Ital. J. Agron. / Riv. Agron., 2010, 5:3-11

The Biochar Option to Improve Plant Yields: First Results From Some Field and Pot Experiments in Italy

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Received: 22 August 2009. Accepted: 9 November 2009.

Abstract

The pyrolysis conversion of agricultural residues into biochar and its incorporation in agricultural soil, avoids CO_2 emissions providing a safe long-term soil carbon sequestration. Furthermore, biochar application to soil seems to increase nutrient stocks in the rooting zone, to reduce nutrient leaching and to improve crop yields. This study reports some preliminary results obtained using biochar in two typical Italian agricultural crops. Two field experiments were made on durum wheat (*Triticum durum* L.) in Central Italy and maize (*Zea mays* L.) in Northern Italy. In both the field experiments, an increase in yields (+ 10% and + 6% in terms of grain production, respectively) was detected after a biochar application of 10 t ha^{-1}. A further increase in grain production (+24%) was detected when biochar was added with maize residues. The biochar dose-effect curve was studied on perennial ryegrass (*Lolium perenne* L.) in a pot experiment. The highest increase of dry matter (+120%) was obtained at a biochar rate of 60 t ha^{-1} and above this threshold, a general reduction of biomass was observed. Results demonstrate the potential of biochar applications to improve in terms of dry matter production, while pointing out the needs for long-term field studies to better understand the effects of biochar on soil.

Key-words: Black carbon, crop yield, durum wheat, maize, sustainable agriculture

Introduction

Biochar is fine-grained and porous substance, similar in its appearance to charcoal produced by natural burning. It is produced by pyrolysis, a thermo-chemical process where biomass is heated in the absence of oxygen. As results, bio-oil, synthesis gas with different energy values and black carbon (biochar) are obtained. Biochar can be used as soil amendment to improve soil quality, crop yield and as a carbon (C) sequestration method. It may improve the physical structure of the soil (Chan et al., 2007) and can also modify soil hydraulic properties (Chan et al., 2007; Gaskin et al., 2007). Given that the pore size of biochar is relatively fixed, it increases available moisture in sandy soils while has a neutral effect in medium textured soils and decreases moisture availability in clay soils. In general, soil organic matter increases soil water holding capacity. In biochar-enriched *terra preta* with their associated high levels of organic matter, Glaser et al. (2002) found a water retention capacity that was 18% higher than in the adjacent soils. Biochar has been found to decrease nutrient leaching thus enhancing nutrient availability (Chan et al., 2007; Yamato et al., 2006). Evidence suggests that biochar porosity contributes to nutrient adsorption or covalent interaction on a large surface area. Furthermore, its cation exhange capacity (CEC) is consistently higher than that of the whole soil (Liang et al., 2006, Lehmann et al., 2003, Skjemstad et al, 1996; Lehmann et al., 2005). In fact, the concentration of negative charges on biochar surfaces increases with age (Cheng et

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al., 2006) as well as the adsorption of charged organic matter (Liang et al., 2006). According to Lehmann et al. (2003), leaching of ammonium after biochar addition to soil was reduced by more than 60% over four days of cropping rice compared to control treatments. Furthermore, these authors measured a decrease in Ca, Mg and nitrate-N leaching.

Field experiments involving biochar application have been made for some crops and at different locations, and positive yield responses have been often reported (Lehmann et al., 2003; Yamato et al., 2006; Chan et al., 2007; Rondon et al., 2006; Rondon et al., 2007; Van Zwieten et al., 2008). Most of these studies attributed the positive plant response to the effects of biochar on nutrients availability (i.e. nutrient savings in terms of fertilizers or improved fertilizer use-efficiency). Some studies (Yamato et al., 2006; Rondon et al., 2006; Van Zwieten et al., 2008) attributed the positive plant response to the ability of biochar to increase or maintain the pH of soil, through liming. However, most of studies made so far have been conducted in tropical, semi-tropical and savannah environments (Kimetu et al., 2008; Van Zwieten et al., 2008; Sinclair et al., 2008) while there is a substantial lack of studies at mid-latitudes and in temperate climates.

