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Surface albedo following biochar application in durum wheat

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Abstract
The agronomic use of charcoal from biomass pyrolysis (biochar) represents an interesting option for increasing soil fertility and sequestering atmospheric CO_2. However, before moving toward large-scale biochar applications, additional research must evaluate all possible land–atmosphere feedbacks. Despite the increasing number of studies investigating the effect of biochar on soil physical, chemical and biological properties, only a few have been done on surface albedo variations on agricultural lands. The present work had the aim of characterizing the annual albedo cycle for a durum wheat crop in Central Italy, by means of a spectroradiometer measurement campaign. Plots treated with biochar, at a rate of 30–60 t ha^{-1}, showed a surface albedo decrease of up to 80% (after the application) with respect to the control in bare soil conditions, while this difference tended to decrease during the crop growing season, because of the prevailing effect of canopy development on the radiometer response. After the post-harvesting tillage, the soil treated with biochar again showed a lower surface albedo value (<20–26% than the control), while the measurements taken in the second year after application suggested a clear decrease of biochar influence on soil color. The modeling of the surface energy balance highlighted changes in the partitioning of heat fluxes and in particular a substantial increase of ground heat fluxes on an annual basis.

Keywords: mitigation strategies, carbon sequestration, land-surface feedbacks, geo-engineering

1. Introduction

The application of charred biomass residues (biochar) to soils is considered one of the most promising strategies to sustainably sequester atmospheric CO_2 in agricultural soils (Lehmann 2007, Woodward *et al* 2009, Sohi *et al* 2010). Mitigation potentials of biochar were estimated to be as high as 12% of current anthropogenic CO_2 emissions (Woolf *et al* 2010), something that might be possibly achieved under a win–win framework leading to a substantial enhancement of soil fertility (Sohi *et al* 2010), increased crop yields and renewable energy production (Lee *et al* 2010).

Most of the recent research on biochar focused on its effect on plant productivity (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, Vaccari *et al* 2011). Biochar application consistently increased crop yields, but no unifying mechanism to explain such an effect was found. The majority of published papers agree that further studies are needed before recommending large-scale biochar application as soil amendment: the long-term stability of biochar in soil has not been fully demonstrated, the safety for human health not fully assessed and the impact on the radiative balance not yet evaluated (Meyer *et al* 2011).

It is well known that anthropogenic changes in land surface properties have an impact on climate (Forster *et al* 2007, Bonan 2008, Jackson *et al* 2008). In particular, there is evidence that the variation in surface albedo, which inevitably follows changes in land use, is one of the most important bio-geophysical drivers on climate (Myhre and Myhre 2003, Kvalevåg *et al* 2010) altering the radiative balance and consequently the partitioning of sensible, latent and heat soil fluxes (DeFries *et al* 2002) with important impact on regional climate (Georgescu *et al* 2009, 2011).

Indeed, the application of a black material to the soil may have consequences on the amount of solar radiation reflected back to space (albedo) and, as a consequence, on soil sensible heat flux, surface temperature and evaporation. A consistent decrease in albedo has already been reported for charcoal production sites (Oguntunde *et al* 2008) and in post-fire savannah (Scholes and Walker 1993), proclaiming the need to better investigate the surface energy balance before recommending large-scale application, as for other climate change adaptation and mitigation strategies (Betts 2007).

Conceptually the net flux of radiation at Earth's surface is the sum of latent energy (LE), sensible energy (H) and soil heat flux (G) or can be expressed by the equation (Peixoto and Oort 1992):

$$F_{\mathrm{sfc}} = F_{\downarrow \mathrm{SW}}(1-\alpha) - \varepsilon\sigma T_{\mathrm{sfc}}^4 + F_{\downarrow \mathrm{LW}} \tag{1}$$

where F_{sfc} is the net radiation flux at the surface, $F_{\downarrow \mathrm{SW}}$ is the incoming shortwave radiation, α is the albedo of the surface, $\varepsilon\sigma T_{\mathrm{sfc}}^4$ is the infrared radiation emitted by the surface expressed with Stefan–Boltzmann law as a function of surface temperature (T), and $F_{\downarrow \mathrm{LW}}$ is the incoming long-wave radiation.

