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Reductions in soil surface albedo as a function of biochar application rate: implications for global radiative forcing

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Abstract
Biochar can be defined as pyrolysed (charred) biomass produced for application to soils with the aim of mitigating global climate change while improving soil functions. Sustainable biochar application to soils has been estimated to reduce global greenhouse gas emissions by 71–130 Pg CO_2-C_e over 100 years, indicating an important potential to mitigate climate change. However, these estimates ignored changes in soil surface reflection by the application of dark-coloured biochar. Through a laboratory experiment we show a strong tendency for soil surface albedo to decrease as a power decay function with increasing biochar application rate, depending on soil moisture content, biochar application method and land use. Surface application of biochar resulted in strong reductions in soil surface albedo even at relatively low application rates. As a first assessment of the implications for climate change mitigation of these biochar–albedo relationships, we applied a first order global energy balance model to compare negative radiative forcings (from avoided CO_2 emissions) with positive radiative forcings (from reduced soil surface albedos). For a global-scale biochar application equivalent to 120 t ha^{-1}, we obtained reductions in negative radiative forcings of 5 and 11% for croplands and 11 and 23% for grasslands, when incorporating biochar into the topsoil or applying it to the soil surface, respectively. For a lower global biochar application rate (equivalent to 10 t ha^{-1}), these reductions amounted to 13 and 44% for croplands and 28 and 94% for grasslands. Thus, our findings revealed the importance of including changes in soil surface albedo in studies assessing the net climate change mitigation potential of biochar, and we discuss the urgent need for field studies and more detailed spatiotemporal modelling.

Keywords: geo-engineering, radiative forcing, spectroscopy, soil, biochar
S Online supplementary data available from stacks.iop.org/ERL/8/044008/mmedia

1. Introduction

Application of biochar to soils is increasingly considered as a geoengineering technique because of its potential to aid in global climate change abatement, by sequestering carbon [1–4]. However, a quantification of the effects of biochar application rate on soil albedo with a potential impact on the global radiation balance has so far not been addressed in the primary literature. In addition to abating global climate change, biochar may improve organic waste management [5], agronomic performance [1, 6, 7] and energy production [4, 8]. Reported biochar application rates equivalent to 120 t ha^{-1} (converted from 50 t ha^{-1} biochar-C at a 41.9% biochar-C content; supplementary table 3, available at stacks.iop.org/ERL/8/044008/mmedia) to global agricultural soils [1], have the potential for long-lived changes to fundamental soil properties, processes and functions [2, 8, 9]. The reflectance properties of charcoal (or black carbon) have received considerable research attention, e.g. developing remote sensing methods [10], quantifying climate forcing due to black carbon dust deposited on snow [11], and burnt area mapping [12]. Even so, only three studies seem to have directly measure soil albedo changes due to charcoal/biochar. These measured albedo decreases ranged from 4–8% [13] at unknown application rate, up to 80% at 30–60 t ha^{-1} biochar following shallow incorporation in Italy [14], and by 12% at varying biochar incorporation rates in a field in Germany [15]. Despite being valuable studies, they do not provide insight into the relationships between albedo and biochar application rates for different soils and biochar application strategies, i.e. incorporation or surface application. One recent study reported a 13–22% reduction in climate mitigation [15], but only at one specific biochar application rate and application strategy. Surface-atmosphere energy exchange and planetary radiative forcing (RF) are known to be sensitive to surface albedo. For example, Betts *et al* [16] found that changes in surface albedo during the industrial period (1750–present) produced a planetary RF of −0.18 W m^{-2}, which is similar in magnitude as planetary RFs due to the direct effect of individual greenhouse gases (such as sulfate, halocarbons, and N_2O) [17].

