Journal of Soil Science and Plant Nutrition (2020) 20:1524–1531
https://doi.org/10.1007/s42729-020-00242-w

SHORT COMMUNICATION

Effect of Biochar on Emission of Greenhouse Gases and Productivity of Cardoon Crop (*Cynara cardunculus* L.)

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Received: 6 December 2019 / Accepted: 27 March 2020 / Published online: 15 April 2020

Abstract

Cardoon could be cropped for agro-environmental, industrial, and pharmaceutical purposes. The aim of this study was to assess the effects of biochar on emissions of nitrous oxide (N_2O), carbon dioxide (CO_2), and methane (CH_4), and productivity of cardoon crop. A pot experiment was run outdoors from April to August 2018, with a cardoon plant per pot. The following four treatments, with four replicates each, were applied: control, soil only; mineral, soil amended with mineral fertilizer (2.5 g N m^{-2}); biochar, soil amended with biochar (1 kg m^{-2}); and mineral+biochar, soil amended with mineral fertilizer (2.5 g N m^{-2}) and biochar (1 kg m^{-2}). The morphological characteristics and biomass production of cardoon plants were evaluated, and the fluxes of N_2O, CO_2 and CH_4 were measured by using the closed chamber technique. The application of biochar combined with mineral reduced N_2O emissions by 36% and global warming potential (GWP) by 26% relative to mineral. However, the cumulative CO_2 and CH_4 emissions as well as yield-scaled GWP were not significantly different among amended soil treatments. Furthermore, the biomass production was increased by 50% by the application of biochar combined with mineral fertilizer relative to mineral. It was concluded that biochar combined with mineral fertilizer is recommended as a pathway mitigation for agro-environmental purposes, because it reduces the global warming potential and could increase the biomass production of cardoon plants.

Keywords Biochar · Methane · Nitrous oxide · Plant biomass · Yield-scaled GWP

Abbreviations

ANOVA	Analysis of variance
DW	Total plant dry weight (g)
GHG	Greenhouse gas
GWP	Global warming potential
H	Plant height (cm)
HLB	Height of lower branch (mm)
ID	Inflorescence diameter (mm)
IDW	Inflorescence dry weight (g)
IL	Inflorescence length (mm)
LDW	Leaf dry weight (g)
NI	Number of inflorescences
NPR	Number of primary ramifications
NS	Number of stems
NSR	Number of secondary ramifications
SDB	Stem diameter at the base (mm)
SDT	Stem diameter at the top (mm)
SDW	Stem dry weight (g)
TAW	Total achene dry weight (g)
TFW	Total flower dry weight (g)
TNI	Total number of inflorescences

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1 Introduction

Cardoon could be cultivated in Mediterranean climatic conditions as a non-food agricultural crop for a wide range of uses. Previous studies reported that cardoon crop has the potential to grow in regions with low rainfall and hot dry summers, being exploited in the following applications: soil and water conservation in agroecosystems (Grammelis et al. 2008), forage for animal feed (Cajarville et al. 1999), production of biomass for bioenergy and wood technology (Fernández et al. 2006; Gominho et al. 2018), cheese coagulant and antimicrobial agent for food technology (Roseiro et al. 2013; Scavo et al. 2019), and extracts for human nutrition and phytochemical and pharmacological uses (Lattanzio et al. 2009; Mileo et al. 2012; Pandino et al. 2011). Thus, cardoon is a multi-purpose and versatile perennial plant adapted to the Mediterranean climate conditions and there is an increasing interest in promoting integrated exploitation of cardoon for different biomass resources and by-products, in order to maximize the crop value (Barracosa et al. 2019). In fact, cardoon can be suggested as a potential alternative crop for conserving the fragile agroecosystems, with low fertility, with positive effects on the environment through water management and soil erosion control (Francaviglia et al. 2016). However, few studies reported the agricultural aspects of the cardoon production, particularly the relationship between N fertilization and crop yield (biomass and seed), quality, and sustainability (Gominho et al. 2018).

Biochar is a carbon-rich material, obtained through the pyrolysis process of organic waste (in the absence of oxygen, at 300–1000 °C), with the potential to reduce greenhouse gas (GHG) emissions, in particular nitrous oxide (N_2O) and methane (CH_4) (Cayuela et al. 2014; Kookana et al. 2011; Nanda et al. 2016). Biochar is increasingly being recognized for its potential role in carbon sequestration, renewable energy, and waste mitigation (Kookana et al. 2011). Additionally, biochar amendments have the potential to improve the key properties of soils and increase crop yields (Brassard et al. 2016; Cayuela et al. 2014; Liu et al. 2019; Nzediegwu et al. 2019).