The expectation is that large-scale biochar application will decrease surface albedo of bare agricultural soils, producing a substantial modification of the surface energy balance; this effect is expected to diminish with increasing plant cover. The experiment described in this letter aimed at the characterization of seasonal changes in albedo on a durum wheat crop, (i) comparing different biochar application rates versus a control, thus exploring the interplay between changes in soil surface reflectance, crop growth and canopy development in the control of surface albedo in realistic field conditions and (ii) analyzing the influence of biochar application on surface energy fluxes over the whole annual cycle.

2. Materials and methods

The experiment was conducted during the 2009/10 growing season in an experimental field near Pistoia (Tuscany, lat. 43°56′N, long. 10°54′E, 65 m asl) on a winter durum wheat crop (*Triticum durum* cv. Neolatino). Hourly meteorological parameters (rainfall, air temperatures, solar radiation) were collected at an automatic weather station, installed close to the experimental field. Total rainfall from August 2009 to July 2010 was 1230 mm and the mean air temperature was 15 °C for the same period. The soil is a silty-loam (USDA, soil classification).

A randomized block experiment with four replicates was done in plots of 25 m^2 each with three treatments: control (C), biochar at a rate of 30 t ha^{-1} (B30) and biochar at a rate of 60 t ha^{-1} (B60). Biochar was applied manually, before crop sowing and incorporated in the top 10 cm with a rotary hoeing tillage. Wheat was sown on 14th December 2009 with a density of 450 seeds m^{-2}. A nitrogen–phosphate and phosphorous fertilizer was distributed at sowing (22 kg ha^{-1} of N and 50 kg ha^{-1} of P_2O_5) and a second fertilization was done in April, when ammonium nitrate was added at a rate of 100 kg N ha^{-1}. Wheat was harvested on 6th July 2010.

The biochar applied was a commercial horticultural charcoal provided by Lakeland Coppice Products, UK (carbon content of 84%), obtained from coppiced woodlands (beech, hazel, oak and birch) at a pyrolysis temperature of 500 °C; details on the biochar are reported in Vaccari *et al* (2011). It was crushed into particles of less than 1 cm before application to the soil in order to increase the area–volume ratio and enhance its expected effects on soil properties.

In parallel, the study made use of a previous experimental layout established in 2008/09 with the same treatments and doses (C_w; $B30_W$; $B60_w$) (Vaccari *et al* 2011) that was re-seeded in 2009/10 without biochar application. Reflectance measurements were thus also taken in plots in the second year after biochar application.

Three destructive biomass samples were taken during the wheat growing season at Zadoks scale (Zadoks *et al* 1974) of: 32 (stem elongation or jointing, second node detectable), 50 (heading, first spikelet of head visible) and 91 (ripening, kernel hard difficult to separate by fingernail). Total above ground biomass (AGB) was oven-dried and weighed.

The surface albedo (α) was measured with an ASD FieldSpec Pro spectroradiometer (ASD Inc, Boulder, CO, www.asdi.com/), having an overall range of 350–2500 nm and using three internal sensors with high signal-to-noise ratio (SNR) to measure radiation: UV/VNIR (350–1050 nm), SWIR1 (900–1850 nm) and SWIR2 (1700–2500 nm). The spectral resolution of the spectrometer is 3 nm at 700 nm and 10 nm at 1400/2100 nm. Integration time is set automatically for each of the three arrays to optimize incoming radiation levels in all three regions. Mainly due to the absorption of atmospheric water vapor within the measured spectral range, there are some intervals (1350–1460, 1790–1960 and 2250–2500 nm) where the SNR is very small. Those wavelengths ranges were excluded for albedo calculation. Assuming a Lambertian behavior of the surface, the reflectance measurement is directly convertible into the surface albedo value (Disney *et al* 2004).

