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The effects of biochar on the physical properties of bare soil

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ABSTRACT: The pyrolysis conversion of vegetable residues into energy and biochar, and its incorporation in agricultural soil, reduces CO_2 emission and provides a longterm soil carbon sequestration. Moreover, biochar application in soil seems to increase nutrient stocks in the rooting layer, improving crop yield. Compared with the numerous studies assessing the positive effect of biochar on yield, however, little research has been published elucidating the mechanisms responsible for the reported benefits. Few studies cited soil moisture as the key factor, attributing the increased yield to the higher soil water availability.

The aim of this study was to investigate the effect of biochar on the physical and hydraulic properties of a bare Padana Plain (Cadriano, Bologna) agricultural soil. A preliminary plot experiment in 2009 explored the influence of 10 and 30 kg ha^{-1} of biochar on soil moisture, without effects from plants. Results of the first experiment suggested using higher biochar rates in a similar experimental scheme. During the second experiment, 30 and 60 t ha^{-1} doses were investigated. Soil water content, bulk density, electrical conductivity and soil water retention were measured. The comparison between treated soils and the control indicates that the biochar rate is directly correlated to electrical conductibility and inversely correlated with bulk density. The effect on the density of soil can be very positive in case of heavy soils. The dark colour of the char increased the surface temperature with respect to the control, while no differences were detected at 7·5 cm depth. No influences were found on other soil characteristics, including soil pH, moisture and water retention.

KEY WORDS: soil carbon sequestration, soil temperature, soil water content, soil water retention.

There has been a growing interest in biochar and its applications in recent years, due to biochar's capacity to sequester carbon and its generally positive impact on soil and agricultural productivity. Biochar can be used as soil amendment with considerable beneficial effects in terms of increased crop yield and improved soil quality (e.g., Iswaran *et al.* 1980; Glaser *et al.* 2002; Lehmann *et al.* 2003; Yamato *et al.* 2006; Chan *et al.* 2007; Rondon *et al.* 2007; Van Zwieten *et al.* 2008; Baronti *et al.* 2010). Notwithstanding the success of biochar, the published research incorporates considerable variability in experimental design, including a wide range of biochar application rates (0·5–135 t of biochar/ha), and a wide range of plant responses has been obtained (0–300% yield increase) (Glaser *et al.* 2002; Pratt & Moran 2010). For a given rate of biochar application, differences in yield response are probably due to the interactive effect of many variables, and mainly to differences in biochar organic material, physical and chemical characteristics of the experimental site soil, cover vegetation and land management, and pyrolysis process characteristics (Lehmann & Rondon 2006; Chan *et al.* 2007; Pratt & Moran 2010). For example, biochar produced under 400°C has a low surface area and may not be useful as a soil amendment (Lehmann 2007). Moreover, the basic material, chemical and physical characteristics (e.g. level of metal contaminants) and pyrolysis condition will affect the amount and type of substances produced. In some cases, phytotoxic and potentially carcinogenic organic materials can be generated (Lima *et al.* 2005, as cited by Lehmann 2007).

Together with numerous studies assessing the positive or indifferent effect of biochar on crop yield, crop growth, production and soil quality, research exploring the mechanisms responsible for the reported benefits is needed.

Some studies attributed the positive response of crops to the indirect effects of biochar on nutrient availability, such as the improvement of the cation exchange capacity of soil (Lehmann & Rondon 2006; McHenry 2009), which increases soil fertility, and the reduction of soil acidity and of nutrients needs. Moreover, the biochar seems to have a high potential to immobilise previously plant-available N. This could be from the mineralisation of the labile, high C-to-N fraction of the biochar drawing N into microbial biomass; sorption of ammonium; or sequestration of soil solution into fine pores (Sohi *et al.* 2010). In addition, some research (Rondon *et al.* 2007; Yamato *et al.* 2006; Van Zweieten *et al.* 2008) has highlighted the ability of biochar to increase or maintain soil pH, through liming, as a fundamental element in the positive yield responses, especially in acid soils.

Finally, other studies have cited moisture retention as a key factor. This hypothesis suggests that the increased yield is due to higher soil water availability, affected by soil temperature, soil cover, evapotranspiration and evaporation. In accordance with this hypothesis, Laird *et al.* (2010) found that amending a fine loamy soil with biochar leads to a greater water retention at gravity-drained equilibrium (up to 15%) and at −1 and −5 bar soil water matric potential (13% and 10% greater, respectively).

