Appendix 4 Method for Estimating the Change in Mineral Soil Organic Carbon Stocks from Biochar Amendments: Basis for Future Methodological Development

This appendix provides a basis for future methodological development of a Tier 1 method for estimating the change in mineral soil organic C stocks from biochar amendments to soils, rather than complete guidance.

For the purpose of this methodology, biochar is defined as a solid material generated by heating biomass to a temperature in excess of 350°C under conditions of controlled and limited oxidant concentrations to prevent combustion. These processes can be classified as either pyrolysis (in which oxidants are excluded), or gasification (in which oxidant concentrations are low enough to generate syngas). The change in soil organic C stocks from biochar amendments is estimated separately from other organic amendments over a 100-year time frame. This method does not deal with pyrolytic organic materials that result from wild fires or open fires, and is only applicable for biochar added to mineral soils in grasslands and croplands. Biochar is more persistent with only a small portion mineralised each year at a decreasing rate over many centuries, and therefore the stock change method cannot be used to track changes in biochar C stocks over time as is done for other management practices in mineral soils.

The methodology used to estimate biochar C additions to minerals soils is based on a top-down approach in which the total amount of biochar generated and added to mineral soil in cropland and grassland[1] is required to estimate the contribution of biochar to annual changes in mineral soil C stocks. Information is not needed on the application rate. Interactions between biochar C fate and soil type or land management are not considered with this method. However, the method does require compilers to track the source of feedstock and temperature of the pyrolysis. The total change in carbon stocks of mineral soils receiving biochar amendments is estimated with Equation 4Ap.1.

EQUATION 4AP.1
ANNUAL CHANGE IN BIOCHAR CARBON STOCK IN MINERAL SOILS RECEIVING BIOCHAR ADDITIONS

$$\Delta BC_{Mineral} = \sum_{p=1}^{n} \left(BC_{TOT_p} \bullet F_{C_p} \bullet F_{perm_p} \right)$$

Where

$\Delta BC_{Mineral}$ = the total change in carbon stocks of mineral soils associated with biochar amendment, tonnes sequestered C yr^{-1}

BC_{TOT_p} = the mass of biochar incorporated into mineral soil during the inventory year for each biochar production type p, tonnes biochar dry matter yr^{-1}

F_{C_p} = the organic carbon content of biochar for each production type p, tonnes C tonne^{-1} biochar dry matter, Table 4Ap.1

F_{perm_p} = fraction of biochar carbon for each production type p remaining (unmineralised) after 100 years, tonnes sequestered C tonne^{-1} biochar C, Table 4Ap.2

n = the number of different production types of biochar

[1] This method is not applicable for application of biochar to soils in forest land, settlements, other lands or wetlands. The studies used in the derivation of F_{perm} values included only cropland and grassland mineral soils. Thus the F_{perm} values provided in Table 4Ap.2 are only applicable to mineral soils under those land uses.

Global estimates of the organic C content of biochar (F_{C_p}) as a function of feedstock and heating temperature are provided in Table 4Ap.1, as well as estimates of the proportion of biochar C that would persist for 100 years (F_{perm_p}) years in Table 4Ap.2[2].

The biochar-C addition is estimated for cropland and grassland, or in total without disaggregation to the amounts applied in cropland and grassland. If biochar-C is entered without disaggregation, then the C stock change should be associated with the land use receiving the majority of the biochar.

TABLE 4AP.1
VALUES FOR ORGANIC C CONTENT FACTOR OF BIOCHAR BY PRODUCTION TYPE (F_{C_p}).

Feedstock	Pyrolysis Production Process	Values for F_{C_p} [2]
Animal manure	Pyrolysis [1]	0.38 ± 49%
	Gasification [1]	0.09 ± 53%
Wood	Pyrolysis	0.77 ± 42%
	Gasification	0.52 ± 52%
Herbaceous (grasses, forbs, leaves; excluding rice husks and rice straw)	Pyrolysis	0.65 ± 45%
	Gasification	0.28 ± 50%
Rice husks and rice straw	Pyrolysis	0.49 ± 41%
	Gasification	0.13 ± 50%
Nut shells, pits and stones	Pyrolysis	0.74 ± 39%
	Gasification	0.40 ± 52%
Biosolids (paper sludge, sewage sludge)	Pyrolysis	0.35 ± 40%
	Gasification	0.07 ± 50%

Notes:

[1]An explanation of the conversion technologies is provided in Annex 2A.2.