In this letter, we first quantified, in a laboratory study, the effects of different biochar application rates, application strategies, and soil moisture on soil surface albedo and subsequently modelled their implications for planetary RF for four contrasting scenarios. Specifically, we conducted a broadband shortwave albedo experiment for a range of five representative soils with albedo characteristics typical for crop- and grasslands across the globe (section 2). Biochar was applied at the surface as well as mixed into the soil samples at rates ranging from 1 to 200 t ha^{-1} (under both wet and air-dry soil moisture conditions) for both topsoil mixing and surface application strategies (see supplementary table 1, available at stacks.iop.org/ERL/8/044008/mmedia). The closed-chamber orthogonal spectroscopic measurement of the soil samples provided consistent estimates of shortwave broadband albedo under the assumption of Lambertian reflectance. To demonstrate the planetary RF implications of the obtained biochar–albedo relationships, we applied a first order global energy balance model [3] to four scenarios comprising a single, global-scale biochar application of 10 or 120 t ha^{-1} (converted from biochar-C ha^{-1}, according to section 2.2) applied onto the soil surface versus mixed into the topsoil.

2. Data and methods

2.1. Soils

Five soil types [29] were primarily selected to be representative of the range of colours (brightness) encountered in the majority of global cropland and grassland soils (supplementary table 1). The selection of the samples was based on the distribution of Munsell soil colour from the WISE database [28] to cover the whole range of Munsell values (MVs), a measure of brightness, of the soil profiles in cropland and grassland. A haplic chernozem (MV of 2.9) represents the first class of topsoil MVs (2.55–3.35; 21% of topsoil MVs in WISE database); a haplic Luvisol (MV 3.5) represents the second class of topsoil MVs (3.36–3.67; 51% of topsoil MVs in WISE database); an arenic Cambisol (MV 3.7) represents the third class of topsoil MVs (3.68–3.86; 16% of topsoil MVs in WISE database); a Luvisol subsoil horizon (MV 4.2) represents the fourth class (MVs 3.89–4.37; 10% of topsoil and 41% subsoil MVs in WISE database, typical in marginal drylands), and a truncated soil on marl consisting of a C horizon (MV 4.9) represents a subsoil class (MVs 4.39–5.89), corresponding to 43% subsoil MVs in WISE database (supplementary table 1). Secondly, to test for the influence of soil properties on treatment effects, the five soils were selected to have varying parent materials, textures and organic carbon contents (supplementary table 1). Soil samples were air-dried and sieved (<2 mm).

2.2. Biochar application

Biochar from pine feedstock pyrolysed at 500 °C and sieved (<2 mm) was used in this study (supplementary table 3). Prior to spectral analysis, biochar was applied randomly to the soil (40 g) surface, at rates of 1, 10, 50, 100, and 200 t ha^{-1} of biochar, corresponding to 0.9, 8.8, 43.8, 87.6, and 175.2 t ha^{-1} of biochar-C, at a gravimetric biochar-C content of 41.9% (see supplementary table 3). These were selected based on the reported range of biochar application rates (with varying C-contents) [7], i.e. from 1.5 to 135 t ha^{-1} and assuming a bulk density of 1.3 g cm^{-3} and incorporation to the upper 15 cm of soil. Incorporation of biochar into the topsoil was simulated by thorough mixing. In the case of mixing into wetted soil (using 20 g of water), mixing was followed by an overnight period to achieve moisture conditions near field capacity (∼50% gravimetric water content). A flow chart explaining the experimental dataset is shown in supplementary figure 1 (available at stacks.iop.org/ERL/8/044008/mmedia).

2.3. Spectroscopic analysis

A closed-chamber spectroscope with an internal light source (High Intensity Reflectance Probe A12 ML902 DC9.6v, Analytical Spectral Devices Inc., Boulder, Colorado) was used to measure a total of 675 soil reflectance spectra (350–2500 nm; 10 nm resolution) at ambient conditions (supplementary figure 1). Each sample was measured thrice, while rotating the sample dish (∼120°) between measurements. Three replicate samples were used for each combination of soil type, biochar application rate, application method, and soil moisture content. Before each set of three sample measurements, a white reference measurement was taken using a Spectralon panel. The soil surface reflectance spectra were directly converted into the surface albedo values (supplementary table 2, available at stacks.iop.org/ERL/8/044008/mmedia) using supplementary equation (1) (available at stacks.iop.org/ERL/8/044008/mmedia), assuming Lambertian reflectance. In total, only one extreme outlying albedo value (Luvisol Ap) was excluded from the analysis. For the five soils, broadband (300–2500 nm) albedo values ranged from 0.235 to 0.532 (air-dry samples) and from 0.087 to 0.268 (wet samples).

