land

MDPI

Supplementary Materials

Supplementary S2: Biochar soil effects

1. Soil carbon sequestration

The majority of the C present in the biochar is in a highly stable state and has a mean residence time of 1000 years [1–4]. The carbon sequestration effect of biochar comes from its resistance to biological, chemical, and physical degradation in soils. However, the net fraction of carbon that can be effectively sequestered depends on the residence time of biochar in the soil, which is known to be very variable. In this work, the contribution was calculated based on the fixed carbon content of the biochar (80.84%). The carbon stability of biochar was set to 80% over 100 years [4–8], the remaining 20% of the C is degraded and released into the atmosphere as biogenic CO_2. What happens after the first 100 years was not considered here.

Table S1. Soil carbon sequestration data.

Activity/characteristic	Unit	Amount
Carbon remaining in soil after 100 years	%	80%
Fixed carbon in biochar	%	80.84%
Raw biochar applied to soil	kg	637.50
Carbon added to soil	kg	412.28
C to CO_2 factor (kg CO_2/kg C)	-	3.67
CO_2 sequestration (for a F.U. of biochar applied to soil)	kg	1,513.07

The following calculation is an easier way to asses a complicated decay process and therefore there are uncertainties related to this value. To verify this expectation, further analysis and better data are needed.

Carbon added to soil (kg):

$$637.50 \cdot 80\% \cdot 80.84\% = 412.28 \quad (1)$$

C to CO_2 factor (kg CO_2/kg C):

$$44/12 = 3.67 \quad (2)$$

where 12 and 44 is the atomic mass of C and CO_2, respectively; furthermore CO_2 sequestration (kg) was obtained with the following equation:

$$412.28 * 3.67 = 1{,}513.07 \quad (3)$$

2. Greenhouse gas emissions from the soil: nitrous oxide and methane

Land application of biochar has been reported to significantly reduce GHG emissions such as N_2O and CH_4 in diverse agroecosystems.

The effect of biochar on these GHG emissions is highly variable and depends on many factors such as biochar characteristics, soil characteristics, climatic factors, rate of application, etc. Consequently, the literature data are highly variable and case specific.

In this work, only the effects of biochar on N_2O emissions were considered for the following reasons: in literature there are more meta-analysis; the values are affected by a lower variance; the GWP of N_2O is much higher than that of CH_4 (298 vs 25 kg CO_2 eq.). The N_2O formation in soil occurs mainly through nitrification and denitrification processes. N_2O emissions derive from biogeochemical cycling of N sources such as inorganic and organic fertilizer, biological soil and crop fixation, N depositions, mineralization of soil organic carbon and plant litter.

From the examination of 4 scientific articles [9–12], -30% was chosen as a reduction factor for N_2O emissions with a biochar application rate of 25 t ha^{-1} yr^{-1}.

For the assessment of reduced N_2O emissions, the analysis conducted by Lugato et al. (2017) has been used [13]. They run the DayCent biogeochemistry model for more than 11.000 LUCAS (Land Use/Cover statistical Area frame Survey) sampling points under agricultural use in Europe and the results showed that current annual N_2O emissions followed a skewed distribution with a mean value of 2.27 kg N ha^{-1} yr^{-1} [13].

Table S2. N_2O emission data.

Activity/characteristic	Unit	Amount
Raw biochar applied to soil	kg	637.50
Mean annual agricultural soil N_2O fluxes in Europe	kg ha^{-1} yr^{-1}	2.27
N_2O emissions reduction factor	%	30%
Avoided N_2O emissions (for a F.U. of biochar applied to soil)	kg	0.017

Avoided N_2O emission (kg) was calculated as follows in equation (4):

$$\frac{2.27 * 30\% * 637.5}{25{,}000} = 0.017 \tag{4}$$

3. Use of fertilizers

The application of mineral fertilizers is the quickest and easiest way to increase the availability of nutrients and to increase agricultural production. Especially the manufacture of nitrogenous fertilizer is an emissions-intensive process due to the consumption of natural gas as a hydrogen and energy source. Emissions range from 3 kg CO_2 eq. per kg^{-1} N to 10 kg CO_2 eq. per kg^{-1} N, depending upon processing technologies, energy sources and utilization of co-products [14]. Nitrous oxide emissions from added fertilizers and manure occur directly from the soil on which they are applied and indirectly through the translocation of nitrogen by volatilization, leaching and runoff [15–17].

As part of the application to soil, biochar not only sequesters C, but also improves crop performance [18,19] which is the result of improved efficiency in the use of fertilizers. This improvement can therefore reduce the amount of the commercial chemical fertilizers applied. The use of biochar can displace fertilizers use in two ways:

by directly replacing other sources of fertilizer, especially when biochar is produced from nutrient-rich feedstock;

by increasing the efficiency with which fertilizers are used because biochar increases the nutrient retention capacity of the soil.

According to Hammond et al. (2011), 30 t ha^{-1} application of woody biochar for wheat crops can lead to a 10, 5, 5 decrease in N, phosphoric anhydride (P_2O_5), potassium oxide (K_2O) fertilizers, respectively [20]. In this study these values have been scaled considering the application rate of 25 t ha^{-1}. In common practice, in the Marche region, an average of 120 kg ha^{-1} of N fertilizers, 100 kg ha^{-1} of P fertilizers, 30 kg ha^{-1} of K fertilizers are distributed for the cultivation of wheat [21]. Therefore, the total amount of N, P, K fertilizers avoided were calculated as reported in Table S3.

Table S3. Fertilizers saving data.

Activity/characteristic	Unit	Amount
Raw biochar applied to soil	kg	637.50
N fertilizer application for wheat crops	kg ha^{-1}	120.00
P_2O_5 fertilizer application for wheat crops	kg ha^{-1}	100.00
K_2O fertilizer application for wheat crops	kg ha^{-1}	30.00
N fertilizer decrease	%	8.33

P_2O_5 fertilizer decrease	%	4.17
K_2O fertilizer decrease	%	4.17
N fertilizer saved (for a F.U. of biochar applied to soil)	kg	0.21
Mass of P_2O_5 fertilizer saved (for a F.U. of biochar applied to soil)	kg	0.09
Mass of K_2O fertilizer saved (for a F.U. of biochar applied to soil)	kg	0.03

4. Use of irrigation

Biochar improves the ability to retain moisture and soil infiltration in some soils, which can lead to a reduction in the frequency and duration of irrigation. Therefore, applying biochar to irrigated crops and pastures can reduce emissions associated with irrigation process.

In the Marche region (region where the plant is located and where it has been assumed that the biochar will be used) the water volume for irrigation is 2,551.37 m^3 ha^{-1} $year^{-1}$ [22]. The reduction in irrigation requirements deriving from the application of biochar has been estimated by 20% (with a biochar application rate of 25 t/ha and taking into account that the effect lasts one year from application), based on data from the literature [23–25].

Consequently, the avoided water volume for irrigation (m^3), scaled to the F.U., is equal to:

$$\frac{510{,}27 * 637{,}50}{25000} = 13.01 \quad (5)$$

Table S4. Avoided water data.

Title 1	Title 2	Title 3
Raw biochar applied to soil	kg	637.50
Irrigation volumes for the Marche region	m^3 ha^{-1}	2,551.37
Water reduction	%	20%
Avoided water (for 25 t of biochar applied to soil)	m^3	510.27
Avoided water (for a F.U. of biochar applied to soil)	m^3	13.01

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