Management of pasture soils: biochar stability, carbon storage potential and its effect on production and quality

Bhupinder Pal Singh, Yunying Fang, Mark Boersma, Damian Collins, Lukas Van Zwieten and Lynne M Macdonald

ABSTRACT

The use of biochar has been proposed as a stable carbon (C) amendment with long-term carbon (C) storage potential in agricultural soils while improving primary productivity. However, this concept has not been widely tested in contrasting soils under temperate pasture systems. To address this knowledge gap, a ^{13}C-labelled biochar, produced from *Eucalyptus saligna* biomass by slow pyrolysis (450° C; d^{13}C -36.7‰) was surface (0"10 cm) applied in C_3 dominated, annual temperate pasture systems across Arenosol, Cambisol and Ferralsol. The results show that only 2% of the applied biochar-C was mineralised in a relatively clay- and C-poor Arenosol, 4.6% in a clay- and C-rich Cambisol, and 7% in a clay- and C-rich and earthworm-abundant Ferralsol over 12 months. Biochar application increased soil C stock, while the mean residence time of biochar-C, an indicator of its stability in soil, decreased with increasing native C content and/or pasture productivity across the soils *i.e.* Arenosol (71 years) < Cambisol (39 years) < Ferralsol (29 years). Biochar application increased pasture growth rate only on two occasions over 12 months in the Ferralsol but not in the other pasture-soil systems. The biochar-C recovery to 12"30 cm depth varied as 1.2% (Arenosol), 2.7% (Cambisol) and 15.7% (Ferralsol) after 12 months. Cumulative CO_2-C emission from native soil-plant sources was lower (p <0.10) in the biochar-amended *vs.* non-amended Ferralsol. This study shows that the downward migration of biochar-C exceeded its loss *via* mineralisation in the Arenosol and Ferralsol but in the Cambisol. This migration of biochar to deeper soil layers could enhance C sequestration potential in soil systems.

Keywords: Arenosol, Biochar stability, ^{13}C, Cambisol, Carbon sequestration, Ferralsol, Pasture.

Introduction

Biochar is a form of pyrolysed carbon (PyC) produced intentionally *via* pyrolysis under controlled conditions from plant biomass or bio-waste. The global interest in using biochar for organic waste management, C management, and as a soil amendment to improve soil health, long-term soil C sequestration, and agricultural productivity has risen rapidly over the last decade (Lehmann and Joseph, 2015). Additionally, because of its ability to improve nutrient retention and use efficiency, reduce nutrient leaching, and mitigate GHG emissions, biochar application has been recommended for 'high input' temperate pasture systems to achieve the above-mentioned multiple benefits (Taghizadeh-Toosi *et al.*, 2011). Temperate pastures cover 1.25 × 10^9 ha worldwide and are an important sink of soil C, representing approximately 12% of the soil organic C globally (Lal, 2004). The C storage potential, GHG mitigation and plant productivity of the temperate pasture systems could be enhanced through improved management practices (Rutledge *et al.*, 2015), including through the application of biochar (Schimmelpfennig *et al.*, 2014).

Several laboratory (Fang *et al.*, 2014; Knicker *et al.*, 2013; Kuzyakov *et al.*, 2009; Singh *et al.*, 2012; Zimmerman, 2010) and some field studies (Major *et al.*, 2010; Singh *et al.*, 2014) showed that biochar is a highly persistent organic material in soil. The persistence of biochar in soil is a function of its parent biomass and formation conditions [*e.g.* pyrolysis temperature, resdience time and oxygen supply (Crombie *et al.*, 2013; Singh *et al.*, 2012)]; soil characteristics [*e.g.* mineralogy, native SOC content, texture, microbial activity (Fang *et al.*, 2014; Hamer *et al.*, 2004)]; plant residue input (Keith *et al.*, 2011); and environmental factors [*e.g.* temperature, moisture (Glaser and Amelung, 2003; Nguyen *et al.*, 2010)]. These factors also play a role in influencing the extent and direction of priming of native SOC mineralisation by biochar (Fang *et al.*, 2015), with implications for altering native soil C stocks. On the other hand, biochar in the field can also translocate from the applied soil layer *via* lateral movement across the landscape or downward migration in the soil profile (Haefele *et al.*, 2011; Rumpel *et al.*, 2006; Singh *et al.*, 2014). For example, surface erosion by wind and water, and subsurface leaching and infiltration has been suggested as main pathways of biochar export from the terrestrial to marine systems (Rumpel *et al.*, 2015). However, thus far, there have been only limited field-based *vs.* laboratory-based studies, and particularly field studies assessing the fate and persistence of biochar-C across different soil types and environmental conditions are lacking. Hence, our current understanding of how plant C input and soil factors (such as C and clay content, moisture and earthworm activity) interact to influence biochar-C mineralisation is limited under field conditions. Hence, the sequestration potential of biochar-C in terrestrial ecosystems remains highly uncertain (Lehmann *et al.*, 2015).