[2] All values are presented in the format of the mean value ± the 95% confidence limit expressed as a percentage of the mean (that is ± 1.96 * standard error /mean *100).

Source:

F_{Cp} was calculated from the organic carbon content of biochar from regressions by Neves et al. (2011), corrected for ash content using biochar yield from Woolf et al. (2014). Data on ash, lignin, and carbon content of biomass feedstocks, which are parameters in these regression equations, were taken from ECN (2018).[3]

[2] Estimating biochar C remaining for durations of <100 years, such as 20 years, would require additional detailed information on the chemical nature of the biochar, how it is applied, as well as climatic and edaphic properties of the location it was applied.

[3] https://phyllis.nl/Home/Colophon (24/10/2018).

TABLE 4AP.2
VALUES FOR F_{perm_p} (FRACTION OF BIOCHAR C REMAINING AFTER 100 YEARS)

Production	Value for F_{perm_p} [1, 2]
High temperature pyrolysis and gasification (> 600 °C)	0.89 ± 13%
Medium temperature pyrolysis (450-600 °C)	0.80 ± 11%
Low (350-450 °C)	0.65 ± 15%

Notes:

[1] All values are presented in the format of the mean value ± the 95% bootstrap confidence limit expressed as a percentage of the mean (note that the bootstrap confidence intervals are symmetric about the mean to within 2 significant digits and are therefore given as ± a percentage of the mean value).

[2] The studies used in the derivation of F_{perm_p} values included only cropland and grassland mineral soils. Thus the f F_{perm_p} values provided are only applicable to mineral soils under those land uses, and not for forest land, settlements, other land or wetlands.

Sources:

Major *et al*. 2010; Zimmerman 2010; Singh *et al.* 2012; Zimmerman & Gao 2013; Fang *et al.* 2014; Herath *et al.* 2015; Kuzyakov *et al.* 2014; Dharmakeerthi *et al.* 2015; Wu *et al.* 2016

Background Information on Derivation of F_{C_p} and F_{perm_p} Values

F_{C_p} was calculated using the organic carbon content of biochar on a dry ash-free (daf) basis according to equation 14 from Neves et al. (2011), which was based on a regression (n=128) of data from 26 papers. This daf organic carbon content was corrected for ash content of the biochar to provide F_{C_p} as the carbon content per unit mass of biochar using the regression equation (n=146 from 18 articles) of biochar yield from Woolf et al. (2014). Data on ash (n=1276), lignin (n=516), and carbon (n=1276) content of biomass feedstocks, which are parameters in these regression equations, were taken from ECN (2018).

The values for F_{permp} were calculated from field and laboratory studies for biochars that were made under different conversion conditions based on a comprehensive survey of the literature. The amount of biochar C remaining after 100 years was estimated by fitting a two-pool double-exponential model to only those datasets within the list of references that exceeded one year and allowed a two-pool model to be fitted following the rationale outlined by Lehmann *et al.* (2015). The data included all available studies that met these stringent quality criteria (Major *et al*. 2010; Zimmerman 2010; Singh *et al.* 2012; Zimmerman & Gao 2013; Fang *et al.* 2014; Herath *et al.* 2015; Kuzyakov *et al.* 2014; Dharmakeerthi *et al.* 2015; Wu *et al.* 2016). F_{permp} values were adjusted to an ambient temperature of 20°C, which is higher than current estimates of approximately 10°C average land surface temperature (Rohde *et al*., 2013) and therefore conservative since decomposition increases with increasing temperature. F_{permp} values were then calculated for the three categories shown in Table 4Ap.2 as means for each of the three temperature categories (Figure 4Ap.1). Categories were preferred to using a linear regression due to the non-linear relationship between pyrolysis temperature and biochar C persistence (Whitman *et al*., 2013; Bird *et al*., 2015). Long-term field data of naturally accumulated char and anthropogenically added biochar with unknown production temperatures were assessed separately as a cross-check on the results (Figure 4Ap.1) and include all available studies with periods exceeding 10 years of observation (Cheng et al., 2008; Hammes et al., 2008; Lehmann et al., 2008; Liang et al., 2008; Nguyen et al., 2008; Vasilyeva et al., 2011; Lutfalla et al., 2017). These data do not utilize isotopes or determine physical losses by leaching and erosion, and therefore do not allow actual mineralization rates to be quantified. Rather, the biochar and char C remaining can be understood as a minimum value below which persistence will not fall over decadal to millennial time scales.