Eight field measuring campaigns were conducted from December 2009 to July 2010 on all experimental plots to characterize different stages of the crop cycle: biochar application, wheat emergence to harvest, post-harvesting and tillage. The first measurement was taken after biochar application (5th December 2009) and the last after soil tillage operations that followed crop harvest (21st July 2010).

The frequency of measurements was higher in the period January–July to encompass the different stages of crop development. All measurements, replicated three times for each plot, were taken around noon on days with a clear sky. On the same date the albedo measurements were also taken in plots treated in 2008/2009 season. The measurements were taken at the Nadir at about 100 cm above the soil or top of the canopy; considering that the field of view (FOV) is 25°, each measurement covered a surface 0.15 m^2. After each soil measurement, data of sky reflectance in opposition to the sun (with a solar Zenith angle of 45°) were acquired to assess the clearness of the atmosphere, and eventually reject the soil measurement in case of a sky reflectance value higher than 0.25.

Analysis of variance was used to compare the treatment effects on surface albedo values, using the Repeated Measures ANOVA model (R version 2.12.1). The Student–Newman–Keuls test at significance level 0.05 was used as means multiple comparison test.

Soil temperature at a depth of 5 cm was measured hourly in C and B60 plots by mean of thermocouples (J-type) connected to a CR10 datalogger (Campbell Scientific, Inc.) during the first stages of the crop cycle (in March–April).

In order to evaluate the surface energy balance, the simultaneous heat and water (SHAW) model was applied to simulate heat and water transfer within a one-dimensional profile that includes 11 soil layers and incorporates the effects of plant cover (Flerchinger 2000). Measured soil texture, bulk density and organic carbon content (Vaccari *et al* 2011) were implemented in the model, while hydraulic characteristics were estimated by the SHAW pedotransfer function.

AGB and hourly meteorological data (rainfall, air temperature, solar radiation) were used to force the model along the year to simulate sensible (H), latent (LE) and ground (G) heat fluxes over the crop cycle and to represent the surface radiation balance. Moreover, the model was initialized with α values of control and treated plots at sowing. After the plow (July), due to the mixing effect of the soil matrix with residues and/or biochar, the model was re-calibrated with the albedo measured after the tillage.

3. Results

Average values of surface albedo measurements for control, B60 and B30 plots over the growing season are shown in figure 1(a) for plots treated in 2009/2010 and figure 1(b) for those treated in 2008/2009. Data on above ground biomass are shown in figure 1(c). The comparison of measured and modeled soil temperatures is shown in figure 2. SHAW model outputs of simulated diurnal cycle of soil temperatures, H and LE for the control treatment as well as the difference with B60 treatment are shown in figure 3.

The application of biochar on a winter durum wheat crop in central Italy caused a significant decrease of surface albedo before crop emergence and during the first crop growth stages in the first year (figure 1(a)). Shortly after the application, plots amended with biochar (B30 and B60) had a low reflectance at all wavelengths while surface albedo was about 1/3 that of the control (average α of B30 and B60 = 0.062 ± 0.001; control = 0.208 ± 0.004). The difference still persisted at the time of the second measurement (11th March), when plant cover was very limited and its contribution to the overall surface reflectance was negligible (AGB lower than 1 t ha^{-1}). Albedo effects decreased with crop growth and tended to converge in response to crop growth and increasing crop cover (figure 1(a)), although significant differences were still observed at the beginning of April when above ground biomass was about 1.5 t ha^{-1} (figure 1(c)). Differences in surface albedo between the control, B30 and B60 plots were, instead, not detectable later in the season until crop harvest (figure 1(a)). When the plants had been removed from the soil (post-harvest measurement), biochar effects on albedo were again detectable and a significant difference persisted after the soil tillage on 21st July .