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Thus, the application of biochar modifies the physical structure of the bulk soil, which may result not simply in increasing the capacity of soil to retain water, but also in increased capacity to retain nutrients in soil solution (Sohi *et al.* 2010). These biochar properties and beneficial effects probably also depend on site-specific conditions, including soil type, temperature and moisture. This issue is not negligible, if most of the cited field experiments are conducted in tropical, semi-tropical and savannah environments, while there is a substantial lack of field researches at mid-latitudes and temperate climates.

Field studies have only begun to test the agronomic benefits, and understanding of the optimal locations for biochar use await more extensive experiments. Such understanding is essential for the development of agricultural markets for biochars and for the future development of technology for the production of biochar of improved quality and value (Chan *et al.* 2007).

The objective of the present study was to evaluate the effects of biochar on the moisture and temperature of a bare arable soil with a long history of cropping. The absence of a crop simplified the system and helped the assessment of whether the presence of biochar changes physical characteristics of soil, water content and water retention, and if changes in these characteristics may be responsible for the improvements in crops productions and yields.

1. Materials and methods

1.1. Soil

The experiment was conducted at the experimental farm of the University of Bologna in Cadriano (Bologna, 44°33′N, 11°24′E, 33 m a.s.l.). The site, in a typical fertile cultivated area of the Padana Plain, has a continental climate, with a mean annual temperature of 13·6°C and a large diurnal temperature range. The mean annual rainfall amount is 740 mm (1952–2008 average), concentrated in Spring and Autumn.

The site's water table ranges in depth from −0·8 m in April to −2·4 m in September (all climatological information from Matzneller *et al.* 2010). The soil has a clay loam texture, with a subalkaline pH; textural and chemical characteristics are listed in Table 1. The plots were located within a large field in the experimental farm, that is usually cultivated with herbaceous crops. The field was tilled and then maintained bare for the duration of the experiments.

1.2. Biochar

The biochar studied here was derived from fruit tree pruning residues of the agricultural area of Ravenna (about 50 km east of Bologna). It was the waste material of the traditional pyrolysis process for producing barbecue charcoal. The pyrolisis process was carried out in a traditional oven, and there is no record of the process temperature.

The biochar was analysed to determine pH and chemical composition: carbon and nitrogen were analysed with a CHN Elemental Analyzer (Carlo Erba Instruments, Hindley Green, Wigan, UK), and other minerals were determined by means of ICP-OES simultaneous sequential (Ametek-Spectro, Kleve, Germany). Biochar chemical characteristics are listed in Table 2.

Table 1 Textural and chemical characteristics of the experimental soil.

Soil Characteristic	Value
Texture (USDA)	Clay Loam
Sand (%)	38
Silt (%)	33
Clay (%)	29
Bulk Density (g cm^{-3})	1·2–1·5
OM	1·06%
CEC (mEq/100g)	17·75
pH	6·65

Table 2 Chemical characteristics of biochar.

Chemical Element	Unit	Value
Total C	%	57·81
Total N	%	0·91
C/N	–	63·5
Ca	(g kg^{-1})	25
Cu	(mg kg^{-1})	0·02
Fe	(g kg^{-1})	0·333
K	(g kg^{-1})	13·9
Mg	(g kg^{-1})	28·7
Mn	(mg kg^{-1})	84
Na	(g kg^{-1})	11·9
P	(g kg^{-1})	23·3
S	(g kg^{-1})	0·481
Zn	(g kg^{-1})	0·104
pH (1:2·5 H_20)	–	9·8

1.3. Plot experiments

1.3.1. Experiment 1. A short preliminary experiment in 2009 used six experimental plots (1 × 1 m) to explore the influence of biochar on soil moisture. Biochar was applied at two rates, Q1 = 10 t ha^{-1} and Q2 = 30 t ha^{-1}, in a fully randomised experimental design, with two replications. Two plots were used as control (Q0). Biochar was spread uniformly by hand at the two application rates on the surfaces of the plots and incorporated into the soil to a depth of about 20 cm using a cultivator.