This study aimed to provide insights into the persistence, fate and mobility of biochar and its impact of native C sources in contrasting soil systems varying in SOC content, clay content, earthworm activity or environmental conditions under 'high input' pasture systems. For this field-based study, we hypothesised that (i) biochar-C mineralisation would be higher in the SOC-rich soil (Cambisol or Ferralsol) that simultaneously supported greater plant productivity and/or earthworm activity than in the SOC-poor soil (Arenosol) with limited plant productivity or no earthworm activity; (ii) biochar will decrease native C emission from the relatively clay- and C-rich soil (Ferralsol) *vs.* a clay- and C-poor soil (Arenosol), possibly due to negative priming of SOC; and (iii) a coarser-textured characteristic of the Arenosol or a greater earthworm activity in the Ferralsol (combined with relatively high rainfall events) will favour downward migration of biochar in the soil profile.

Materials and Methods

In this study, biochar produced from Eucalyptus saligna with a depleted ^{13}C signature (relative to soil of predominantly C_3-vegetation origin) at 450° C by slow pyrolysis was used. This allowed to estimate the fate of biochar-C in respired CO_2 (biochar-C mineralisation), its impact on the combined native soil and plant C sources, and its downward migration over a 12-month period in three contrasting soils under managed pastures. The experimental field sites were located in (a) Cobbitty, New South Wales, Australia and (b) Elliot, Tasmania, Australia. The Cobbitty site was under a relatively warm and dry temperate environment, whereas the Elliot site was under a relatively cold and wet temperate environment. The field site in Cobbitty was previously under a mix of arable and fallow land uses during the experimental period. The field site in Elliott was previously under long term dairy pastures. The soils at the Cobbitty site are classified as Arenosol (-34.02140°, 150.66227°) and Cambisol (-34.02340°, 150.66350°) and the soil at the Elliott site is classified as Ferralsol (-41.08110°, 145.77035°), as per the World Reference Base (FAO, 2006).

The experimental areas were established as strips of approximately 13 m length and 7 m width (one strip for each soil type). A randomised block design was used to establish biochar-amended and non-amended (control) micro-plots within the strips. Micro-plot areas (0.66 m in diameter) were marked with a circular ring and the soil was excavated to 10-cm depth and mixed uniformly with (and without) biochar at 1 kg (dry wt) /micro-plot (equivalent to ~29.2 t/ha) by hand tools. The strips were fertilised (urea) and sown (broadcast seeding) with C_3 pastures (mixed grass and legume pasture species for the Cobbitty site and ryegrass and self-regenerated white clover for the Elliott site), as appropriate practices for the regional areas. Aboveground biomass was collected after the establishment of pasture sward at 4 to 6 weeks interval. The pasture plants were cut to 5 cm height. Dry weight of the biomass was measured after oven drying for 2 to 3 days at 70°C. Description of the initial properties of biochar and soils is given in Tables 1. A two-source C isotope mixing model was used to determine the proportion of biochar-C in total soil C [$C_{Biochar}$ (%)] in soil (Singh *et al*., 2012). The static alkali absorption method (Singh and Gupta, 1977) was used to determine (i) total C emission and (ii) associated $d^{13}C$. In this method, the CO_2 evolved from soil is absorbed in alkali (NaOH) placed in a static closed chamber over a specific time period (~24 h in the present study). To estimate MRT of biochar in soil, the cumulative pattern of biochar-C mineralised over 12 months was fitted to a two-pool exponential model (Fig. 1).