Agricultural management may play a role in reducing the net greenhouse gas (UNFCCC, 2008) and different agronomic strategies have been suggested and tested to reduce soil respiration rates and to increase soil organic carbon. Those measures include the conversion of arable land to grasslands, forest plantations and the implementation of crop management practices, such as conservation tillage and the introduction of rotations based on nitrogen fixing crops (Lal and Bruce, 1999; Lal et al., 1999; Lal, 2002). Recently, Lehmann et al. (2002) and Steiner et al. (2004) introduced the concept of converting residues to biochar as an alternative agricultural method to reduce carbon dioxide (CO_2) emissions. In fact, biochar can remain into soil for a long time (Glaser et al., 2001) due to its stable structure and complex aromatic polycyclic form (Baldock and Smernik, 2002) thus enhancing the resistance of C to microbial decay (Shindo, 1991; Cheng et al., 2008). Although information about turnover time of biochar is scarce and mostly comes from short-term decomposition experiments, it has been suggested that biochar stores atmospheric C from millennial (Kuzyakov et al., 2009) to centennial timescales (Hamer et al., 2004). Based on those results, biochar is currently considered as an interesting option to meet mitigation targets discussed by United National Framework Convention on Climate Change (UNFCCC).

The objectives of the present study were to assess: 1) the effect of biochar doses on ryegrass (*Lolium perenne* L.) production; 2) the effect of biochar application on durum wheat (*Triticum durum* L.) and maize (*Zea mays* L.) yields; 3) the effect on maize yield of biochar application with or without maize‘s crop residues.

Materials and methods

Biochar

Both field and pot experiments described in this paper were made using commercial horticultural charcoal by Lakeland Coppice Products (England) obtained from coppiced woodlands (beech, hazel, oak, birch). Biochar was prepared at pyrolysis temperatures of 500 °C in a transportable ring kiln (215 cm in diameter and holding around 2 t of hardwood). The material used was crushed into particles smaller than 1 cm before application to the soil in order to increase the area: volume ratio and to enhance its expected effects on soil properties.

C and N biochar contents were determined using a CHN Elemental Analyzer (Carlo Erba Instruments, mod 1500 series 2). Samples of biochar were screened by means of a 2 mm sieve and finally oven dried at 105 °C for 24 h. The dry samples were acid digested with a microwave oven (CEM, MARSXpress) according to the EPA method 3052 (USEPA, 1995). The solutions obtained after the mineralization were filtered (0.45μm PTFE) and diluted. The Available N was determined by KCl extraction technique. Total contents of P, K, S, Ca, Mg were determined by an ICP optical spectrometer (Varian Inc., Vista MPX) using scandium as internal standard.

The pH was measured in a soil/water solution at a 1/2.5 ratio. The main chemical characteristics of the biochar used in the present study are reported on Table 1.

Table 1. Characteristics of the biochar used in this study.

Biochar Characteristics	
Chemical Element	*Value**
Total C (g kg^{-1})	840
Total N (g kg^{-1})	12
Available N (g kg^{-1})	0.03
P (g kg^{-1})	0.5
K (g kg^{-1})	4.3
Ca (g kg^{-1})	2.6
S (g kg^{-1})	1.1
Mg (g kg^{-1})	2.8
C:N	70
pH (1:2.5 H_2O)	7.2

* all concentrations are on a DM basis.

Pot experiment

In order to asses the dose-response curve of biochar, a pot experiment was made with perennial ryegrass. Seeds were sown in pots of 5 l (0.2 m of diameter; 0.2 m of height) filled with a sandy-loam soil at rate of 60 seeds per pot corresponding to 24 kg seeds ha^{-1}. Six application rates of 0%, 0.3%, 0.8%, 1.7%, 2.8%, 3.3% (kg of biochar per kg of soil) where tested in a fully randomized experimental design with three replicates. The biochar doses were equivalent to application rates of 0, 10, 30, 60, 100 and 120 t biochar ha^{-1} assuming a soil bulk density of 1.2 g cm^{-3} up to a depth of 30 cm. After mixing, the pots were filled in order to ensure the same soil bulk density. Main soil characteristics are reported in Table 2.

Biochar was added before sowing and the pots were regularly irrigated to prevent water stress, but not fertilized. Aboveground biomass production was determined for two growth cycles (one and two months after plant emergence) by manual clipping. Dry matter was determined on oven-dried samples.

Field experiments

Two field experiments were performed in 2008. The first experiment was made in agricultural farm near Empoli (Toscana, Central Italy) with durum wheat (cv. SOLEX). The field was located at an altitude of 50 m a.s.l. with a sub-humid typical Mediterranean climate. According to long term weather data, total rainfall was 750 mm and the mean annual temperature was 14 °C (ARSIA Toscana, Italy). Main soil characteristics of the site are reported in Table 2.