Soil water-content probes (EC-5 Decagon Devices, Pullman, WA, USA) were inserted in the middle of the plots to depths of 10 and 20 cm. Data were collected and stored in a CR10X datalogger (Campbell Scientific Inc., Logan, UT, USA), downloaded weekly and analysed. The experiment was initiated in June 2009, and data were analysed from July 20 to September 20 2009, having given the sensors time to adjust in the soil. To have clear indications of the response of soil moisture to biochar, and because it was a dry summer (only 46 mm of rain in two months, compared to a 121 mm average), the experiments were irrigated twice; first on August 13 (98 mm) and then on August 23 (170 mm).

Calibration equations were determined, measuring the water content of the soil samples in the laboratory using the gravimetric method. Three samples per plot and per depth were taken during the experiments, giving a total of 36 samples. Details on sampling dates, depth and repetitions are summarised in Table 3. Samples were weighed and oven-dried at 105°C for 24 hours, and then re-weighed to determine water content. Soil moisture values obtained in this way are in percentages of weight, while soil water-content probes give results in percentages of volume. The bulk density of the plots was measured by the cylinder method (Blake & Hartge 1986) in both years, to allow the conversion of the gravimetric water content to percentages of volume, and their comparison with capacitive results. In 2009, thirty-six volumetric samples were taken for measuring the bulk density (Table 3).

1.3.2. Experiment 2. In the second year of experiments, six plots of 2 × 2 m were set. Two biochar rates (T1 = 30 t ha^{-1} and T2 = 60 t ha^{-1}) were tested in a fully randomised experimental design, with two replications. Two plots were used

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Table 3 Details of the two experiments: number of plots, treatments, repetitions, irrigations, soil sampling characteristics and dates. (NB: dates in month/day format.)

experiment	number of plots	number of treatments	number of irrigations	irrigation dates	soil sampling depth	soil sampling dates for U	soil sampling dates for bulk density
1 2009	6 (3 treatments × 2 repetitions)	3 (Q0 = 0; Q1 = 10 t ha^{-1}; Q2 = 30 t ha^{-1})	2	08/13, 08/23	10 cm, 20 cm	08/10, 08/14, 08/24	08/10, 08/14, 08/24
2 2010	6 (3 treatments × 2 repetitions)	3 (T0 = 0; T1 = 30 t ha^{-1}; T2 = 60 t ha^{-1})	1	07/19	5 cm, 10 cm	05/31, 06/08, 06/14, 06/22, 07/05, 07/12, 07/19, 07/20, 07/22, 07/28	06/14, 07/19, 07/20, 07/22, 07/28

as control (T0). As in Experiment 1, plots were tilled with a cultivator after the application of the biochar to incorporate it to a depth of about 20 cm.

Water-content probes (EC-5 Decagon Devices, Pullman, WA, USA) were inserted in the middle of the plots, this time at shallower depths (5 and 10 cm), to be sure that they were completely embedded into the layer of treated soil. Data were collected and stored as in Experiment 1. Temperature probes (107 Campbell Scientific Inc., Logan, UT, USA) were inserted into the soils, setting them parallel to the soil surface at a depth of 7·5 cm; data were recorded using a CR-1000 datalogger (Campbell Scientific Inc., Logan, UT, USA). The experiment was begun at the start of May 2010, and data analysis covered the period May 31 to September 3 2010, giving the sensors time to adjust into the soil.

Rainfall in 2010 was typical for the site, with 170 mm in the 100 days of the experiment (the 1952–2008 average = 174 mm), distributed throughout the experimental period. Calibration curves of the soil moisture probes, for each plot and depth, were constructed. The plots were irrigated on July 19 (66 mm), to help with obtaining a good calibration curve. During the experiment, ten samples per plot and per depth were taken (Table 3), weighed, oven-dried for 24 hours at 105°C, and re-weighed to determine water content. Bulk density of soil, or soil plus different amounts and types of biochar, was experimentally measured to allow the conversion of water content data from percentages of weight to percentages of volume, and their comparison to probe measurements. In 2010, sixty volumetric samples were taken for measuring bulk density (Table 3).

