction of emissions of N_2O from soil (Case et al., 2015). However, the contribution of these variables to different impact categories throughout the life cycle of biochar has not been evaluated. To perform this analysis, an average increase of 26.5% in the yield of barley (*Hordeum vulgare*) in inceptisol and ultisol was considered, which allows for estimating urea savings of 80.8 kg ha^{-1} (due to expansion of the system by product avoided) when nitrogen doses of 140 kg ha^{-1} are applied. A 50% reduction in N_2O emissions due to use of biochar and that 20% of the carbon from the biochar would be released during the first few years was considered. Based on this information, the application of 20 t ha^{-1} of biochar was evaluated, determining that carbon storage in the biochar represents 92% of the environmental benefits in the climate change impact category and natural gas avoided represents 6.7%, while reduction of N_2O represents just 0.6% of the impact (Fig. 5). The dose of biochar applied to the soil is the main hotspot in the process, an aspect that is important to emphasize considering that different studies varied the dose of biochar applied to the soil from 4.5 t ha^{-1} (Zhang et al., 2014) to 40 t ha^{-1} (Li et al., 2015). The minor contribution of N_2O to the climate change impact category is notable. Even discarding the emissions of N_2O, its contribution would have values close to 1%. Although recent studies of LCA have included the application of biochar to soil (Miller-

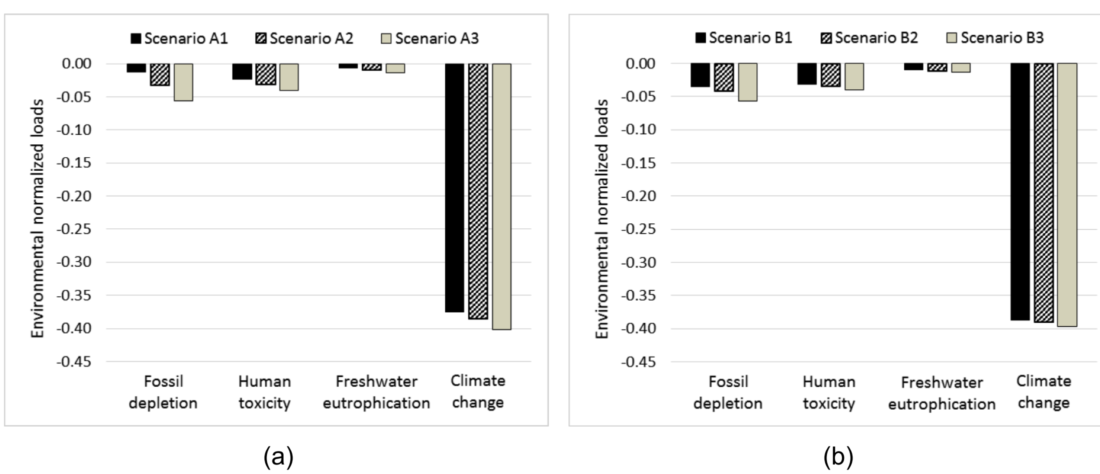

Fig. 4. (a) Normalized results for the impact categories of scenarios A1, A2 and A3; (b) Normalized results of scenarios B1, B2 and B3. Both (a) and (b) using RéciPe Midpoint (H) methodology.

Table 2
Results of impact evaluation for use in soil of 1 t of biochar.

Impact category	Unit	Scenarios					
		A1	A2	A3	B1	B2	B3
Climate change	kg CO_2 eq	−2590	−2657	−2698	−2665	−2689	−2736
Human toxicity	kg 1.4 DB eq	−2.7	−3.6	−3.7	−3.7	−4.0	−4.7
Freshwater eutrophication	kg P eq	−0.0018	−0.0028	−0.0030	−0.0029	−0.0033	−0.0040
Fossil depletion	kg oil eq	−16.5	−44.2	−47.9	−47.7	−57.5	−77.3

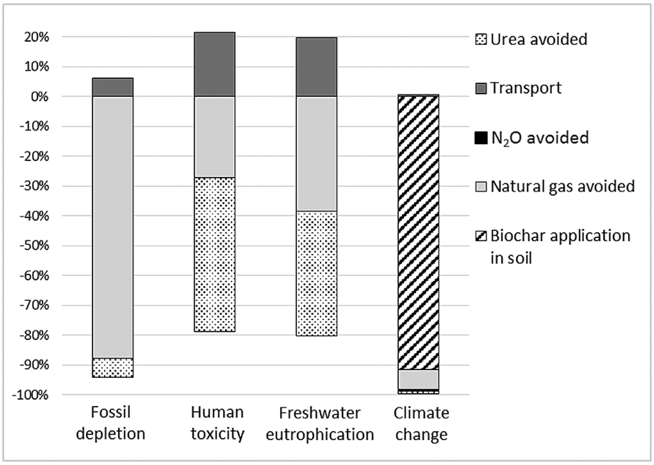

Fig. 5. Main environmental hotspots of the life cycle of biochar use.

Robbie et al., 2015), the results do not show the calculation of N_2O emissions and their contribution to climate change impact category.