2.4. Global annual average bare soil albedo (GAABSA)

To estimate effects of biochar application to soils on global radiative forcing (RF), it was essential to derive accurate estimates of global bare soil albedos of global croplands and grasslands, prior to biochar application. Global annual average bare soil albedo (GAABSA) was estimated separately for cropland and grassland, using two distinct global databases, i.e. Wilson and Henderson-Sellers (1985) [20] and Houldcroft *et al* (2009) [21].

Using the Houldcroft *et al* (2009) database [21], bare soil albedo values derived from MODIS were used as the input data for the land use specific GAABSA estimation. In this database, the soil background albedo is derived from a method which assumes a linear relationship between albedo and the normalized difference vegetation index (NDVI). The soil albedo values are calculated from a linear albedo-NDVI model as the albedo corresponding to the NDVI value of grid cells exclusively comprising of zero vegetation cover (zero green leaf area index), i.e. bare soil. Since the MODIS white-sky albedo product accounts for the solar angle and the anisotropy of the surface reflectance field, white-sky radiation at visible and NIR wavelengths was used to make the results comparable with the laboratory measurements. The spectral wavelengths covered by the instrument used in the laboratory experiment (350–2500 nm) did not exactly match those covered by the MODIS sensor (300–5000 nm), but this discrepancy was not expected to compromise the compatibility of the two albedos for the purpose of this study. The MODIS product is distributed at a resolution of 0.05° × 0.05°. The global spatial extents of cropland and grasslands were obtained from Ramankutty *et al* (2010) [30]. The data represents the proportion of a pixel that is either cropland or pasture. Weighted averages were calculated by the share of

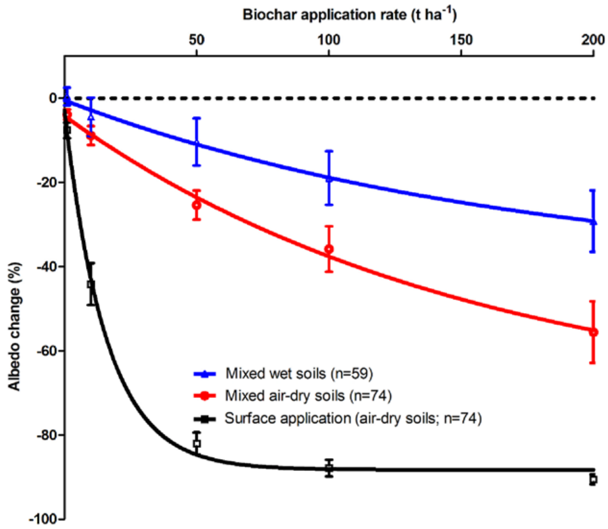

Figure 1. Overall decreases in soil surface albedo with increasing biochar application rates for two application methods. The albedo–biochar relationships differed significantly ($P < 0.01$) between the two application methods (surface application versus mixed into topsoil) and, with mixing into the soil, between dry and wet initial soil moisture conditions. Error bars depict 95% confidence intervals for all five soil types ($n = 74$), except in the 'mixed wet soils' case ($n = 59$) where the samples of the haplic Chernozem were excluded (see figure 2(b)).

given land use at the pixels. The coverage of the values used for calculation was limited to pixels with values available for both rasters. The resulting GAABSA values for cropland and grassland are: 0.117 and 0.186 [21] and 0.140 and 0.165 [20], respectively. Averaged values of 0.129 (cropland) and 0.176 (grassland) were used for the RF estimates and the lower and upper values for the uncertainty estimate (figure 3).

For the RF estimates, we estimated the global average annual bare soil albedo pre-biochar application (GAABSA) from two global datasets [20, 21] and averaged the two values. The GAABSA for cropland was 0.129 and for grassland 0.176. To simplify the RF estimations, we further assumed that: (i) surface application of biochar on wet soils causes half of the reduction in albedo on air-dry soils; (ii) soils were snow-free throughout the year, (iii) soil albedo and the fractions of bare soil did not exhibit spatiotemporal variation, (iv) other factors such as vegetation cover and soil moisture contents remained constant.