At several times on selected dates (a total of nine measurements), soil surface temperature was measured in all plots by means of an infrared thermometer (Fluke 61, Fluke Corporation, Everett, WA, USA). These data were compared to the 7·5 cm-depth temperature recorded at the time by means of temperature probes.

1.4. Soil water retention measurements

Soil water potential curves were determined only in Experiment 2, on treated and untreated samples, measuring soil moisture at −10, −33, −100, −500 and −1500 kPa. Representative samples of soil with and without biochar were carefully ground, and organic matter and carbonates removed (Whittig & Allardice 1986). Particle size distribution was then determined by sieving below 2 mm.

Soil structure affects water retention, and so it is generally preferred to analyse undisturbed samples (Dane & Hopmans 2002). Cresswell *et al.* (2008), however, reported their laboratory experience that better pressure plate measurements at low potentials are obtained by using disturbed samples. We followed this procedure in taking measurements only on disturbed samples, at both low and high potentials.

Plastic rings 2·8 cm in diameter and 0·9 cm high were filled with 6·5 g of air-dried soil, sieved under 2 mm. The rings were placed on ceramic plates of a Richards pressure apparatus (Soil Moisture, Santa Barbara, CA, USA). For each sample three replicates were measured. The ceramic plates suited to measurements had bubbling pressures of 50 kPa (for −10 kPa and −33 kPa measurements), 300 kPa (−100 kPa) and 1500 kPa (−500 kPa and −1500 kPa). Samples were wetted from below by pouring 200 ml of 2% boric acid solution on the ceramic plates. They were allowed to saturate for about 48 hours, then the pressure was adjusted to −10 kPa. After equilibrium (usually three days) the samples were removed and weighed. The whole operation was repeated on the other sets of samples, applying the pressure heads of −33 kPa (usually seven days to reach equilibrium) −100 kPa (seven days), −500 kPa (seven days) and −1500 kPa (11 days). Finally, the soil samples were oven dried at 105°C and the gravimetric moisture content (kg kg^{-1} expressed in %) was measured.

1.5. Data elaboration

When more repetitions of the same measure were available, data were compared using ANalysis Of Variance (ANOVA). This was possible with data of bulk density, electrical conductivity, soil moisture measured by water probes, soil water retention and soil temperature. When ANOVA gave positive results, the analysis was completed by applying the LSD test, to determine which treatment was significatively different.

2. Results and discussion

2.1. Effect of biochar on soil characteristics

At the end of the experiment, pH and electrical conductivity (EC), of the treated soils (T1 and T2), and the control (T0), were measured. Results, shown in Table 4, indicate that treatments had no effects on the soil pH, while they produced significant differences in EC. In particular, there is a direct relationship between biochar rate and EC: higher rates of application of biochar resulted in higher EC.

2.2. Calibration curves and bulk density

As stated by Ventura *et al.* (2010), it is preferable to calibrate the capacity probes for soil moisture measurement before every use. Moreover, the biochar could not be perfectly homogeneously distributed into the soil, because the cultivator incor-

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Table 4 Characteristics of soil (pH and electrical conductivity, EC) in different treatments.

Treatment	Biochar amount (t ha^{-1})	pH		EC (μS)	
T0	0	6·65	a	498·5	a
T1	30	6·95	a	500·0	b
T2	60	7·10	a	504·0	c

Table 5 Soil bulk density as an average for treatments for two depths.

Soil bulk density		5 cm		10 cm	
treatment	*biochar quantity (t ha^{-1})*	*bulk density (g cm^{-3})*		*bulk density (g cm^{-3})*	
T0	0	1·20	a	1·23	a
T1	30	1·06	b	1·15	b
T2	60	0·98	c	1·09	b