Results

Over the 12-months of experiment period, proportions of biochar C mineralised were 2.0, 4.6, and 7.0% in the Arenosol, Cambisol and Ferralsol, respectively (Fig. 1). Of the total biochar-C mineralised, 54–62% was mineralised in the first 4 months across three soils. The mean residence times (MRT) of biochar were estimated to be 71, 39 and 29 years using the two-pool exponential model in the Arenosol, Cambisol and Ferralsol, respectively. Cumulative C emission over 12 months from the combined native soil and plant sources

Table 1. Key properties of biochar and soils.

	Biochar	Arenosol	Cambisol	Ferralsol
Carbon (%)	66.79±0.22	0.66±0.04	1.67±0.20	6.25±0.17
Organic C (%)	66.66±0.25	-	-	-
H/C_{org}	0.63±0.08	-	-	-
Nitrogen (%)	1.04±0.02	0.06±0.00	0.15±0.01	0.53±0.01
$\delta^{13}C$ of soil (‰)	-36.7±0.2	-24.9±0.1	-24.9±0.1	-27.0±0.1
pH (1:5 H_2O)	9.8±0.1	6.1±0.3	6.9±0.1	6.0±0.1
Clay (%)	-	7.6±0.3	17.8±2.3	15.1±1.7
Texture		Loamy fine sand	Coarse sandy loam	Fine sandy loam

The numbers after "±" are the standard deviation (n = 3). """ means it was not applicable or measured. "H/C_{org}" is the molar ratio of hydrogen and organic C in biochar.

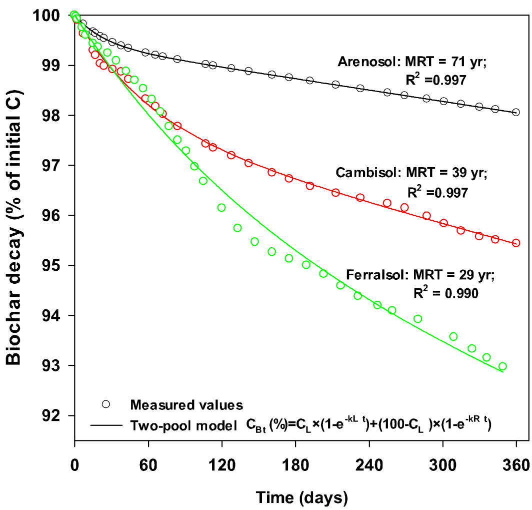

Fig. 1. Percent of biochar-C decayed in Arenosol (black), Cambisol (red) and Ferralsol (green) over 12 months. A two-pool exponential (solid line) model was employed to estimate the biochar-C mean residence time.

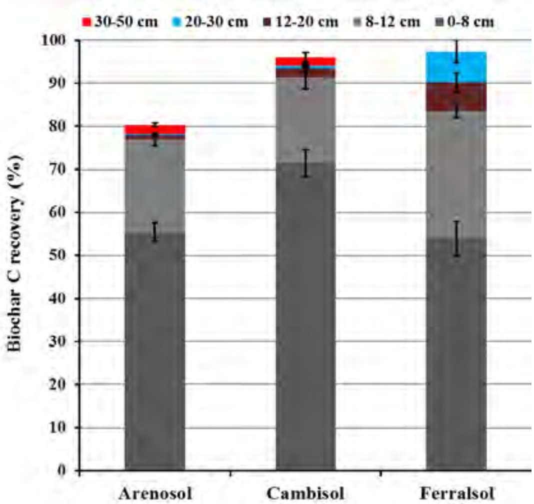

Fig. 2. Biochar-C recovery (%) at different depths at 12 months in the biochar-amended Arenosol, Cambisol and Ferralsol of the surface (0-10 cm) applied biochar-C on day zero. The data are presented at different depths and times after biochar incorporation in the soils. Error bars are standard errors (n = 4).

from the biochar-amended micro-plots was similar (Arenosol and Cambisol) or lower (Ferralsol; $p < 0.01$) compared to the control micro-plots (Fig. 2).