In the second year after application biochar effects on surface albedo were less appreciable and no significant differences were observed at the April measurement, while biochar effect on albedo totally disappeared after the second tillage (figure 1(b)).

The observed enhancement of above ground biomass in the biochar-amended plots (Vaccari *et al* 2011) did not translate into a surface albedo difference in the final stages of the crop cycle. The lack of biomass sampling during the first stages of crop development did not enable it to be clarified whether or not the presence of biochar caused a faster growth during those stages nor to clarify the role of the observed increased soil temperatures on early crop development.

The SHAW model adequately simulated variations in soil temperature that were caused by changes in surface albedo (figures 2(a) and (b)). The normalized RMSE ($RMSE/O_{avg} \times 100$) between observed–simulated hourly data was 8.85% for the control and 8.55% for the treated plots (B30 and B60) and quite invariant with respect to the daily temperature cycle (figure 2(c)). These results provided confidence in the model's ability to appropriately simulate key aspects of the soil's evolution after biochar application, allowing us to further evaluate impacts on the surface energy balance. Simulations showed that soil surface (5 cm depth) temperatures of treated plots were higher than the control from January to March, with higher differences observed in the central part of the day in January–February (figure 3(b)) in coincidence with anomaly on sensible (figure 3(d)) and latent (figure 3(f)) heat fluxes; from April there was a drop in modeled soil temperatures in treated plots, compared to control plots, suggesting a preeminent role of higher above ground biomass in biochar-amended plots (Vaccari *et al* 2011) in enhancing evapotranspiration, causing soil cooling (figure 3(b)). At this stage of crop development, the influence of vegetation on soil temperatures prevails over the warming effect associated to a lower albedo. After the harvest, when the soil was bare, soil temperatures were, again, substantially higher in the treated plots.

The model also allowed the overall effects of the reflected light reduction caused by biochar application on surface energy balance to be quantified at different temporal scales. Sensible (H), latent (LE) and soil (G) heat fluxes were all