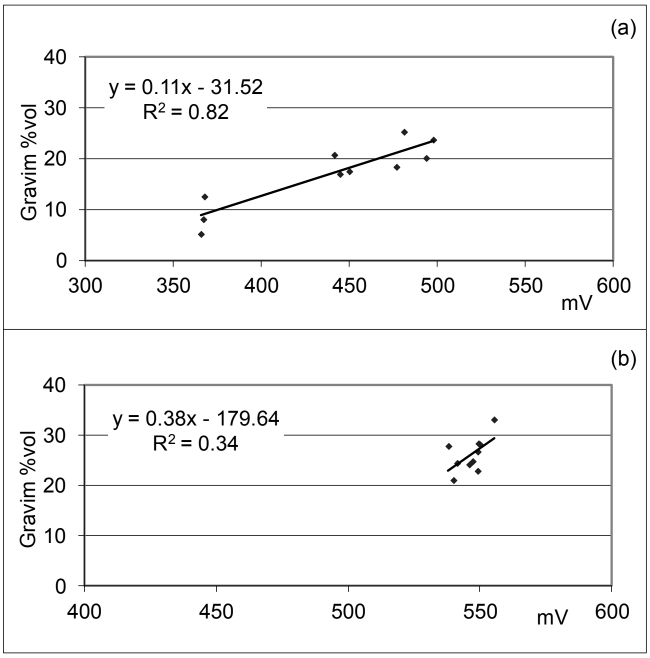

Figure 1 Calibration equations for water content probes (EC-5 Decagon Devices) in a plot treated with T2 = 60 t ha^{-1} at depths of (a) 5 cm and (b) 10 cm.

porates the material into the soil to a depth that may vary depending on soil resistance. In both years, the soil had been previously prepared for seeding, and consequently it was quite homogeneous, but to be more accurate it was considered appropriate in both years to have a specific calibration curve for each probe.

Curves were acquired by comparing the water content from gravimetric and probe measurements, three times during the first experiment, and ten times during the second, as shown in Table 3. Figures 1a and 1b show an example of calibration curves in 2010 for a plot with the treatment T2, at the two depths, 5 cm and 10 cm. The 10 cm-depth samples, in both years, and in all plots and treatments, showed a low range of water content (Fig. 1b). This may be due to the absence of a crop, which would have depleted the soil water content in the deeper layers.

2.2.1. Experiment 1. The value of soil bulk density is necessary to compare the two types of measurements, gravimetric and capacitive, by means of the EC probes, but it is also an important soil characteristic in its own right. In particular, the addition of biochar, which is a low-density material, should result in a lowering of bulk density. The amount of data from the first experiment was insufficient to discern significant differences among the treatments (only three replicates per depth/quantity of biochar) but a difference at 10 cm depth was found (bulk density was 1·33 g cm^{-3}, 1·22 g cm^{-3} and 1·26 g cm^{-3} for Q0, Q1 and Q2 respectively). In comparison, bulk density at 20 cm was 1·56 g cm^{-3}, 1·57 g cm^{-3} and 1·59 g cm^{-3} for Q0, Q1 and Q2 respectively, most likely because samples were taken below the layer containing biochar. In any case, these preliminary results suggested that the sampling depths and biochar rates should be changed.

2.2.2. Experiment 2. Bulk density results show that, in the first 5 cm, there were significant differences between the control (T0) and the plots with added biochar (T1 and T2) (Table 5). The differences between the control and the treated plots were still evident at greater depths, but it was impossible to distinguish any effect of rates of application. This could be explained by considering that biochar in soil is not homogenously distributed, and the border between the two soil layers (with and without biochar) is not well defined. The control plot had the highest bulk density (Table 5).

As expected, there is an inverse linear correlation between bulk density and biochar application rate ($R^2 = 0{\cdot}98$ and 0·99 for the 5 cm and 10 cm depths, respectively; Fig. 2).

2.3. Soil moisture data

2.3.1. Experiment 1. In the 2009 experiment, no significant differences between the control and the treated plots were found, in either capacitive or gravimetric measurements.

2.3.2. Experiment 2. In the second experiment, probe depths and biochar rates were shallower than in Experiment 1, to avoid errors in the water content determination due to either incomplete probe incorporation in the biochar soil layer, or to the low amount of char in the soil. Moreover, closer to the soil surface there is a higher water content variation during the season, related to the atmospheric vapour pressure deficit.

Comparing the 2010 daily and hourly soil moisture data in the various plots, no differences were again found between treated and untreated plots. This result was obtained with both gravimetric and capacitive data. The total water content of the explored layer (in mm) was also calculated, and no differences were found.