In relation to the hotspots of the life cycle of biochar use, it was observed that transportation is the only stage that contributes environmental loads to the system with 6%, 20% and 21% on fossil depletion, freshwater eutrophication, and human toxicity impact categories, respectively, while the natural gas avoided and urea avoided generate environmental benefits. Natural gas avoided contributes to 88% of the positive impacts in the fossil depletion category, 28% in the human toxicity category, and 39% in the freshwater eutrophication category. Urea avoided contributes to 51% of the environmental benefits in the human toxicity category and 41% in the freshwater eutrophication category; these categories show the greatest benefits from this item.

From the sensitivity analysis of the natural gas and urea avoided (Fig. 6), it is shown that the system boundary expansion influences on the fossil depletion, freshwater eutrophication and human toxicity impact categories. Avoided natural gas influences on the three impact categories, being fossil depletion the most sensible impact category, varying up to a 111% when no system expansion is considered. The system expansion associated to urea only affects human toxicity and freshwater eutrophication categories, reaching variations of 90% and 70%. Climate change was the only one category which was not affected by the methodological considerations of system boundary expansion, as the carbon content in biochar represented over 90% of this category (Fig. 5) and its relative importance is higher compared to the other evaluated impact categories (Fig. 4).

The sensitivity analysis showed the high influence of the allocation procedure on the environmental impacts of biochar life cycle, as recently discussed by Sandin et al. (2015). This implies that pyrolysis process and biochar use in cultivars are important hotspots when determining the potential of avoided natural gas and urea. The results associated with fossil depletion, freshwater eutrophication and human toxicity must be carefully analyzed when decisions regarding biochar use are made, because the choice of allocation methods directly influences the final results (Sandin et al., 2015).

4. Conclusions

Production and use of biochar in soil generate environmental benefits in all evaluated impact categories (fossil depletion, freshwater eutrophication, human toxicity, and climate change) regardless of the pyrolysis temperature employed in the process and the type of residual biomass used. Greater environmental benefits can be achieved using forestry waste at pyrolysis temperatures of 500 °C.

It was observed that the contribution of N_2O to climate change was low, and with the significant variables in this category being the dose of biochar applied to the soil and to a lesser extent the syngas generated in the pyrolysis process. Carbon storage, natural gas avoided due to the production of synthesis gas and urea avoided represent the main environmental hotspots of the biochar life cycle, contributing together to almost 100% of the system's positive environmental impacts. Transportation is the only hotspot that contributes with negative environmental impacts in the life cycle of biochar.

It was established that the climate change impact category is the most important in relation to the life cycle of biochar-soil system, while carbon storage associated with the biochar application is the main hotspot in the system related to climate change. Other relevant hotspots related to fossil depletion, human toxicity and freshwater eutrophication are natural gas and urea avoided. These hotspots influence on fossil depletion, freshwater eutrophication, and human toxicity impact categories, which are highly sensitive to the system boundaries expansion. LCA results of biochar life cycle depend on the methodological choices and assumptions, forcing a clear justification and guaranteeing data quality when the system expansion is considered.

This study considered one agricultural season, and future works

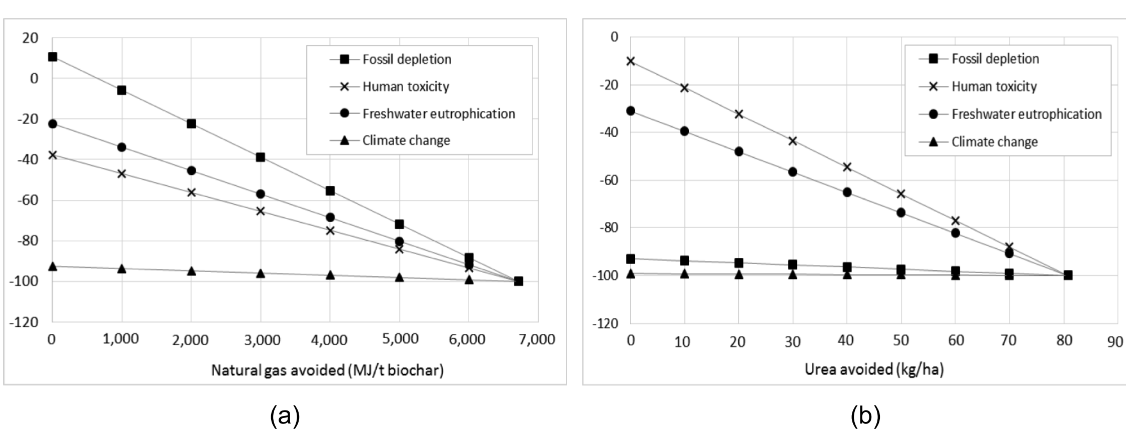

Fig. 6. Sensitivity analysis (a) Natural gas avoided (b) Urea avoided.

should include biochar amounts used as soil amendment in each agricultural season for evaluating residual effects of biochar use regarding fertilizers savings.

Acknowledgment

The authors thank the financial support of the Chilean FONDEF Project D07I1096.

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