At day zero, the recovery of biochar-C in the applied 0"10 cm depth was 95.8%±2.0%, 100.6%±2.4% and 104.1%±1.8% in the biochar-amended Arenosol, Cambisol and Ferralsol, respectively. At 12 months, including all sampling depths, between 80.3%±2.7%, 96.1%±4.3% and 97.4%±4.6% of the initial biochar-C was recovered in the Arenosol, Cambisol and Ferralsol, respectively (Fig. 2). The proportion of biochar-C recovered in the deeper soil depth (below 12"30 cm) varied with soil ($p < 0.05$), at 1.2%, 2.6% and 13.8% in the biochar-amended Arenosol, Cambisol and Ferralsol, respectively. Furthermore, 2.1% and 2.0% of the applied biochar-C was recovered in the 30"50 cm depth after 12 months in the Arenosol and Cambisol, respectively. When including total biochar-C mineralised (Fig. 1) and the recovery of biochar in the soil profile to 30 cm in the Ferralsol or 50 cm in the Arenosol and Cambisol, the total recovery were 82.2%±2.3%, 100.7%±2.9% and 104.4%±4.9% in the Arenosol, Cambisol and Ferralsol, respectively.

The growth rate of the aboveground biomass across the sites was in the order of Arenosol < Ferralsol d" Cambisol. The pasture growth rate was either similar between the biochar-amended and control micro-plots in the Arenosol and Cambisol, or higher by up to 60% in the biochar-amended than the control micro-plots in the Ferralsol on two occasions (Fig. 3).

Discussion

The proportion of biochar-C mineralised in our field study was in the range (0.5–9%) reported from other field studies (Maestrini *et al.*, 2014; Major *et al.*, 2010; Ventura *et al.*, 2014).

The estimated shorter MRT of biochar-C in the range of a few decades using a two-pool exponential model may due to the fact that biochar-C mineralisation over 12 months may still be originating more from labile (e.g. alkyl functional groups) than recalcitrant (aryl functional groups) biochar-C. Indeed, we observed 54–62% of the total biochar-C mineralisation occurred with the first 4 months across the three sites. Hence, longer term C mineralisation observations are warranted to obtain realistic estimates of biochar MRT.

Impact of soil type and characteristics on biochar carbon mineralisation:

The C- and clay-poor Arenosol had 57% lower biochar-C mineralisation than the C- and clay-rich Cambisol. As these two soil systems were located in the same environment, so these results suggest the greater importance of native soil C (which also supported high plant productivity; Fig. 3) than the clay content in relation to degradation versus stabilisation of biochar-C in soil. Furthermore, our results of positive correlation between biochar-C mineralisation and total C content across the three soils (data not shown) suggest increased co-metabolic effect on biochar persistence with increasing native SOC content (Keith *et al.*, 2011; Luo *et al.*, 2011). On the other hand, the higher clay content in the Cambisol (17.8%) or the Ferralsol (15.1%) than the Arenosol (7.6%) could favour a greater biochar-clay interaction. However, in our study, we did not observe