2.5. Radiative forcing estimates

We applied a first order global energy balance model, designed specifically to compare geoengineering options [3], to estimate the implications of biochar-induced changes in surface albedo for biochar's climate change mitigation potential. As input to the model, we used the GAABSA values (section 2.4) as estimates of pre-biochar soil albedo and our experimental results on relative albedo change after biochar application (figure 1) as estimates of the degree of soil darkening (reduction in soil albedo). We calculated planetary RF values with equations (1) and (2), obtaining parameter values from Lenton and Vaughan [3], and using estimates of global bare soil fractions (f_{Earth}) i.e. 0.14 (range: 0.10–0.20) for croplands and 0.20 (range: 0.10–0.29) for grasslands [19, 20], with bare soil assumed to be the inverse of the fractional vegetation cover. We then used equation (3) to convert the 'maximum sustainable technical potential' of biochar's climate mitigation potential [1], i.e. 130 Pg CO_2–C_e, to a negative planetary RFs of -0.65 W m^{-2}.

$$\mathrm{RF} = -S_0 \Delta\alpha_p \quad (1)$$

$$\Delta\alpha_p = f_a f_{Earth} \Delta\alpha \quad (2)$$

$$\mathrm{RF}(t) \approx \frac{\Delta C_{atm}}{k} \frac{\beta}{CO_2(t)}. \quad (3)$$

The following parameter values were obtained from Lenton and Vaughan [3]: $S_0 = 330$ W m^{-2} (solar radiation at the top of the atmosphere over the terrestrial land surface); $\Delta\alpha_p$ is the change in planetary albedo; $f_a \approx 0.48$ (two-way transmittance of the atmosphere); f_{Earth} (fraction of the Earth over which the change in albedo applies); ΔC_{atm} = (in PgC) the amount of CO_2 removed from the atmosphere at time t; $k = 2.14$ PgC ppm^{-1} (conversion factor); $\beta = 5.35$ W m^{-2} (radiative forcing in pre-industrial period); $CO_2(t) = 500$ ppm (reference value of atmospheric CO_2, in the absence of geoengineering by time t).

3. Results and discussion

3.1. Albedo measurements

The combined results for the different soils revealed robust power decay functions ($P < 0.01$) of decreasing soil albedo with increasing biochar application rates (figure 1). From the two application methods, application of biochar to the soil surface resulted in the largest albedo reduction ($R^2 = 0.97$; RMSE = 5.83). Mixing the biochar with the soil sample resulted in a stronger drop in albedo when the samples were air-dry than wet ($R^2 = 0.83$; RMSE = 8.58 versus $R^2 = 0.56$; RMSE = 9.55). The comparatively poor fit in the latter case was to a large extent caused by one of the soil types, i.e. a 'haplic Chernozem', having a dark colour and showing little change in albedo with biochar application (figure 2(b)). This soil type covers only 1.6% of global agricultural land and its very low albedo when wet (0.087) may indicate a threshold (see below). Without this soil, the R^2 increased to 0.91 and the RMSE dropped to 4.01. The observed difference between mixing biochar with air-dry and wet soils was in line with the wetting effect reported for 26 USA soils, with a wide range of colours and textures, i.e. a reduction in albedo between 32 and 58% [18].

Individually, the five soil types revealed power decay functions that, in general, were very similar for the different application methods (figure 2; supplementary table 2, available at stacks.iop.org/ERL/8/044008/mmedia). In the case of mixing biochar into wet soil, however, both the arenic Cambisol (Ca) and the haplic Chernozem (Ch) showed deviant patterns. The relative decrease in albedo was approximately twice as large for Ca compared to L1, L2, and Ma. Possibly this effect was due to the very sandy texture of Ca (75% sand), so that the amount of water used to wet the sample may have resulted in oversaturation and, hence, the formation of a thin film of water at its surface that enhanced light absorption. In contrast, the decrease in albedo was hardly discernible for Ch, most likely caused by its low albedo under wet conditions (0.087 versus 0.125–0.268 for the other four soils), and ultimately its relatively high SOC content (supplementary table 1, available at stacks.iop.org/ERL/8/044008/mmedia). This implies the existence of an albedo transition between 0.087 and 0.125, below which the soil albedo is not altered by mixing in biochar.