A fully randomised experiment was made in 1.5 m^2 plots with two treatments (control C- and biochar C+) and four replicates. Biochar addition corresponded to an overall rate of 10 t ha^{-1} that was incorporated in December 2007, an half (5 t ha^{-1}) immediately before sowing and half after germination. Wheat was sown on 17th December with a seeds density of 450 seeds m^{-2}. A NP fertilizer was distributed at this time (22 kg N ha^{-1} and 50 kg ha^{-1} of P_2O_5) and a second nitrogen fertilization using urea (92 kg N ha^{-1}) was made in February 2008. Plots were manually harvested on 30th June 2008 in a central subplot of 0.7 m^2 to minimize edge effects. Total aboveground dry matter was oven-dried at 105 °C for 48 hours. Then, wheat ears were separated using a laboratory thresher (LD 350, Wintersteiger, Ried, Austria). Nitrogen concentration of seeds was determined by Kjeldahl analysis.

The second field experiment was performed in Beano (Friuli Venezia Giulia, Italy) on a soil cropped with irrigated continuous maize rotation. The mean annual temperature was 13.5 °C

Table 2. Texture and chemical Characteristics of the experimental soils.

	Pot experiment	Empoli	Beano
Gravel (% of dry bulk soil) ∅ > 2mm	n.a.	n.a.	32
Sand (g kg^{-1})[a] 2 mm > ∅> 0.05mm	550	350	270
Silt (g kg^{-1}) 0.05 mm> ∅> 0.002mm	300	360	580
Clay (g kg^{-1}) ∅ < 0.002 mm	150	290	150
Bulk density (Mg m^{-3})	1.6	n.a.	1.2
OC (g kg^{-1})[a]	n.a	18	19
N (g kg^{-1})[a]	n.a.	1.6	2
CEC (meq/100g)[b]	n.a.	16	n.a.
pH[c]	6.7	8.0	7.1

a) Organic Carbon (OC) content was determined using a CHN auto-analyser (CHN 1500, Carlo Erba).
b) Cation Exchange Capacity (CEC) was determined using NH_4OAc method.
c) The pH was measured in a 1:2.5 (mass/vol) soil solution.

with a total rainfall of 1216 mm (OSMER Friuli Venezia Giulia).

The treatments were control (C-) and biochar addition (10 t ha^{-1}) with (CR) or without (C+) residues of preceding maize. The three treatments where arranged in a randomized block experiment with three replicates. Each experimental plot had an area of 20 m^2. On April 4th the cv Kermess (from KWS maturity FAO class. 600) was sown at 7.2 seeds m^{-2}.

Fertilization was made at sowing adding 54 kg N ha^{-1} and 138 kg P_2O_5 ha^{-1} in the form of di-ammonium phosphate. Urea was then added at two dates for a total of 359 kg ha^{-1} of N (83 and 276 kg N ha^{-1} on 09/05/2008 and 03/06/2008, respectively). The plots were weekly irrigated and no water stresses were detected. Aboveground dry matter and yield were measured at harvest in a area of 9 m^2 avoiding border effects of each plot. Main soil characteristics of the site are reported in Table 2.

Statistical analyses

Treatment effects were analysed by analysis of variance (ANOVA) using SAS 9.1 (SAS Institute Inc., Cary, NC, USA). The ANOVA included treatment C- and C+ in the durum wheat experiment and C-, C+ and CR in the maize experiment. Since the experiment was a block design, block effect was also included. Significant treatment effects ($p < 0.05$) were explored further via a posteriori treatment comparison using the Least-Squares means (LSMEANS) test with Bonferroni adjustment for multiple comparison.

Results

Pot experiment

The higher was the rate of biochar added to the soil, the higher was the dry matter of ryegrass up to a threshold of 60 t biochar ha^{-1} (Fig. 1). A significant difference among treatments was detected ($p = 0.012$). The ryegrass biomass increased by +29% and +120% at first clipping and +40% and 140% at second clipping in 0.8% of biochar (30 t ha^{-1}) and 1.7% (60 t ha^{-1}) treatments, respectively. Germination was accelerated in the pots were biochar was added as likely consequence of increased soil temperature (data not shown). Negative effects of biochar were observed above 1.7% of biochar (60 t ha^{-1}).