Pyrolysis temperature is used for this methodology, as it is more easily available than biochar property measurements for country-wide estimation. Methods could employ biochar property measurements, e.g., H/Corg (Lehmann *et al.*, 2015) or O/Corg (Spokas, 2010) ratios, together with country-specific soil properties, temperatures and moisture regimes, but these properties are not considered in this method.

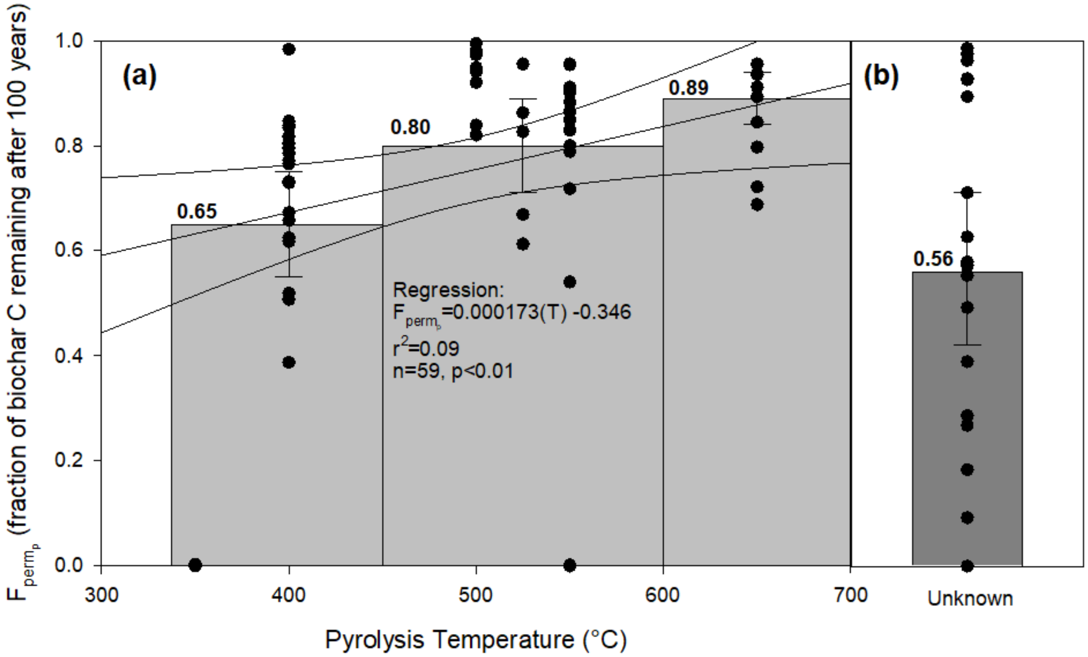

Figure 4Ap.1 F_{perm_p} calculated from field and laboratory studies for biochars that were made under different conversion conditions: (a) F_{perm_p} estimated for biochars with known production temperatures by fitting a two-pool double-exponential model to 59 datasets from eight mineralization experiments that exceeded one year and allowed a two-pool model to be fitted and adjusted to a decomposition temperature of 20°C recalculated as shown in Lehmann *et al*. (2015) (Sources of data include: Major *et al*. 2010; Zimmerman 2010; Singh *et al.* 2012; Zimmerman & Gao 2013; Fang *et al.* 2014; Herath *et al.* 2015; Kuzyakov *et al.* 2014; Dharmakeerthi *et al.* 2015; Wu *et al.* 2016); (b) F_{perm_p} estimated for naturally occurring chars and added biochars with unknown production temperatures using 20 observations from eight long-term field assessments (decadal to millennial time scales) where physical export is not determined (Cheng et al., 2008; Hammes et al., 2008; Lehmann et al., 2008; Liang et al., 2008; Nguyen et al., 2008; Vasilyeva et al., 2011; Lutfalla et al., 2017; mean residence times taken directly from the sources without recalculation).

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