To our knowledge, no published studies has been made regarding the influence of biochar addition on cardoon crop production. Hence, it was hypothesized that the application of biochar could reduce the emission of GHG and increase cardoon crop yields. Thus, the aim of this study was to assess the effects of biochar on emissions of greenhouse gases (N_2O, CO_2 and CH_4) and productivity (morphological characterization and biomass production) of cardoon crop.

2 Material and Methods

2.1 Experimental

A Dystric Cambisol (WRB 2015) with a loamy-sand texture (446-g kg^{-1} coarse sand (0.2–2 mm), 161-g kg^{-1} fine sand (0.02–0.2 mm), 259-g kg^{-1} silt (0.002–0.02 mm), and 134-g kg^{-1} clay (< 0.002 mm); by the international pipette method) was collected from the arable soil layer (0–300 mm) of an agricultural field cultivated with ryegrass and located in Viseu, Portugal (latitude 40.641618°, longitude − 7.910135°).

The physico-chemical properties of the soil were the following (mean ± standard deviation of 3 replicates): bulk density (by the Keen & Raczkowski method—Wrigth 1934) = 1.1 ± 0.1 g cm^{-3}, pH (H_2O, 1:2.5; EN 1999) = 5.5 ± 0.1, water retention capacity at pF 2.0 (by the gravimetric method, dried in a heater at 105 °C to constant weight for at least 24 h) = 337.0 ± 2.6 g kg^{-1}, organic matter (by the Dumas method—Houba et al. 1989) = 26.2 ± 0.7-g kg^{-1} dry soil, extractable P (by the Enger-Riehm method—Enger and Riehm 1958) = 225 ± 20-mg kg^{-1} dry soil, and extractable K (by the Enger-Riehm method—Enger and Riehm 1958) = 275 ± 3-mg kg^{-1} dry soil.

A pot experiment was run outdoors from April to August 2018, with a cardoon plant per individual pot (Ø = 1000 mm, h = 820 mm). Previously, plants of *Cynara cardunculus* L. var. *altilis* DC. were propagated by offshoots and replanted in individual pots in January 2017.

The following four treatments, with four replicates each, were applied to cardoon pots: (i) control, soil only; (ii) mineral, soil amended with mineral fertilizer; (iii) biochar, soil amended with biochar; and (iv) mineral+biochar, soil amended with mineral fertilizer and biochar. On April 13, 2018, the treatments mineral and mineral+biochar received conventional mineral fertilizer at a rate of 2.5 g N m^{-2} (in ammonium nitrate form), whereas the treatments biochar and mineral+biochar received commercial biochar (Piroeco Bioenergy, S.L., Spain) at a rate of 1 kg m^{-2}, being obtained from wood shavings (Ø = 2 mm) pyrolyzed in a muffle furnace at 900 °C. The main physico-chemical properties of the biochar were the following: granulometry (by the sieving method—Wrigth 1934) = 552 g kg^{-1} with Ø > 0.30 mm, 364 g kg^{-1} with Ø = 0.20–0.30 mm, 41 g kg^{-1} with Ø = 0.15–0.20 mm, and 43 g kg^{-1} with Ø < 0.15 mm; bulk density (by the Keen & Raczkowski method—Wrigth 1934) = 0.1219 g cm^{-3}; pH (H_2O 1:2.5—EN 1999) = 10.0; humidity (by the gravimetric method, dried in a heater at 105 °C to constant weight for at least 24 h) = 20.3 g kg^{-1}; C = 806.0 g kg^{-1}; N = 1.9 g kg^{-1}; H = 2.2 g kg^{-1}; S = 0.4 g kg^{-1} (CNHS by the Dumas method—Houba et al. 1989); extractable P (by the Enger-Riehm method—Enger and Riehm 1958) = 0.7 g kg^{-1}; and extractable K (by the Enger-Riehm method—Enger and Riehm 1958) = 15.7 g kg^{-1}.

Treatments were added homogenously and incorporated (50-mm depth for mineral fertilizer and 150-mm depth for biochar) by hand in each pot. Soil moisture content was maintained close to 30% water filled pore space by drip irrigation during the whole growing season. Weed control was performed manually, and air temperature and rainfall pattern were measured daily (Fig. 1A–B) by a meteorological station (CR800, Campbell Scientific, UK) located in the experimental field.