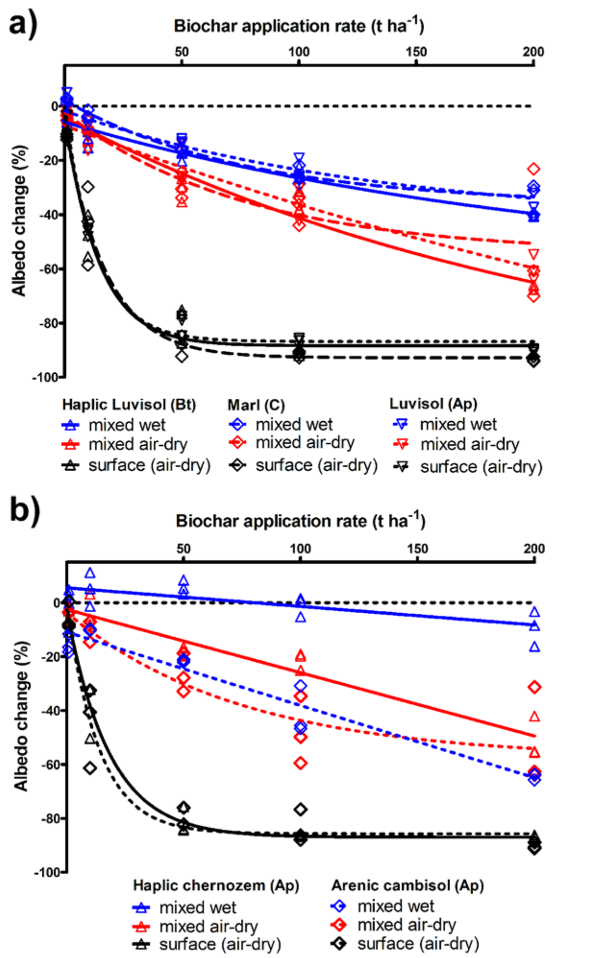

Figure 2. Soil type-specific decreases in soil surface albedo with increasing biochar application rates for surface application and topsoil mixing. Graph (a) shows three of the five soils with similar responses; graph (b) shows the remaining two soils with similar responses for surface application, but different responses when the biochar is mixed into the soil, particularly when wet. The significant ($P < 0.01$) albedo–biochar relationships differed little between the 5 soil types, except when biochar was mixed into wet soil (a). See also supplementary table 1 (available at stacks.iop.org/ERL/8/044008/mmedia).

3.2. Global radiative forcing estimates

As a proof of concept of the implications of the observed soil albedo–biochar relations for the potential of biochar