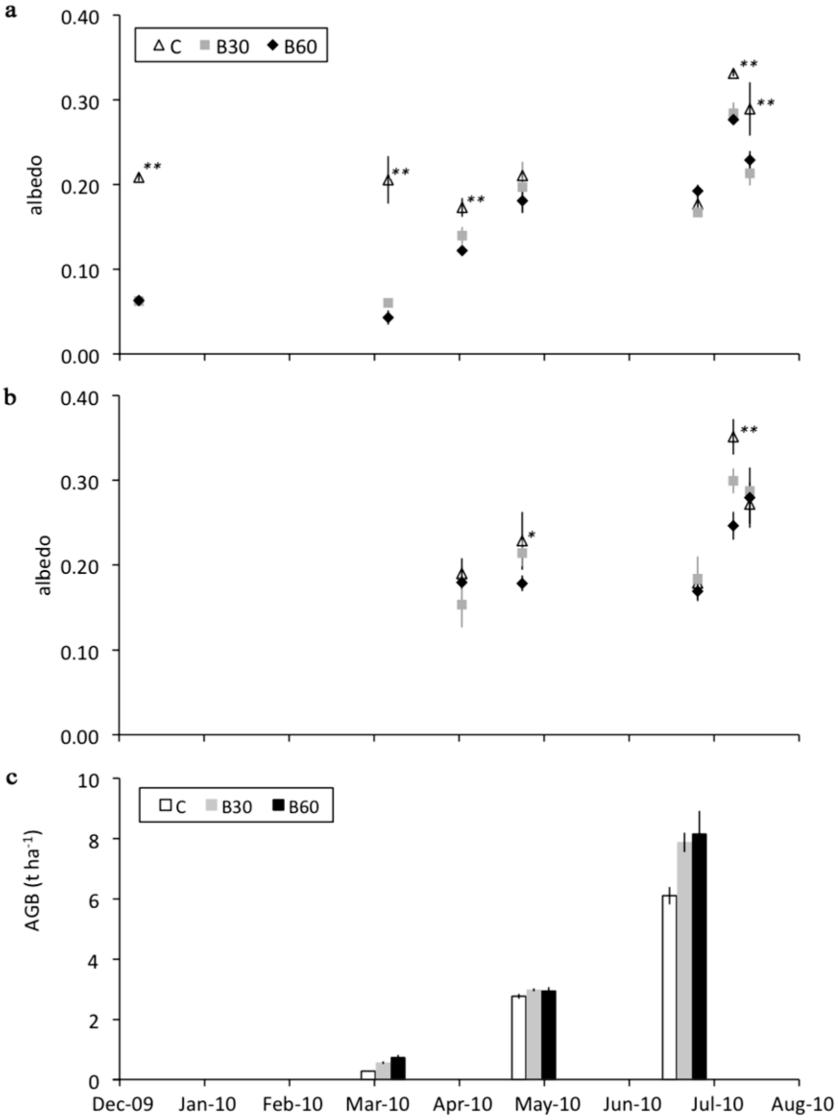

Figure 1. Surface albedo measurements: (a) α values of plots treated in 2009/2010; (b) α values of plots treated in 2008/2009 (re-seed experiment). Error bars represent the 95% confidence error. Measurements with $**$ indicate that surface albedo values of control (C) treatment are significantly different from both B30 and B60 ($P < 0.05$) and with $*$ only from B60. (c) Above ground biomass (t ha^{-1}) in B60, B30 and control plots in 2010.

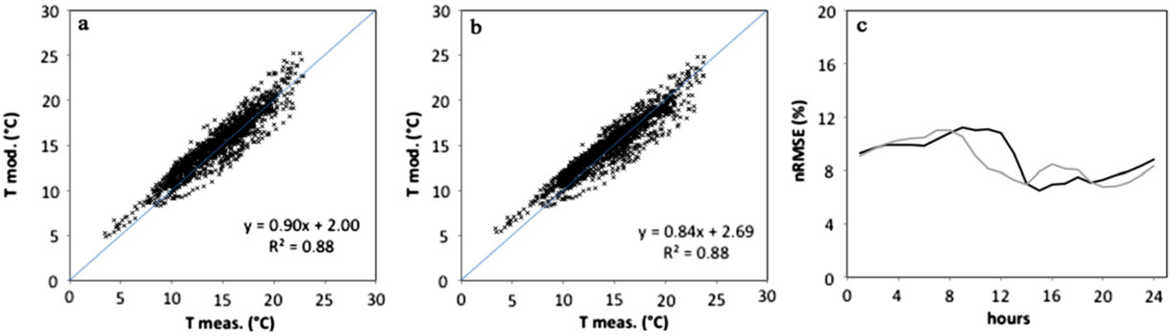

Figure 2. Measured and modeled soil temperature data in the period 15 March–15 May for control (a) and B60 (b) plots, and (c) values of RMSE (%) over the diurnal cycle for B60 (black line) and control (gray line) plots.

higher at both seasonal and annual scales (figures 3(d) and (f) and table 1) but with differences in energy partitioning and anomalies in the diurnal cycle. In particular a substantial variation in *LE* diurnal cycle was observed in the post-harvest period with treated plots tending to reach the evaporation peak earlier than control plots (figures 3(f)). Net ground heat