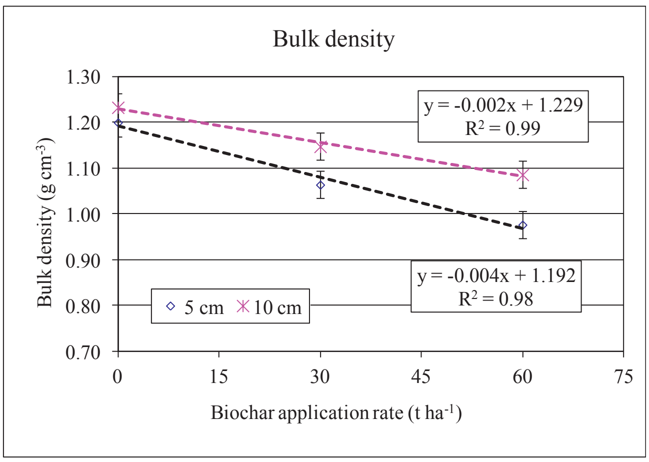

Figure 2 Bulk density as a function of the quantity of biochar in soil.

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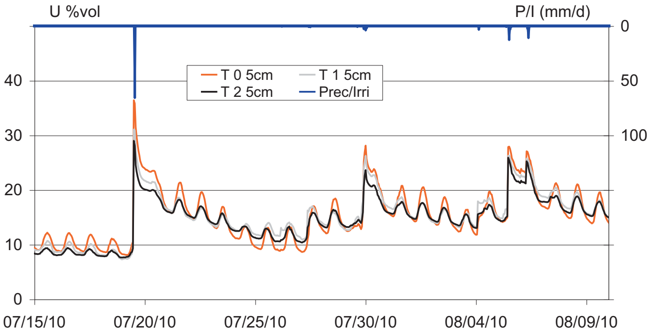

Figure 3 Precipitation/irrigation and soil moisture as measured by EC-5 probes at 5 cm in soil, for the different treatments (T0 = 0, T1 = 30 t ha^{-1} and T2 = 60 t ha^{-1}). NB: dates in month/day format.

Figure 3 shows soil moisture probes measurements for a period before and after the 7/20/2010 irrigation that was applied in order to have reliable data for probe calibration. In both periods on a daily basis, there were sometimes significant differences between the treated and untreated plots, but without a clear trend (sometimes biochar has lower moisture, sometimes higher). In general, there are no significant differences. Figure 4 shows the gravimetric data from the experiment. Gravimetry is a 'primary' measurement method, and is not instrument or measurement technique-dependent. This result is free from problems related to capacitive measurements of soil moisture, and should be definitive for this soil. Both Figures 3 and 4 show that adding biochar to bare soil does not lead to differences in soil moisture, as has been found by other researchers for similar soils and with lower biochar contents (e.g., Laird *et al.* 2010).

2.4. Soil-water retention curves measurements

The literature also presents data on variation of water retention capacity of soils with biochar (Jha *et al.* 2010; Novak *et al.*

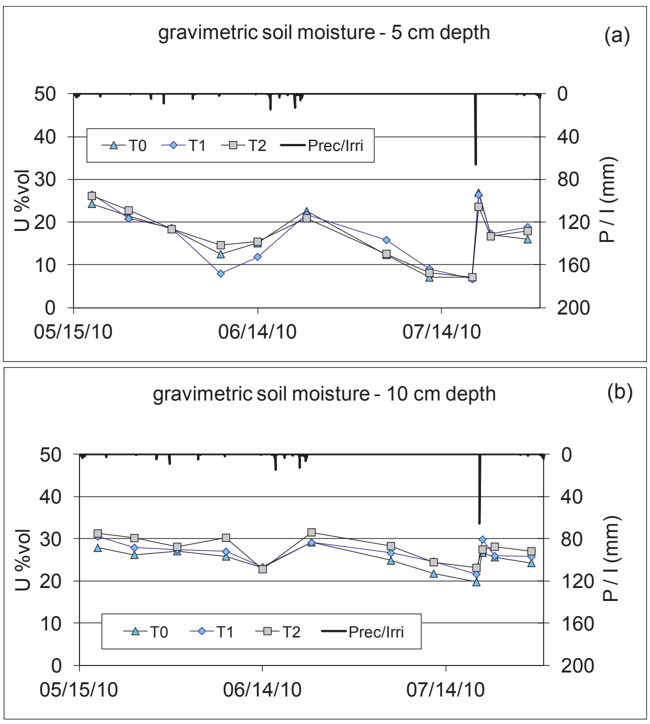

Figure 4 Gravimetric soil moisture, transformed in % volume by means of bulk density measured at the same time: (a) 5 cm depth; (b) 10 cm depth. NB: dates in month/day format.