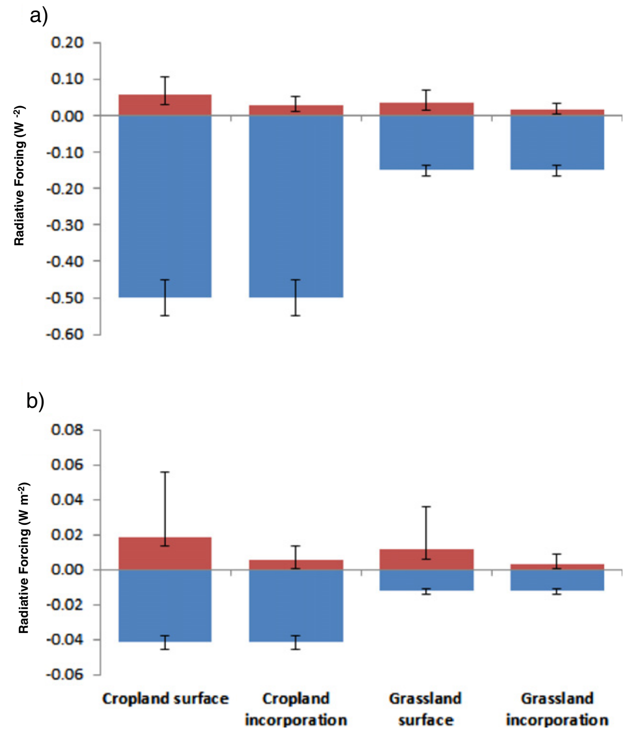

Figure 3. Estimated effects of global biochar application on planetary radiative forcings (RFs). Negative RFs (due to avoided CO_2 emissions) and positive RFs (due to changes in surface albedo) planetary were estimated for two rates and methods of biochar application to croplands and grasslands across the globe. Graph (a) shows the results for the 'maximum sustainable technical potential' of 120 t ha^{-1} global biochar application, according to Woolf *et al* [1]; graph (b) shows results for a less ambitious scenario of 10 t ha^{-1} global biochar application (note the different scale on the *y*-axis).The error bars in negative RF assume a 10% uncertainty in avoided GHG emissions[1], whilst those in positive RF are based on uncertainty estimates in the albedo measurements (figure 1), the present day soil albedo (section 2.4), and bare soil fractions [19, 21].

to mitigate climate change, we estimated planetary RFs resulting from changes in soil albedo. We used the relative albedo decrease relationships for all five soils pooled (figure 1), because insufficient data are available on the aerial representation within each land use of the five individual soils. Global annual average bare soil albedo (GAABSA; section 2.4) values for cropland (0.129) and grassland (0.176) are relatively low compared to the five soils used in this study (see supplementary table 1). However, the relative albedo decrease with biochar application rate for the pooled soils is significant (figure 1) and was used for RF estimates, which were then compared against associated planetary RF estimates from avoided CO_2 emissions (1). To this purpose, we applied a first order global energy balance model [3], with simplification to meet model input requirements (section 2.5).

The uncertainty in positive planetary RF values was estimated based on the 95% confidence intervals of the measured albedo values (figure 1), ranges in present day soil surface albedo values from the literature [20, 21] (section 2.4) and the above-mentioned ranges in bare soil fractions (f_{Earth}) [19, 20]. The uncertainty of the negative planetary RF values, caused by avoided GHG emissions, was fixed at 10%, in accordance with Woolf *et al* [1].

In a scenario of a single biochar application of 120 t ha^{-1} to global croplands and grasslands, i.e. the 'maximum sustainable technical potential' [1], the changes in soil albedo resulted in a positive planetary RF of 0.017–0.027 W m^{-2} for biochar incorporation as opposed to 0.035–0.055 W m^{-2} for surface application (figure 3). Thus, depending on how the 120 t ha^{-1} biochar were applied, biochar's potential to mitigate climate change was reduced by 5 and 11% for croplands and 11 and 23% for grasslands, following biochar incorporation into the topsoil or soil surface application, respectively (figure 3(a)). In a less ambitious scenario of a single biochar application rate of 10 t ha^{-1} to global croplands and grasslands, changes in soil surface albedo reduce biochar's climate change mitigation potential to a markedly greater extent of 13–28% (incorporated) and 44–94% (surface applied—figure 3(b)). Our findings suggest that two strategies need to be considered to minimize positive RFs due to soil surface albedo changes: (i) biochar incorporation instead of surface application; (ii) increasing soil cover throughout the year. A third consideration is the existing bare soil albedo, i.e. if it is already low (e.g. around the indicated threshold of 0.087 and 0.125) then incorporation into topsoil is unlikely to result in significantly less albedo reduction compared to surface application. Similarly, if vegetation covers the soil (nearly) completely all year round, e.g. grasslands in regions without seasonal water limitation, then the biochar application rate and method are unlikely to significantly affect the land surface albedo and RF. Of course, other effects, such as wind erosion, may impose additional restrictions on the suitability for biochar surface application, and future changes in land use would need to be considered carefully as well. Depth application of biochar, i.e. in a soil layer that does not include the surface, would prevent any soil surface albedo reductions. However, this is a more expensive application method and future mechanical soil operations may expose the biochar to the surface.

