Short- and long-term impacts of plant-biochar-soil interactions on soil carbon cycling in a subtropical pasture

by

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Certification

I certify that the substance of this thesis has not already been submitted for any degree and is not currently being submitted for any other degree or qualification

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Publications

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Journal publications

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Conference proceedings

Oral presentation

Weng, Z., Van Zwieten, L., Singh, B.P., Joseph, S., Kimber, S., Morris, S., Cowie, A., and Macdonald, L.M., 2015. Negative priming still evident in the field 9 years after biochar application. Proceedings of the Joint International Biochar Symposium 2015. Geisenheim University, Geisenheim, Germany, 28-30 September, 2015.

Weng, Z., Van Zwieten, L., Singh, B.P., Kimber, S., Morris, S., and Cowie, A., 2014. Assessing mechanisms for stabilisation of recent carbon in freshly-applied and 8-year-aged biochar-treated pastures. Proceedings of the National Soil Science Conference, Melbourne, Australia, 23-27 November, 2014. http://www.soilscience2014.com/proceedings/Weng.pdf

Van Zwieten, L., **Weng, Z.**, Quin, P., Kimber, S., and Morris, S., 2014. Using biochars in different agricultural systems. Proceedings of the International Perspectives on Biochar Research and Application. Australian Technology Park, Sydney, Australia, 10 December, 2014.

Van Zwieten, L., Quin, P., **Weng, Z.,** Kimber, S., 2013. Mitigation of N_2O emissions and assessment of biochar stability: an Update of Results from National DAFF Biochar 1 and 2 Projects. Proceedings of the National Biochar Workshop: Recent advances and future research directions. Australian Technology Park, Sydney, Australia, 16 December, 2013.

Poster presentation

Weng, Z., Van Zwieten, L., Singh, B.P., Kimber, S., Morris, S. and Cowie, A., 2014: Assessing biochar stability and native soil carbon stabilisation in pasture. Proceedings of the 20th World Congress of Soil Science on Soils Embrace Life and Universe. Jeju, Korea, 8-13 June, 2014. http://www.20wcss.org/data/20WCSS_poster%20schedule.pdf

Macdonald, L. M, Singh, B., Van Zwieten, L., Singh, B.P., Boersma, M., Kookana, R., Kimber, S., Keith, A., Dijkstra, F. , **Weng, Z.**, Fang, Y., and Farrell, M., 2014. The national biochar initiative: a country-wide approach. Proceedings of the National Soil Science Conference, Melbourne, Australia, 23-27 November, 2014. http://www.soilscience2014.com/proceedings/Macdonald_2.pdf

Abstract

While biochar has been widely promoted for its potential to stabilise soil organic carbon (SOC), many laboratory and glasshouse studies (mainly short-term) have demonstrated that biochar can increase (positive priming) and/or lower (negative priming) mineralisation of SOC. There is a clear knowledge gap on both biochar carbon (C) longevity, its priming effects on SOC, and recent root-derived C, under field conditions. This knowledge would allow the potential contribution of biochar to long-term soil C sequestration to be understood. Understanding plant -biochar-soil interactions (Chapter 1) over the long term is crucial to accurately predict the C storage potential of biochar-amended soil, additional to its intrinsic C content.

Most studies on biochar C longevity and its priming effect have been undertaken in plant-free laboratory incubations. To assess the impact of plants on biochar longevity and its priming effect (Chapter 2), a 388-d field study was carried out in the presence of annual ryegrass (C_3) grown on a rhodic Ferralsol with C_3/C_4 plant-derived SOC ($\delta^{13}C$: -20.2‰) in a subtropical climate. A ^{13}C-depleted hardwood biochar ($\delta^{13}C$: -35.7‰, produced at 450°C) was applied at 0 and 30 dry t ha^{-1} and mixed into the top 100-mm soil profile (equivalent to 0 and 3% w/w, respectively). Root respiration and mineralisation of soil-C and biochar-C was differentiated and quantified in this field site. Periodic $^{13}CO_2$ pulse labelling was applied to enrich the $\delta^{13}C$ signature of root respiration during two separate winter campaigns ($\delta^{13}C$: 151.5-184.6‰) and one summer campaign ($\delta^{13}C$: 19.8-31.5‰). Combined soil plus root respiration was separated from leaf respiration using a novel in-field respiration collar. A two-pool isotope mixing model was applied to partition three C sources (i.e. root, biochar and soil). Three scenarios were used to assess the sensitivity associated with the C source partitioning in the planted systems: 1) extreme positive priming of the C_3-dominant SOC derived from the current C_3-ryegrass pasture; 2) equivalent magnitude of priming of recent C_3 and native C_4 vegetation-derived SOC; and 3) extreme positive priming of the native C_4-dominant SOC. The biochar induced a significant negative priming of SOC in the presence of growing plants but no net priming was observed in the unplanted soil. I also demonstrated the importance of the experimental timeframe in capturing the transient nature of biochar-induced priming; from positive (day 0-62) to negative (day 62-388). The presence/absence of plants had no impact on biochar-C mineralisation in this Ferralsol during the measurement period. Based on a two–pool exponential model, the mean residence time (MRT) of biochar varied from 351-449 years in the intensive pasture system to 415-484 years in the unplanted controls.