Field experiments

In the field experiment with durum wheat, the phenological development of the wheat was not affected by biochar addition. In fact, no differences were found between the treatments and no major biotic and abiotic stresses were observed during the experimental period (data not shown). The aboveground biomass was instead enhanced by biochar. The observed stimulation was 23% respect to control with a value of 10.4 t ha^{-1} and 8.6 t ha^{-1} in C+ and C-, respectively (Fig. 2; $p = 0.054$). Similarly, grain production was stimulated by 10% with a value 3.1 t ha^{-1} and 2.4 t ha^{-1} in C+ and C-, respectively, but the significance of difference was low ($p = 0.082$). The nitrogen content of the wheat grains was not appreciably different between treated and

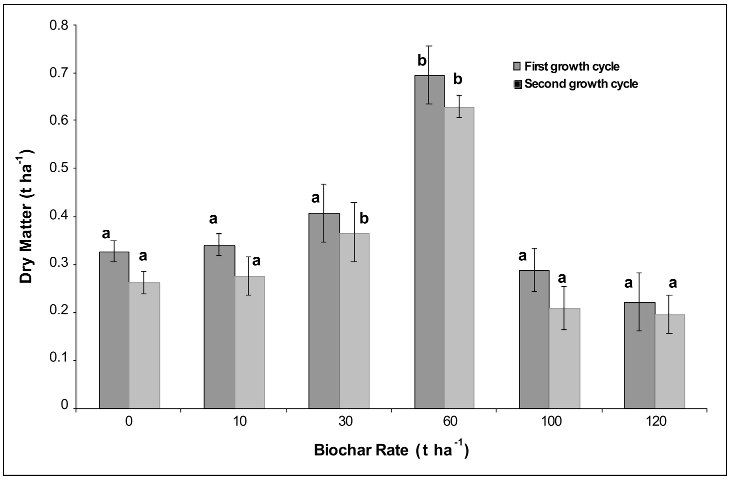

Figure 1. Aboveground biomass of *Lolium perenne* in the laboratory experiment in the first and second growth cycle at different rates of biochar (t ha^{-1}). Each value is the average of 3 replicates. Vertical bars indicate +/- standard error. Different letters indicate a significant difference respect to control (rate of biochar corresponding to 0) ($p < 0.05$).

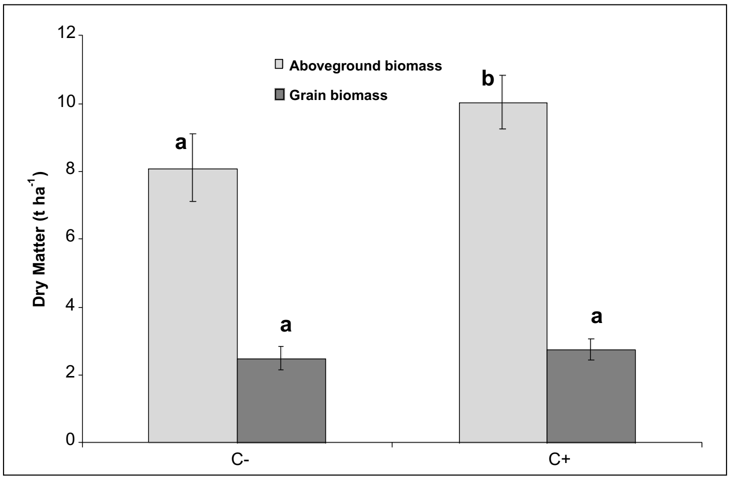

Figure 2. Aboveground biomass (open bars) and grain production (solid bars) of durum wheat in the field experiment in Empoli (Central Italy). C+ is the biochar, C- is the control. Each value is the average of 4 replicates. Vertical bars indicate +/- standard error. Different letters indicate a significant difference ($p < 0.05$).

un-treated plots (1.8% for control and 1.84% for biochar treatment).

In the field experiment on maize, plant density at the end of the growing season was not significantly different among treatments (data not shown). Aboveground biomass was also not significant ($p = 0.068$): 17.9, 22.5 and 25.8 t ha^{-1} in C-, C+ and CR, respectively. Grain production, instead, was significantly different ($p < 0.01$) (Fig. 3). In fact, a relative increase of grain yield in C+ and CR in comparison to C- (+6% and +24%, respectively) was measured: 9.7, 10.3 and 12.1 t ha^{-1} in C-, C+ and CR, respectively. However, Bonferroni test showed a significant difference in grain yield between C+ and CR ($p < 0.05$) and between C- and CR ($p < 0.01$), while no difference was detected between C+ and C- ($p > 0.05$).