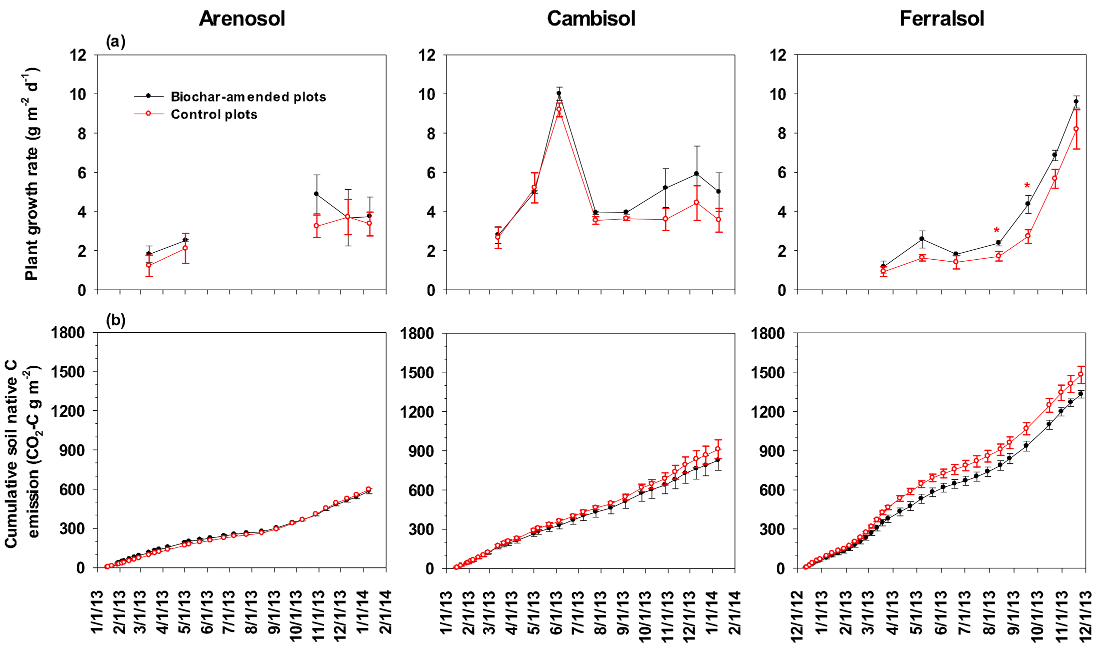

Fig. 3. Above-ground biomass growth rate (g m^{-2} d^{-1}) and cumulative amount of native C emission from plant and soil sources in biochar-amended and control Arenosol, Cambisol and Ferralsol over 12 months. The symbols of biochar-amended and control are black circle and red empty circle, respectively. Error bars are standard errors (n = 4). There were no pasture swards in the Arenosol micro-plots in June, July and September 2013 as we used herbicides to eradicate *Digitaria* species infestation. The red symbol "*" represents the biochar has significant effect on plant growth. Error bars are standard errors (n = 4).

decreased biochar-C mineralisation with increasing clay content from 8% to 18%, possibly due to the stronger co-metabolic effect of native SOC relative to the stabilisation effect of the biochar-clay interaction.

Furthermore, the temperate environment was relatively colder in the Elliott than the Cobbitty site but biochar-C mineralisation was the greatest in the Elliott site, possessing the highest native SOC content. This further highlights the importance of native SOC content relative to the environment. Although Fe and Al oxides in the Ferralsol and its moderately acidic pH (Table 1) could enhance association of biochar with clay minerals (von Lützow *et al*., 2006), the lowest persistence of biochar in the Ferralsol in the current study could be due to several reasons. Firstly, the highest native soil C, volumetric moisture and N fertilisation in the Ferralsol among the three soils could have supported the greatest microbial growth (data not shown), thus consequently resulting in the highest biochar-C mineralisation relative to Cambisol and Arenosol. Secondly, as the clay content in this Ferralsol is only 15.1% and the dominant clay type is kaolinite, this may have limited its interaction with biochar to decrease its mineralisation compared to other Ferralsols with higher clay content of 30"44% and/or dominating Fe and Al oxides (Fang *et al*., 2014). Thirdly, the highest biochar-C mineralisation and consequently its lowest persistence in the Ferralsol could have partly been supported by the greatest earthworm abundance/activity (Ameloot *et al*., 2013) relative to the other soil types. Fourthly, the higher pasture growth rate in the biochar-amended Ferralsol or Cambisol *vs.* Arenosol would have favoured a stronger root-C input driven positive priming effect on biochar-C mineralisation.

Downward migration of biochar in soil profile

In the Arenosol (loamy fine sand), the only 82% recovery of the applied biochar-C after its loss *via* mineralisation and recovery in the soil profile to 50 cm over 12 months suggests that biochar could have migrated through lateral and vertical movements (Major *et al*., 2010; Rumpel *et al*., 2015). In our study, we excluded the possibility of any surface lateral migration of biochar particles from the applied 0"10 cm layer. This was ensured by (i) grinding biochar to < 2 mm, uniformly mixing with the soil at each of the sites, and then repacking close-to-the original soil bulk density; and (ii) placing a ~3 cm raised garden edging to 12 cm soil depth around the soil in the micro-plots. Therefore, the greatest downward migration of biochar, particularly in the Arenosol could have been facilitated by (i) finer fragmentation of biochar particles, (ii) infiltration events following rain, (iii) coarser soil texture with larger pore spaces, and (iv) lower concentrations of clay that favours formation of less mobile organo-mineral complexes. On the other hand, a greater biochar migration rate was found in the Ferralsol (13.7% in below 12 cm depth) than in the Cambisol (4.6% in below 12 cm depth), which can be attributed to bioturbation by earthworms (Chan *et al*., 2008) and possibly the higher annual precipitation rate (1109 *vs.* 788 mm) in the Ferralsol *vs.* Cambisol.