Organo-mineral interactions serve as the principal mechanism for the stabilisation of soil organic matter (SOM) in mineral soils, which can be enhanced by the presence of biochar possibly via ligand

exchange (Singh and Cowie, 2014) or cation bridging mechanisms (Liang et al., 2010). In Chapter 3, I further assessed the contribution of organo-mineral interactions to the reported biochar-induced negative priming in a planted Ferralsol (shown in Chapter 2). Applying a detailed soil physical fractionation coupled with stable ^{13}C isotope partitioning, the magnitude and fate of recently fixed ^{13}C was quantified within various belowground C pools, including: soil plus root respiration, root biomass, soil aggregates and associated fractions. The aggregate-associated fractions consist of free- (>1.6 g cm^{-3}) and occluded- (>53 µm) particulate organic matter (F- and O-POM), and mineral-protected SOM (M-SOM, < 53 µm). The biochar (*E.saligna*, 450°C) amendment increased total belowground ^{13}C recovery by 10% compared to the non-amended control. Retention of rhizodeposits (i.e. ^{13}C) was found in increasing concentrations in the order: O-POM of macroaggregates (macro-, 250-2000 µm) <O-POM of microaggregates (micro-, < 250 µm) <micro-M-SOM <macro-M-SOM. I provide evidence that rapid accumulation of rhizodepsits in organo-mineral (i.e. O-POM and M-SOM) fractions promoted biochar-induced negative priming over 12 months.

Nevertheless, the transient nature of biochar-induced priming highlights the need for longer-term studies to assess the persistence of negative priming as biochar ages in soil (Chapter 4). For this assessment, periodic $^{13}CO_2$ pulse-labelling was applied to ryegrass in the field, and belowground C allocation, SOC priming, and root-derived C stabilisation was monitored on a Ferralsol amended with biochar (hardwood, 550°C)over the period 8.2-9.5 years since amendment. I provide evidence that field-aged biochar (a) enhanced belowground C recovery by 20%, (b) promoted negative priming (lowered C loss through respiration by 160 g CO_2-C m^{-2} y^{-1}) and (c) increased the retention of root-derived ^{13}C in the stable organo-mineral fractions (<53 µm) by 6% ($P< 0.05$). Through synchrotron-based spectroscopic analysis of bulk soil, field-aged biochar and microaggregates (<250 µm), I mechanistically demonstrate the role of biochar in accelerating formation of micro-agglomerates via organo-mineral interactions.

Despite the continued increase in the total soil C stock in the 9.5-year biochar-amended Ferralsol, a decrease in the rate of SOC build-up was detected in Chapter 4. This is interpreted as the biochar amended system approaching a new equilibrium of SOC. The reapplication of biochar has been suggested to restore the originally observed transient agronomic benefits, including improved soil quality by increasing phosphate availability and soil moisture (Quilliam et al., 2012). However, there is no literature on the effect of a repeated (2^{nd}) application of biochar on the priming of native soil organic SOC in a clay-rich soil. This knowledge would allow the potential of recurring biochar application in long-term soil C sequestration to be established. In a previous field study established in 2006 as reported in Chapter 4, an *E. saligna* biochar (550°C) induced negative priming of native