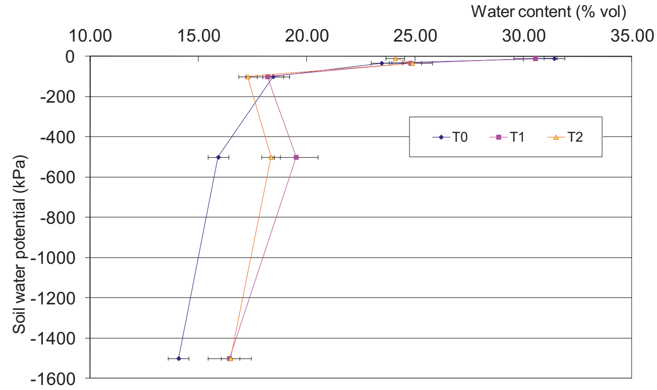

Figure 5 Soil water potentials measured in treated and untreated disturbed soil samples.

2012). Figure 5 shows the water retention curves measured by Richards chambers for soil and biochar specimens. The results for disturbed soil samples with biochar are unusual, in that the application of larger pressure heads normally brings soil samples to lower moistures in a monotonic way. Both the treated soil samples, with 30 t ha^{-1} and 60 t ha^{-1} of biochar, show decreases and increases of detected soil moisture with the application of larger potentials, as in −33 kPa and −500 kPa for T1 and in −500 kPa for T2. Conversely, T0 samples curves showed the expected trends, confirming that the measurements were conducted properly. This unusual result may be the effect of inhomogeneities in the treated soil, because soil moisture for different pressures is measured on different samples. Soil samples were prepared following the standard procedure, which may not actually be appropriate in this case, and larger rings and amounts of treated soil would probably reduce the uncertainty. The result may also be due to intrinsic biochar properties, such as its hydrophobia or its porosity. No consideration about biochar effects on potentials are possible starting from these data, and further experimentation is required.

2.5. Soil temperature data

In Experiment 2, in 2010, soil temperature was measured. As shown in Figure 6a, no effect of biochar rates on soil temperature, measured at a depth of 7·5 cm was detected. This result was quite clear during the experiment, and it was decided to make additional measurements, checking the surface temperature directly. In fact, the appearance of the surface is quite different between treated and untreated soils, due to the dark colour of the biochar. This difference is likely to have affected soil surface temperature, as is confirmed by the samples with added biochar.

Surface temperature was measured at different time of the day, and Figure 6b shows one day of measurements, compared to the subsurface temperature. The control plot has a significantly lower temperature as compared to the treated plots. The higher temperatures in treated plots were probably due to the albedo of the darker soil surface.

3. Conclusions

The research reported here presents results from the application of biochar on a bare, arable and fertile clay loam soil in the Padana Plain. The results show that biochar has different effects on physical and hydrological soil characteristics. In particular, bulk density is clearly affected by increasing amounts of biochar, with an inverse linear correlation. Soils tend to be lighter after treatment, an effect that has potential for dealing