Biochar effect on pasture growth rate and C emission from native plant and soil sources

The lack of significant influence of biochar on pasture growth rate, except on two occasions in the Ferralsol (Fig. 3), is consistent with the study of Slavich *et al*. (2013) who reported the low nutrient content and acid neutralising capacity of their green waste biochar would not alleviate such constraints to pasture productivity. We expected the same results for our wood-derived biochar. Thus, plant productivity may be enhanced through the application of biochar if certain soil constraints are addressed through specific biochars, *e.g.* a nutrient-rich biochar would benefit a poor fertility soil and an alkaline biochar may alleviate acidity constraints in an acidic soil over a shorter term. Over a longer term, biochar presence may improve soil structure and water holding capacity (Quin *et al*., 2014) and thus may enhance soil physical quality. Furthermore, biochar application may also alter pasture species composition e.g. Schimmelpfennig *et al*. (2014) observed greater grass biomass than forb biomass growth in a field study. Similarly, although biochar amendment did not alter total pasture productivity, it had a strong and significant effect on pasture community composition, *i.e.* the legumes were more abundant than grasses or forbs, in a field study by van de Voorde *et al*. (2014).

In our study, the lack of effect on biochar on pasture growth rate provided confidence in using ä^{13}C signature of CO_2-C emitted from the control micro-plots as one of the end members in the two-pool isotope mixing model (Singh *et al*., 2012). On the other hand, the higher pasture growth rate on two occasions in the biochar-amended versus the non-amended Ferralsol may cause an increase in belowground C input, plant respiration and consequently any root C input associated positive priming of native soil C (Major *et al*., 2010; Whitman *et al*., 2014). However, a negative priming of native soil or plant-derived C by biochar occurred as the result shows consistently ($p < 0.01$) decreased C emissions from the plant-soil sources in the presence of biochar in the Ferralsol. This could possibly be due to biochar-induced increase in interactions between native organic matter and reactive clay mineral *via* ligand exchange in the Ferralsol relative to other soils (Fang *et al*., 2015).

Conclusions and implications

The novel use of ^{13}C-labelled biochar (depleted in d^{13}C signature relative to soil) has provided insights into the persistence and fate of biochar in the soil profile across contrasting soils and site-specific characteristics. Between 2.0 and 7.0% of the biochar-C was mineralised in 12 months in the order of Arenosol (Cobbitty, NSW) < Cambisol (Cobbitty, NSW) < Ferralsol (Elliott, Tasmania). The MRT of biochar, based on the short-term (12 months) study that principally accounts for mineralisation of relatively labile biochar-C components, has been estimated to in decades. The MRT of biochar-C was the longest in the Arenosol and shortest in the Ferralsol because of the influence of certain site specific characteristics on biochar-C mineralisation rate in the soils. For example, the Feralsol had high native soil C content, earthworm abundance, N fertilisation and/or pasture growth rate (relative to the Arenosol or Cambisol), which may have contributed to its increased mineralisation in the soil. On the other hand, biochar presence in the Ferralsol decreased C emissions from native C sources (more than the total amount of biochar-C mineralised), possibly due to biochar-induced stabilisation of native soil C and/or root-derived C *via* interactions with reactive clay minerals and polyvalent cations. Our results suggest that the positive priming effect of high SOC content on biochar-C mineralisation could be offset by the biochar-induced stabilisation of SOC in the Ferralsol. Our findings also show that biochar can migrate vertically into the soil profile in the order of Arenosol (NSW) > Ferralsol (Tasmania) > Cambisol (NSW). This is possibly due to direct leaching and infiltration of biochar in soluble or particulate forms, which can be significant in high rainfall areas or in coarser textured soil, and/or *via* ingestion and bioturbation by earthworms. There are implications of biochar migrating downward into the soil profile from the perspective of its persistence in soil. For example, the deeper vs. the surface soil layers may have lower microbial activity, root C input and oxygen concentration and/or higher clay content; these factors would increase the persistence of the migrated biochar in the soil systems. However, the ongoing natural physical (weathering) processes may result in considerable migration of dissolved and finer particulate forms of biochar to waterways, particularly in a sandy soil such as the Arenosol. The findings of this study suggest that a careful examination of site specific characteristics is necessary to optimise biochar production and application for maximum long-term C sequestration benefits within soil systems. The knowledge acquired from this research on the persistence and downward migration of biochar in contrasting soils has relevance for C models to assess its C sequestration potential in managed temperate pasture systems with implications for the global C budget. Although biochar did not impact pasture growth rate, it may have influenced pasture composition, possibly favouring growth of legume over grass species. Future studies should also evaluate the impact of biochar on pasture composition and soil nutrition status, with implications for the overall pasture productivity and composition and its animal feed quality.