Discussion

Agricultural productivity is often reported to increase with biochar application to soil, but always not consistently. It is not yet clear what are the soil climatic conditions that favour increased yields, and what are the most responsive species (Lehmann and Rondon, 2006).

Our results in the laboratory experiment showed that the rate of biochar application of 1.7%, corresponding to 60 t ha^{-1}, caused the maximum stimulation in terms of dry matter production in perennial ryegrass. Aboveground production stimulation by biochar addition was already observed for grasses (Rondon et al., 2006; Lehmann and Rondon, 2006) and this was interpreted as an overall amelioration of growth condition. In our study increased availability of nitrogen was supposed to be responsible for in-

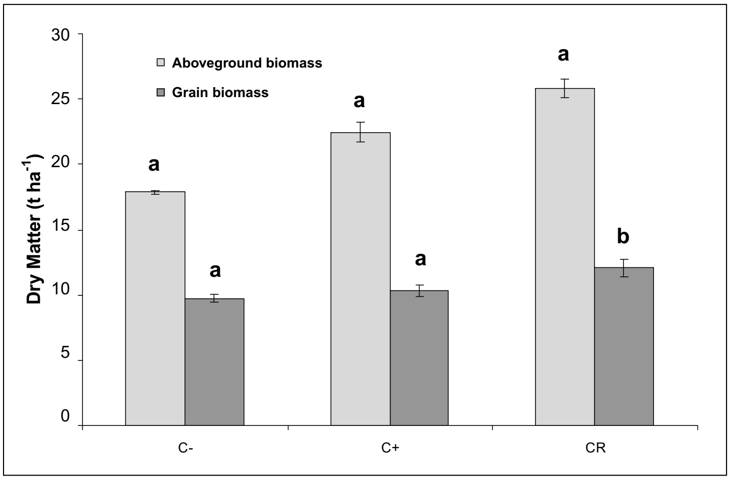

Figure 3. Aboveground biomass (open bars) and grain production (solid bars) of maize in the field experiment in Beano (Northern Italy). C+ is the biochar, C- is the control and CR is the biochar + residues, respectively. Each value is the average of 3 replicates. Vertical bars indicate +/- standard error. Different letters indicate a significant difference ($p < 0.05$).

creased dry matter production (Gathorne-Hardy et al., 2009) as improved water availability associated to biochar addition cannot be considered because the pots were maintained at the field capacity throughout the experiment by means of ample irrigation. Above the 1.7% (60 t ha^{-1}) threshold, the dry matter production of perennial ryegrass started to decline, probably because some chemical and physical properties of the soil were modified by the high rate of biochar applied. A possible explanation was given by Kishimoto and Sugiura (1985) and Mikan and Abrams (1995) who observed a general decrease of the biomass at high rate of the biochar application due to a micronutrient deficiency induced by the increasing soil pH. Direct toxicity effects may also provide an explanation, although these were not specifically investigated. Even a small biochar rate of 10 t ha^{-1} increased aboveground biomass (23%) and grain yield (10%) of durum wheat compared to control. Comparable results were obtained by Steiner et al. (2007). A strict correlation between total biomass production and grain yield is well known to exist in wheat as the harvest index is hardly affected by different management and yield levels (Spaeth and Sinclair, 1995; Bindi et al., 1998). The observed yield stimulation was likely due to a combination of improved soil water conditions (Lehmann and Steiner, 2009), reduced nutrient leaching (Yanai et al., 2007) improved soil structure and aggregate formation in the soil (Lehmann and Steiner, 2009). Increased nutrient availability following biochar addition was observed in other field studies (Rondon et al., 2007). In our experiment, the lack of difference between the N-content of the grains of treated and untreated plants cannot support the soil increased nutrient availability.