and root-derived SOC after being incorporated in a Ferralsol over nearly a decade. The total soil C stock continued to increase beyond the amount of biochar-supplied C in this subtropical pasture. I aimed: 1) to further evaluate the extent of priming on this existing site, including the effects of the 2nd application of biochar in planted and unplanted Ferralsol; and 2) to assess the potential of resetting SOC stabilisation capacity through the use of a 2nd application of biochar. In April 2014, I superimposed a 488 d field trial on this long-term site. Three treatments were: 1) control (0 t biochar ha^{-1}), 2) fresh biochar applied to the unamended soil (10 t biochar ha^{-1}, "fresh biochar"), and 3) fresh biochar applied to the existing 9.5-year field-aged biochar-amended soil (10 t biochar ha^{-1}, "2nd application"). I showed that the 2nd application of biochar after nearly a decade doubled the increase of the total soil C stock found from the prior application. The negative priming of SOC by the 2nd application of biochar contributed to this increase in the total soil C stock. A lowered enzyme to microbial biomass ratio could increase microbial C use efficiency of both total and rhizodeposit-derived C in the biochar-amended soil, which may promote negative priming. The results provide fundamental field-derived evidence of the potential of repeated biochar application in resetting the SOC stabilisation capacity.

Biochar-organo-mineral interactions control the long-term SOC stabilisation in the biochar-amended mineral soils. An *in situ* $^{13}CO_2$-labelling study has shown significant stabilisation of recent (^{13}C-labelled) pasture-derived rhizodeposits in a nearly decade-aged biochar-amended Ferralsol via enhanced organo-mineral interactions (Chapter 4). A repeated biochar application study on this aged biochar-amended Ferralsol was shown to promote negative priming of native and/or root-derived SOC (Chapter 5). In Chapter 6, I assessed the role of repeated biochar application on the stabilisation of recent root-derived C in the organo-mineral fractions in the aged biochar-amended Ferralsol. Repeated biochar application further stabilised recent rhizodeposits in the existing aged biochar-amended soil by facilitating the transformation of belowground ^{13}C from root biomass and exudates to the aggregate-occluded particulates (8 month) and mineral (silt/clay)-protected (12 month) organic fractions. The increased stabilisation of root-derived C in the organo-mineral fractions may explain the reinvigorated soil C sequestration capacity following the 2nd application of biochar into a decade aged biochar amended soil (Chapter 5).

To conclude, using this replicated-design short- and long-term biochar field experiment, the turnover of both rhizodeposits and native SOC was lowered in biochar-amended soils, with biochar-induced negative priming counteracting the co-existing positive rhizosphere priming a decade after biochar incorporation. Further, I suggest that the formation and accumulation of organo-mineral complexes around catalytic biochar surfaces may counteract the dissolution of mineral-protected SOC by root

exudates. The results enable more accurate predictions of the C sequestration potential of woody biochars applied to Fe-dominated clay soils. Resetting the SOC stabilisation capacity is feasible via repeated biochar application.

Abbreviations

AS	Australian Synchrotron
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DAFF	Department of Agriculture, Fisheries and Forestry
NSW DPI	New South Wales Department of Primary Industries
ANOVA	analysis of variance
CEC	cation exchange capacity
CLPP	community level physiological profiles
DOM	dissolved organic matter
DOC	dissolved organic carbon
FOM	fresh organic matte
F-POM	free particulate organic matter
FTY	total fluorescence yield
LOM	labile organic matter
LSD	least significant difference
Mo	molybdenum
MOAs	mineral-organic associations
M-SOM	mineral-protected soil organic matter
MRT	mean residence time
MUF	methylumbelliferyl
OM	organic matter
O-POM	occluded particulate organic matter
POM	particulate organic matter
PDB	Pee Dee Belemnite
PE	polyethylene
PVC	polyvinyl chloride
PyC	pyrogenic carbon
PyOM	pyrogenic organic matter

SIR	substrate induced respiration
SOM	soil organic matter
SOC	soil organic carbon
SPT	sodium polytungstate
SSA	specific surface area
SXR	soft X-ray
UV	ultra-violet
XPS	X-ray photoelectron spectroscopy

°C	degrees Celsius
t	tonne/ metric ton
g	gram
L	litre
m	metre
s	second
ha	hectare (100 m × 100 m)
Pa	Pascals
mol	moles

Prefixes

G	giga (10^{9})
M	mega (10^{6})
k	kilo (10^{3})
c	centi (10^{-2})
m	milli (10^{-3})
µ	micro (10^{-6})
n	nano (10^{-9})
p	pico (10^{-12})

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