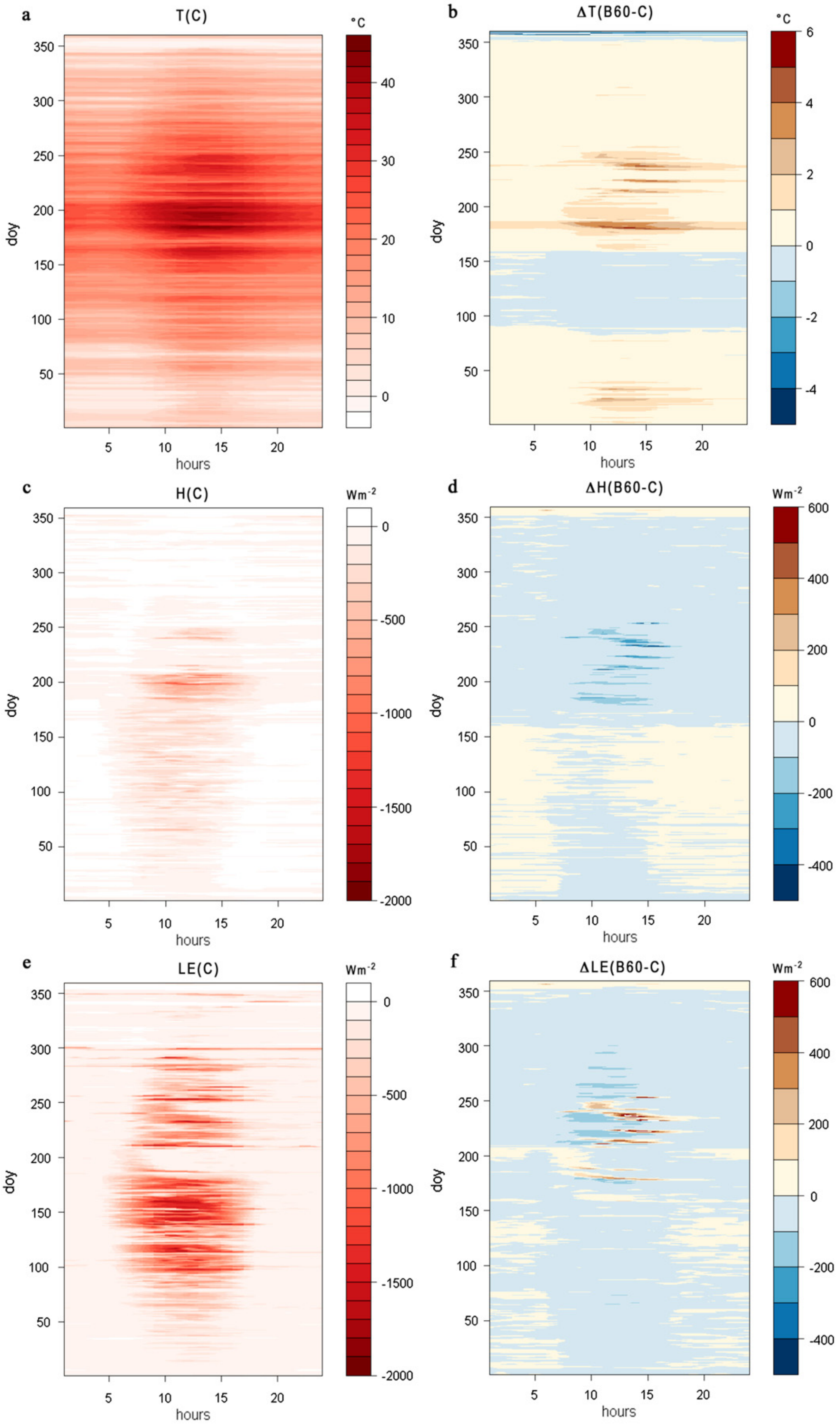

Figure 3. Simulated diurnal cycle of soil surface temperature (*T*) in °C, sensible (*H*) and latent heat (*LE*) fluxes in W m^{-2} for control plots (*C*) ((a), (c), (e)) and differences between B60 and control plots (B60-C) ((b), (d), (f)) during year 2010.

Table 1. Summary of surface energy balance components (in W m^{-2}) for control and B60 treatments calculated with SHAW model in the periods: January–March (JFM), April–June (AMJ), from seeding to harvest (crop) and on the full season (year). By convention, negative values represent outgoing fluxes while positive values incoming fluxes.