References

Ameloot, N., E. R. Graber, F. G. A. Verheijen and S. De Neve. 2013. Interactions between biochar stability and soil organisms: review and research needs. *European Journal of Soil Science* 64: 379–390.

Chan, K.Y., L. Van Zwieten, I. Meszaros, A. Downie and S. Joseph. 2008. Using poultry litter biochars as soil amendments. *Australian Journal of Soil Research* 46: 437-444.

Crombie, K., O. Masek, S. P. Sohi, P. Brownsort and A. Cross. 2013. The effect of pyrolysis conditions on biochar stability as determined by three methods. *Global Change Biology Bioenergy* 5: 122-131.

Fang, Y., B. Singh and B.P. Singh. 2015. Effect of temperature on biochar priming effects and its stability in soils. *Soil Biology & Biochemistry* 80: 136-145.

Fang, Y., B. Singh B. P. Singh. and E. Krull. 2014. Biochar carbon stability in four contrasting soils. *European Journal of Soil Science* 65:60-71.

FAO. 2006. World reference base for soil resources 2006, *World soil resources reports*, pp. 67-100.

Glaser, B. and W. Amelung. 2003. Pyrogenic carbon in native grassland soils along a climosequence in North America. *Global Biogeochemical Cycles* 17: 1064.

Haefele, S.M., Y. Konboon, W. Wongboon, S. Amarante, A. A. Maarifat, E. M. Pfeiffer and C. Knoblauch. 2011. Effects and fate of biochar from rice residues in rice-based systems. *Field Crops Research* 121: 430-440.

Hamer, U., B. Marschner, S. Brodowski and W. Amelung. 2004. Interactive priming of black carbon and glucose mineralisation. *Organic Geochemistry* 35: 823-830.

Keith, A., B. Singh and B. P. Singh. 2011. Interactive priming of biochar and labile organic matter mineralization in a smectite-rich soil. *Environmental Science & Technology* 45: 9611-9618.

Knicker, H., F. J. Gonzalez-Vila and R. Gonzalez-Vazquez. 2013. Biodegradability of organic matter in fire-affected mineral soils of Southern Spain. *Soil Biology & Biochemistry* 56: 31-39.

Kuzyakov, Y., I. Subbotina, H. Q. Chen, I. Bogomolova and X. L. Xu. 2009. Black carbon decomposition and incorporation into soil microbial biomass estimated by ^{14}C labeling. *Soil Biology Biochemistry* 41: 210-219.

Lal, R. 2004. Soil carbon sequestration to mitigate climate change. *Geoderma* 123: 1-22.

Lehmann, J., S. Abiven, M. Kleber, G. Pan, B. P. Singh, S. Sohi and A. Zimmerman. 2015. Persistence of biochar in soil, In: Lehmann, J., Joseph, S. (Eds.), *Biochar for Environmental Management: Science, Technology and Implementation* (second edition). Routledge, New York, pp. 235-282.

Lehmann, J. and S. Joseph. 2015. *Biochar for Environmental Management: Science, Technology and Implementation* (second edition). Routledge, New York.

Luo, Y., M. Durenkamp, M. De Nobili, Q. Lin and P. C. Brookes. 2011. Short term soil priming effects and the mineralisation of biochar following its incorporation to soils of different pH. *Soil Biology & Biochemistry* 43: 2304-2314.

Maestrini, B., S. Abiven, N. Singh, J. Bird, M. S. Torn and M. W. I. Schmidt. 2014. Carbon losses from pyrolysed and original wood in a forest soil under natural and increased N deposition. *Biogeosciences Discuss* 11: 1-31.

Major, J., J. Lehmann, M. Rondon and C. Goodale. 2010. Fate of soil-applied black carbon: downward migration, leaching and soil respiration. *Global Change Biology* 16: 1366-1379.