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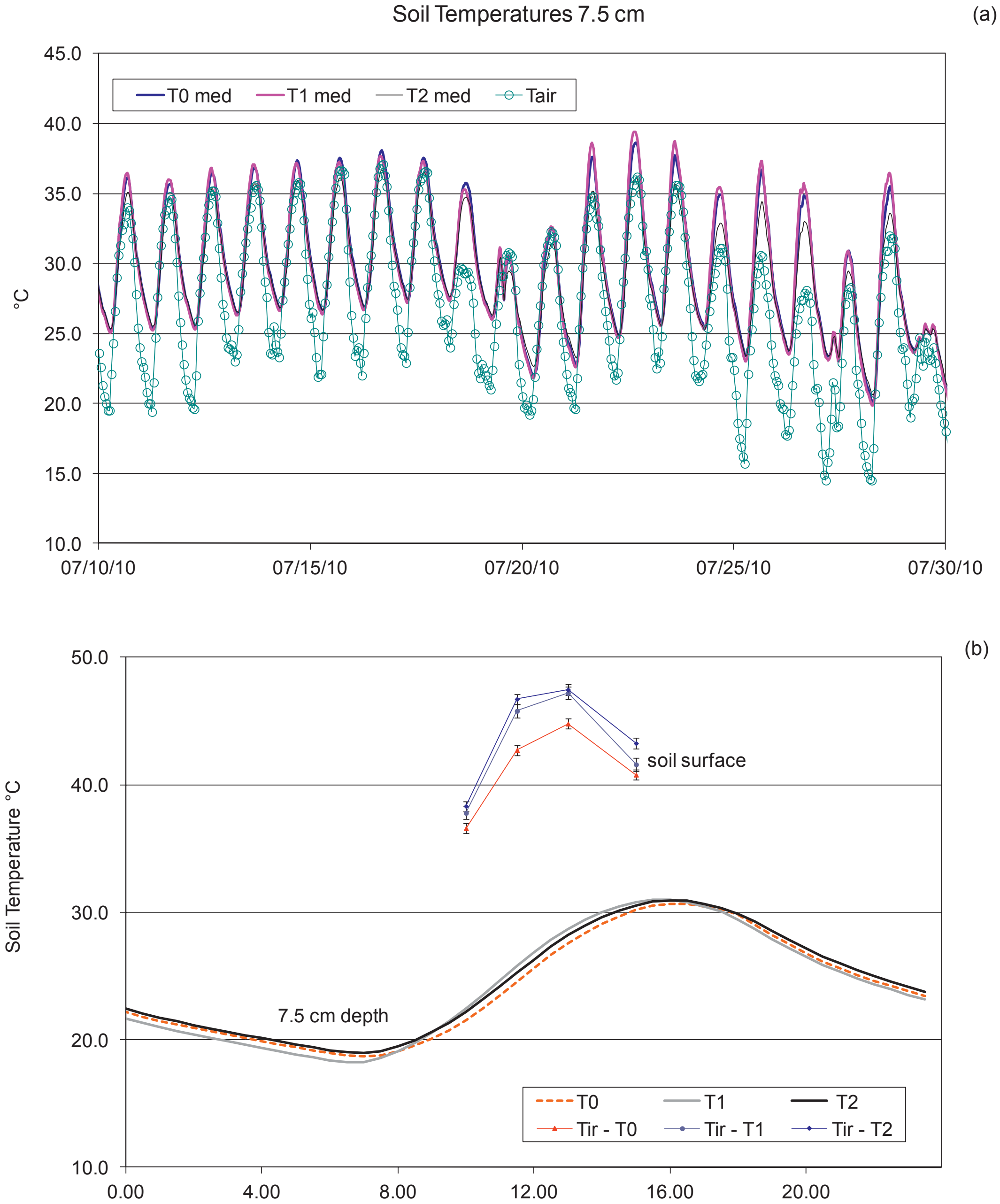

Figure 6 Soil temperature measured (a) at 7·5 cm depth; (b) on 09/01/2010 at 7·5 cm, as compared to soil surface IR temperature. NB: dates in month/day format.

with heavy soil or soil prone to shallow water table conditions. At the same time, electrical conductivity increased with rates of biochar application, indicating an increase of ions in solution. This effect needs to be further investigated, because it can result in a worsening of soil chemical characteristics.

Soil moisture and soil water content showed no significant differences during the three-month field experiment on bare soil. This result may reflect the fact that the study area soil is well structured, with available water equal to about 9%, which was unchanged by the biochar application. Soil water retention showed unexpected results in treated samples, and no definite conclusions are possible based on these data.

Soil temperature was also investigated, 7·5 cm below the soil surface. These measurements provided no evidence of difference between treated and untreated soils, whereas surface temperature, as measured by IR thermometer, was found to be significantly higher in treated soil.

Finally, the experiment suggests that other investigations are needed to clarify the role of biochar on those soil characteristics related to production yield. In particular, biochar, both in this study and in numerous published data, has a positive effect on soil properties, but such effects need to be tied more carefully to distinguishing the specific soil types that benefit from the application of biochar from those which experience little benefit from its application.

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