		JFM	AMJ	Crop	Year
Net solar radiation (10^5 W m^{-2})	C	1.31	3.68	5.27	8.70
	B60	1.44	3.74	5.49	9.31
	Δ (%)	9.6	1.4	4.1	6.9
Long-wave radiation (10^5 W m^{-2})	C	−0.78	−0.99	−1.89	−3.71
	B60	−0.81	−1.01	−1.96	−3.89
	Δ (%)	4.6	1.1	3.4	4.7
Sensible heat flux (H) (10^4 W m^{-2})	C	−0.87	−2.66	−4.06	−5.33
	B60	−1.03	−2.67	−4.41	−7.19
	Δ (%)	17.1	0.6	8.7	34.9
Latent heat flux (LE) (10^5 W m^{-2})	C	−0.42	−2.22	−2.71	−4.23
	B60	−0.49	−2.25	−2.81	−4.42
	Δ (%)	16	1.5	3.8	4.4
Net ground heat flux (G) (10^4 W m^{-2})	C	−0.25	−2.04	−2.58	−2.26
	B60	−0.33	−2.10	−2.73	−2.82
	Δ (%)	28.3	3.1	5.9	24.6

flux of treated plots was 28% higher than the control from germination to tillering (January–March) and 25% yearly, while a lower increase (6%) was observed during the whole crop cycle due to a dominant role of the vegetation shading from stem elongation to harvest (April–June) (table 1).

4. Discussion and conclusions

The use of biochar as a strategy to mitigate anthropogenic CO_2 emission involves large amounts of a dark material, with extremely low reflectivity being added to the soil. According to Woolf *et al* (2010), realistic global scenarios of C-sequestration, which promise to remove 0.49 G t C yr^{-1} from the atmosphere and sustainably store it in agricultural soils, require the conversion of 5.1 G t of feedstock into biochar every year. It is implicit that C-sequestration may either be achieved by distributing such large amounts of biochar over a large surface area using low application rates per unit of land or by concentrating large quantities of biochar on limited surfaces, thus intensifying unit applications. The study by Vaccari *et al* (2011) showed that even very high rates of biochar application (30–60 t ha^{-1}) had no negative effects on growth but rather stimulated wheat grain production by more than 25%. When combined with other observations made for the same species (Baronti *et al* 2010) the data confirmed that yield stimulation is proportional, in wheat, to the rate of biochar application.

Reflectance measurements taken in this experiment confirmed that biochar application greatly affects soil albedo. In the specific case of a conventionally managed winter durum wheat cultivation, albedo may be decreased by up to 40% over the entire crop season, from sowing to harvest, but most of this reduction obviously occurs during the winter months (January–March) before the development of the crop canopy strongly limits the amount of radiation reaching the soil surface (figure 1(a)). During this period the radiation is low and often attenuated by cloudiness in temperate regions, but nevertheless a change in surface reflectance translates into a substantial increase in soil temperature. This may have positive consequences on seed germination as well as on crop establishment and early crop growth, especially where minimum or no-tillage of soils is adopted; this agronomic practice is known to increase surface albedo leading to substantial soil cooling, compared to the more conventional plowing (Licht and Al-Kaisi 2005).

Our study clearly showed that there was no detectable difference in surface albedo in response to the doubling of biochar application rate from 30 to 60 t ha^{-1}. This suggests the existence of saturation, leveling-off above a certain biochar application threshold. This is somewhat unsurprising on the basis of simple and obvious space/volume considerations, but has important practical consequences as it suggests that the use of large unit rates of biochar over relatively small portion of land is relatively less impacting, in radiative terms, than the use of small unit rates on a large surface area. Above a certain threshold, the soil warming potential of increasing doses of biochar does not increase further, while carbon sequestration and yield stimulation both continue to rise.