3.3. Future directions

The results clearly justify follow-up studies. Priorities for future work include validation of the observed albedo changes under field conditions as well as downscaling, because planetary RF values are subject to the 'highly regionalized nature of the anthropogenic surface albedo forcing' [16]. In particular, intra-annual dynamics need to be considered across spatial scales (e.g. using GCMs), taking into account spatiotemporal patterns in key environmental and vegetation properties, such as solar declination angles, evapotranspiration, cloud cover, and vegetation type and cover. In conditions of thin or patchy snow cover, darker soils may affect snow melt. In situations where biochar increases soil moisture content, an additional decrease in soil surface albedo may be expected that was not considered in the RF estimates in this study, although potential confounding increases in vegetation cover may counter this effect. These laboratory experiments were performed with the fraction smaller than 2 mm of one biochar type on a range of soils at two moisture conditions. In addition, field scale research should focus on finding optimal application depths of biochar and soil mixing strategies that minimize reductions in albedo and maximize potential agronomic benefits. Follow-up research, both in the laboratory and in the field, using other biochars from varying feedstocks and with varying C-contents and particle sizes in soils at varying moisture contents may provide useful further insights into the broad relationships found in this study. Long-term, i.e. multiple years, field monitoring can be expected to provide the most relevant data for any specific location.

In conclusion, we found previously unreported power decay functions of decreasing soil surface albedo with increasing biochar application rates, for a variety of soil types typical for croplands and grasslands at different moisture contents. Furthermore, we provided the first evidence that these biochar–albedo relations may have important implications for biochar's climate change mitigation potential. Our results showed that soil surface albedo changes resulting from biochar application need explicit consideration in order to understand associated impacts (positive or negative) on soil properties, processes and services at local scales [2, 14, 22, 23], as well as regional scale climate feedbacks [16, 24], and global RF.

Our broad approach allows a global comparison of albedo-induced RF effects relative to reported biochar climate change mitigation effects [1], but it is intended as a proof of concept. Further work integrating these albedo effects seems urgently needed, particularly when considering: (i) the proposed widespread application of biochar [1]; (ii) the sensitivity of global and regional climates to changes in surface albedo [24]; (iii) the potential implications for soil temperature regimes [14, 22, 23] and, thus, a panoply of soil processes [25, 26]; (iv) the demand by policy makers for comprehensive scientific assessments of geoengineering options for climate change mitigation [2, 27].

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References

[1] Woolf D, Amonette J E, Street-Perrott F A, Lehmann J and Joseph S 2010 Sustainable biochar to mitigate global climate change *Nature Commun.* **1** 1–9

[2] Verheijen F G A, Jeffery S, Bastos A C, van der Velde M and Diafas I 2010 Biochar application to soils—a critical scientific review of effects on soil properties, processes and functions *European Commission JRC Technical Report* EUR 24099 EN (Luxemburg: Office for the Official Publications of the European Communities) p 166

[3] Lenton T M and Vaughan N E 2009 The radiative forcing potential of different climate geoengineering options *Atmos. Chem. Phys.* **9** 5539–61

[4] Roberts K G, Gloy B A, Joseph S, Scott N R and Lehmann J 2010 Life cycle assessment of biochar systems: estimating the energetic, economic, and climate change potential *Environ. Sci. Technol.* **44** 827–33

[5] Navia R and Crowley D E 2010 Closing the loop on organic waste management: biochar for agricultural land application and climate change mitigation *Waste Manage. Res.* **28** 479–80

[6] Atkinson C J, Fitzgerald J D and Hipps N A 2010 Potential mechanisms for achieving agricultural benefits from biochar application to temperate soils: a review *Plant Soil* **337** 1–18

[7] Jeffery S, Verheijen F G A, van der Velde M and Bastos A C 2011 A quantitative review of the effects of biochar application to soils on crop productivity using meta-analysis *Agric. Ecosyst. Environ.* **144** 175–87

[8] Meyer S, Glaser B and Quicker P 2011 Technical, economical, and climate-related aspects of biochar production technologies: a literature review *Environ. Sci. Technol.* **45** 9473–83