Nguyen, B.T., J. Lehmann, W. C. Hockaday, S. Joseph and C. A. Masiello. 2010. Temperature sensitivity of black carbon decomposition and oxidation. *Environmental Science & Technology* 44: 3324-3331.

Quin, P., A. Cowie, R. Flavel, B. Keen, L. Macdonald, S. Morris, B. Singh, I. Young and L. Van Zwieten. 2014. Oil mallee biochar improves soil structural properties—a study with x-ray micro-CT. *Agriculture, Ecosystems & Environment* 191: 142-149.

Rumpel, C., V. Chaplot, O. Planchon, J. Bernadou, C. Valentin and A. Mariotti. 2006. Preferential erosion of black carbon on steep slopes with slash and burn agriculture. *Catena* 65: 30-40.

Rumpel, C., J. Leifeld, C. Santin and S. Doerr. 2015. Movement of biochar in the environment, In: Lehmann, J., Joseph, S. (Eds.), *Biochar for Environmental Management: Science, Technology and Implementation* (second edition). Routledge, New York, pp. 283-298.

Rutledge, S., P. Mudge, D. Campbell, S. Woodward, J. Goodrich, A. Wall, M. Kirschbaum and L. Schipper. 2015. Carbon balance of an intensively grazed temperate dairy pasture over four years. *Agriculture, Ecosystems & Environment* 206:10-20.

Schimmelpfennig, S., C. Muller, L. Grunhage, C. Koch and C. Kammann. 2014. Biochar, hydrochar and uncarbonized feedstock application to permanent grassland-Effects on greenhouse gas emissions and plant growth. *Agriculture Ecosystems & Environment* 191: 39-52.

Singh, B.P., A. L. Cowie and R. J. Smernik. 2012. Biochar carbon stability in a clayey soil as a function of feedstock and pyrolysis temperature. *Environmental Science & Technology* 46:11770-11778.

Singh, J.S. and S. R. Gupta. 1977. Plant Decomposition and Soil Respiration in Terrestrial Ecosystems. *Botanical Review* 43: 449-528.

Singh, N., S. Abiven, B. Maestrini, J. A. Bird, M. S. Torn and M. W. I. Schmidt. 2014. Transformation and stabilization of pyrogenic organic matter in a temperate forest field experiment. *Global Change Biology* 20:1629-1642.

Slavich, P.G., K. Sinclair, S. G. Morris, S.W.L. Kimber, A. Downie and L. Van Zwieten. 2013. Contrasting effects of manure and green waste biochars on the properties of an acidic ferralsol and productivity of a subtropical pasture. *Plant and Soil* 366: 213-227.

Taghizadeh-Toosi, A., T. J. Clough, L. M. Condron, R. R. Sherlock, C. R. Anderson and R. A. Craigie. 2011. Biochar incorporation into pasture soil suppresses in situ nitrous oxide emissions from ruminant urine patches. *Journal of Environmental Quality* 40: 468-476.

van de Voorde, T.F.J., T. M. Bezemer, J. W. Van Groenigen, S. Jeffery and L. Mommer. 2014. Soil biochar amendment in a nature restoration area: effects on plant productivity and community composition. *Ecological applications* 24: 1167-1177.

Ventura, M., G. Alberti, M. Viger, J.R. Jenkins, C. Girardin, S. Baronti, A. Zaldei, G. Taylor, C. Rumpel, F. Miglietta and G. Tonon. 2014. Biochar mineralization and priming effect on SOM decomposition in two European short rotation coppices. *Global Change Biology Bioenergy*, DOI: 10.1111/gcbb.12219.

von Lützow, M., I. Kögel-Knabner, K. Ekschmitt, E. Matzner, G. Guggenberger, B. Marschner and H. Flessa. 2006. Stabilization of organic matter in temperate soils: mechanisms and their relevance under different soil conditions - a review. *European Journal of Soil Science* 57: 426-445.

Whitman, T., A. Enders and J. Lehmann. 2014. Pyrogenic carbon additions to soil counteract positive priming of soil carbon decomposition by plants. *Soil Biology and Biochemistry* 73: 33-41.

Zimmerman, A. R. 2010. Abiotic and microbial oxidation of laboratory-produced black carbon (biochar). *Environmental Science & Technology* 44: 1295-1301.