When seen within a wider crop management perspective, an overall assessment of the biochar effect on albedo and soil warming requires several components to be considered. A wheat field giving a mean yield of 5 t ha^{-1} yr^{-1} of grain produces approximately 6 t ha^{-1} yr^{-1} of straw, if 50% of these residues could realistically be transformed into char via pyrolysis, the net biochar yield of an average wheat crop would be around 250 kg ha^{-1} yr^{-1}. Accordingly, biochar application rates of 30–60 t ha^{-1} would require the entire biochar yield of 120–240 ha to be applied on a single hectare. In this sense, the 40% reduction of albedo that was observed at field scale in this experiment, would translate, in a realistic operational context at farm scale, into a negligible variation of albedo. Nevertheless, considering that even a small alteration of the H and LE partitioning might lead to significant changes in global mean climate (Ban-Weiss *et al* 2011), the consequences of biochar application on complex land–atmosphere feedbacks need to be further addressed.

Moreover, when considered at the scale of individual fields or plots, changes in albedo caused by biochar, can easily be compensated by changes in crop management that may increase surface reflectance. The cultivation of plants and varieties having leaves with higher reflectance is, for instance, a credible option with large global surface cooling potentials that have been estimated to range from 0.11 to 0.21 °C (Ridgwell *et al* 2009). The existence of glaucous wheat cultivars with much higher albedo has been known for a long time (Barber and Netting 1968) and their introduction can be considered realistic (Yoshiya *et al* 2011). The combined use of glaucous varieties and biochar could be advantageous: darker soils in the winter before complete crop cover are likely to be warmer and consequently promote seed germination, crop establishment and early growth, while the higher crop albedo in the spring may largely compensate for wintertime soil warming.

Analysis of the energy balance model output allowed it to be argued that, before full crop cover, biochar application also stimulates evaporation rates. The increase in latent heat is driven by higher soil temperature and occurs during the winter months when the evaporative demand of the atmosphere is low (table 1 and figure 3). As a consequence, the direct impact of biochar on surface properties is likely to slightly increase water losses but, as shown elsewhere, also have an overall positive effect on plant water availability due to increased water retention (Laird *et al* 2010).

A final issue to be considered is that increases in soil temperatures associated to larger soil heat flux may have a direct effect on soil organic matter decomposition and respiration (Fang and Moncrieff 2001), particularly affecting the recalcitrant soil organic pools that are more sensitive to temperature (Craine *et al* 2010). There is substantial evidence that the CO_2 efflux is higher when the soil is warmer, but such an effect may be transient in nature as substrate availability, i.e. the labile fraction of the soil organic matter, rather than microbial activity actually constrains soil respiration over longer (seasonal) time scales. Nevertheless, soil warming effects that are associated to changes in surface albedo, must be included in the ongoing debate on the potential ‘priming’ effects of biochar application (Zimmerman *et al* 2011, Luo *et al* 2011) in which a unifying mechanism driving soil respiration has still to be found. Major *et al* (2010), for instance, produced a review on the mechanisms involved in biochar priming effect, but did not explicitly consider that biochar applications also have a soil warming potential.

Our conclusion, supported by field-scale observations, is that the impact of biochar application on land surface properties is not negligible and substantially modifies surface energy balance, thus suggesting direct impacts on crop cycle and on soil carbon mineralization. Biochar application strategies that can be implemented to mitigate greenhouse gas emissions should consider the entire sequence of negative and positive effects: biochar addition can certainly warm the soil by reducing albedo but it is also likely to sequester substantial amounts of atmospheric carbon in a recalcitrant organic form in the soil and have a positive effect on plant growth and crop yields. The net effect may vary with latitude and land use and may be more critical where the impact on surface albedo and on soil heat fluxes is supposed to be more significant, like in areas with lower vegetation cover. More research is therefore needed to further explore the potentials of the technology, as well as the risks associated to its use. In the short term, we envisage two areas of urgent investigation: (i) the creation of a robust dose–response function of biochar effects on surface albedo for different soil types and different crop/soil management regimes and (ii) the analysis of the effect of amplified soil warming on local-to-regional atmospheric circulation, forcing Regional Climate Models (RCMs) with modifications in surface albedo.

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