[9] Lehmann J 2007 Bio-energy in the black *Front. Ecol. Environ.* **5** 381–7

[10] Clark R N 1983 Spectral properties of mixtures of montmorillonite and dark carbon grains: implications for remote sensing minerals containing chemically and physically adsorbed water *J. Geophys. Res.* **88** 10635–44

[11] Hansen J *et al* 2005 Efficacy of climate forcings *J. Geophys. Res.* **110** D18104

[12] Smith A M S, Eitel J U H and Hudak A T 2010 Spectral analysis of charcoal on soils: implications for wildland fire severity mapping methods *Int. J. Wildland Fire* **19** 976–83

[13] Oguntunde P G, Abiodun B J, Ajayi A E and Van De Giesen N 2008 Effects of charcoal production on soil physical properties in Ghana *J. Plant Nutr. Soil Sci.* **171** 591–6

[14] Genesio L, Miglietta F, Lugato E, Baronti S, Pieri M and Vaccari F P 2012 Surface albedo following biochar application in durum wheat *Environ. Res. Lett.* **7** 014025

[15] Meyer S, Bright R M, Fischer D, Schulz H and Glaser B 2012 Albedo impact on the suitability of biochar systems to mitigate global warming *Environ. Sci. Technol.* **46** 12726–34

[16] Betts R A, Falloon P D, Goldewijk K K and Ramankutty N 2007 Biogeophysical effects of land use on climate: model simulations of radiative forcing and large-scale temperature change *Agric. Forest Meteorol.* **142** 216–33

[17] Ramaswamy V *et al* 2001 Radiative forcing of climate change *Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change* (Cambridge: Cambridge University Press)

[18] Post D F, Fimbres A, Matthias A D, Sano E E, Accioly L, Batchily A K and Ferreira L G 2000 Predicting soil albedo from soil color and spectral reflectance data *Soil Sci. Soc. Am. J.* **64** 1027–34

[19] Zeng X, Rao P, DeFries R S and Hansen M C 2003 Interannual variability and decadal trend of global fractional vegetation cover from 1982 to 2000 *J. Appl. Meteorol.* **42** 1525–30

[20] Wilson M F and Henderson-Sellers A 1985 A global archive of land cover and soils data for use in general circulation climate models *J. Clim.* **5** 119–43

[21] Houldcroft C J, Grey W M F, Barnsley M, Taylor C M, Los S O and North P R J 2009 New vegetation albedo

parameters and global fields of soil background albedo derived from MODIS for use in a climate model *J. Hydrometeorol.* **10** 183–98

[22] Vaccari F P, Baronti S, Lugato E, Genesio L, Castaldi S, Fornasier F and Miglietta F 2011 Biochar as a strategy to sequester carbon and increase yield in durum wheat *Eur. J. Agron.* **34** 231–8

[23] Wollny E 1881 *Forschungen auf dem Gebiete der Agrikultur-Physik* (Heidelberg: Carl Winter's Universitätsbuchhandlung) chapter 1

[24] Otterman J 1974 Baring high-albedo soils by overgrazing: a hypothesized desertification mechanism *Science* **186** 531–3

[25] Bond-Lamberty B and Thomson A 2010 Temperature-associated increases in the global soil respiration record *Nature* **464** 579–82

[26] Zhou J *et al* 2012 Microbial mediation of carbon-cycle feedbacks to climate warming *Nature Clim. Change* **2** 106–10

[27] Shepherd J 2009 *Geoengineering the Climate: Science, Governance and Uncertainty* (London: The Royal Society)

[28] Batjes N H 2009 Harmonized soil profile data for applications at global and continental scales: updates to the WISE database *Soil Use Manage.* **25** 124–7

[29] IUSS Working Group WRB 2006 World reference base for soil resources *World Soil Resources Reports* No. 103 (Rome: FAO)

[30] Ramankutty N, Evan A T, Monfreda C and Foley J A 2010 *Global Agricultural Lands: Croplands, 2000* (Palisades, NY: Socioeconomic Data and Applications Center (SEDAC)) (http://sedac.ciesin.columbia.edu/data/set/aglands-croplands-2000)