A positive effect on both aboveground biomass and grain was also observed in the field experiment on maize. An increase of 26% and 6% in C+ and 44% and 24% in CR for aboveground biomass and grain, respectively, was observed. A similar response was also obteined by Oguntunde et al. (2004). The higher increase observed in CR in comparison to C+, even though not significant, is in agreement with other studies (Glaser et al., 2002) and can be interpreted as a result of the positive effect of maize stover residues of previous crop on the micro-scale physical properties of soil aggregates, promoting their formation and stability (Blanco-Canqui and Lal, 2008).

Beneficial effects of biochar in terms of increased crop yield and improved soil quality have been reported in several other studies (Iswaran et al., 1980; Glaser et al., 2002). However, Glaser et al. (2002) underlined the fact that crop yields can be increased only if biochar is applied together with inorganic or organic fertilizer as in the present study. In fact, Steiner et al. (2008) measured both a higher soil N retention and an enhanced N cycling in fertilized plots that received biochar. This could be due to a reduction in N leaching (higher retention of NH_4^+; N immobilization in microbial biomass) or to a reduction of denitrification (Yanai et al., 2007) and we suppose that this is the main mechanism that can explain the observed yields increase in both our field experiments. However, there could be other important interactions to explain the biochar stimulation of crop yield mostly related to its higher stability in comparison to other organic amendments as well as the native soil organic matter (SOM) (Steiner et al., 2007). Biochar can capture high amounts of exchange cations (Lehmann et al., 2003) because of its high porosity and surface/volume ratio and can improve plant nutrients uptake and P, Ca, K availability (Chan et al., 2007; Yamato et al., 2006). Biochar should no longer be seen as an inert material that remains unaltered in the soil where it is deposited. In fact, during its permanence in soils, biochar is slowly oxidized, carboxylic groups are produced, cation exchange capacity and oxygen carbon ratio on the biochar surface increases (Brodowski et al., 2005), improving the capacity of biochar to retain nutrients in the long term. However, chemical and physical characteristics of biochar depends on the nature of the feedstocks used and on the operating conditions of pyrolysis process (Gundale and De Luca, 2006). Therefore, yield responses are currently difficult to predict, and global patterns need to be identified to move towards an understanding of the crop production potential using biochar.

Conclusions

The results shown in this paper highlight a number of conclusions that can have practical importance for future experiment and real-world application of biochar in agriculture.

A. *Positive effect on growth and yield are sustained even at very high rates of biochar addition to the soil.* In the pot experiment, negative effects were observed when more than 1.7% (60 t ha^{-1}) of biochar were added. The preliminarily type of investigation and the limited prediction capacity of the pot experiment do not allow excessive generalization, but outline the fact that negative effects are unlikely under-realistic application scenarios. The addition of 30-60 t ha^{-1} of biochar, to a 30 cm deep soil would in fact correspond to 0.6-1.2% rate, below the 1.7% rate over which negative effect were observed;
B. *Even relatively small rates of biochar addition can have positive effects on crop growth and yield*. Although the limited scope of our initial trial does not allow to properly understand the mechanism underlying the observed increase in yield, there are convincing indications that biochar acts as a soil amendant capable of enhancing resource availability for the crop. Higher soil N-retention can be responsible for increased productivity (Steiner et al., 2008) but also enhanced N-cycling (reduction of denitrification) can contribute (Yanai et al., 2007). Increased soil water capacity, mechanical characteristics promoting soil organic matter stabilization (Steiner et al., 2007), the availability of high amounts of exchange cations associated to high porosity of biochar (Lehmann et al., 2003) are additional factors that require further specific investigation in field experiments;
C. *Enhanced yield and soil amelioration due to biochar application is always accompanied by long-term C-sequestration*. When plant residues are transformed into char by pyrolisis they reach very stable condition that can only be partly decomposed by soil micro-organisms. There is evidence in literature that the largest part of carbon contained in the biochar can remain undecomposed for hundred years or even millennia;
D. *The positive effects of biochar application and its potential for C-sequestration are accompanied by the production of thermal-energy during the pyrolisis.* When such energy is efficiently used it can replace the use of fossil fuels and therefore further contribute to an overall reduction of net emission of greenhouse gases to the atmosphere.

Our study must be seen as a first attempt to frame the research of biochar within a coherent scientific approach in Italy. More studies are definitely required to expand phenomenological observation and to improve our mechanistic understanding of processes.

Acknowledgment

Diego Chiabà (University of Udine) is acknowledged for valuable technical assistance during the field experiment. This study contributes to the by the Italian Biochar Association (ICHAR http://www.ichar.org).

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