2.2 Soil Greenhouse Gases and Cardoon Productivity

Fluxes of N_2O, CO_2 and CH_4 were measured from April 13 to July 25, 2018 by using the closed chamber technique as described in detail by Fangueiro et al. (2018) and Marques

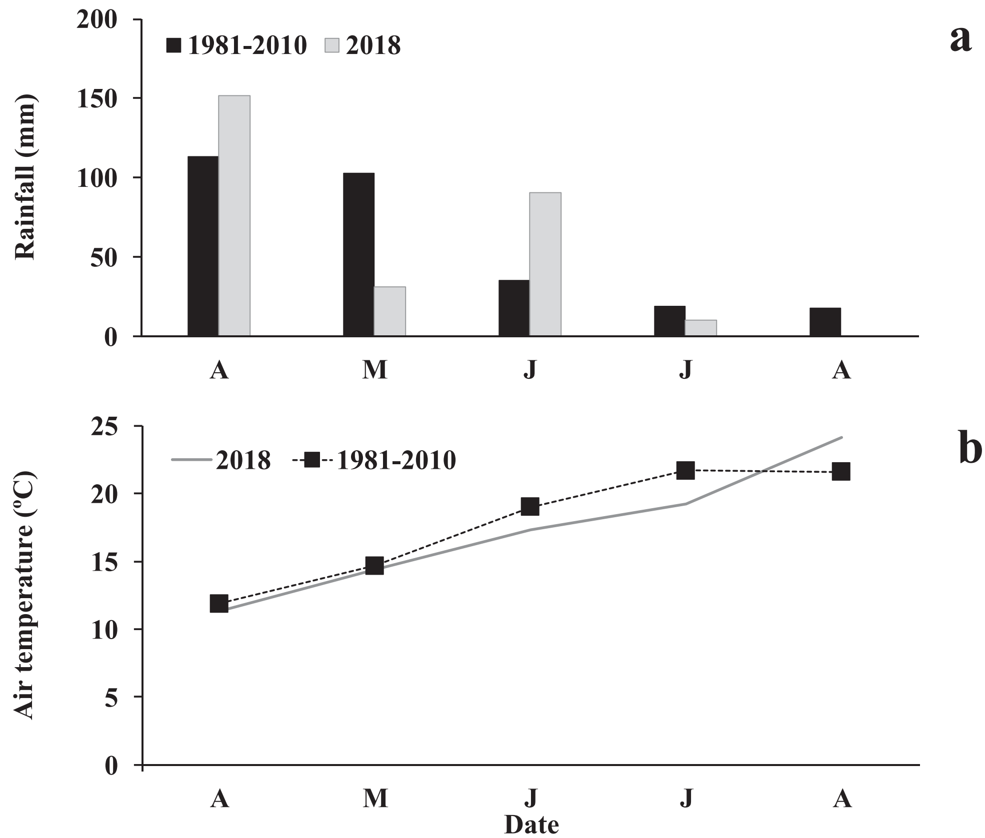

Fig. 1 Monthly cumulative rainfall (A) and monthly average air temperature (B) during the growth of cardoon crop

et al. (2018). Briefly, gas measurements were carried out daily during the first 7 days, every 3 days in the next 2 weeks, and then once a week until the end of the experiment. For evaluating the gas fluxes in each pot, a plastic chamber (Ø = 0.20 m, h = 0.11 m), equipped with a septum to sample the interior atmosphere, was inserted into the soil (depth = 0.03 m). The chamber was kept at fixed locations throughout the sampling dates. After the chamber was closed, a first gas sample (0.025 L) was taken (t = 0 s) using a plastic syringe and flushed through gas vials (0.020 L), and then a second gas sample was taken (t = 3600 s) from the headspace of the chamber and stored in vials. The gas samples were analyzed by using gas chromatography (GC-2014, Shimadzu, Japan) by the following detectors: (i) electron capture ^{63}Ni detector for N_2O (50 ppb to 100 ppm of range of measurements), (ii) thermal conductivity detector for CO_2 (1 ppm to 1% of range of measurements), and (iii) flame ionization detector for CH_4 (0.1 ppm to 1% of range of measurements). The cumulative gas emission and the yield-scaled global warming potential in each treatment were estimated following procedures similar to those described by Fangueiro et al. (2018). The global warming potential (GWP) was determined using the GWP coefficients for N_2O (265), CO_2 (1), and CH_4 (28), and yield-scaled GWP was estimated considering a cardoon density of 10,000 plants ha^{-1}.

The morphological characteristics of cardoon plants were evaluated between July and August 2018, based on International Union for the Protection of New Varieties of Plant descriptors (Barracosa et al. 2018). Thus, the following parameters were evaluated: plant height, number of stems, number of primary and secondary ramifications, number of inflorescences, plant height of lower branch, stem diameter at the base and the top, inflorescence length, and diameter. In order to evaluate biomass production at the harvest (August 27, 2018), all plant material was collected separately, immediately weighed, and oven dried at 65 °C, until a constant weight was reached, to determine the dry matter content of each plant component, namely, leaves, stems, inflorescences, flowers, and achenes.

2.3 Data Analysis

Results (gaseous emissions from soil, morphological characteristics, and biomass production of cardoon) were analyzed (STATISTIX 10, Analytical software, Tallahassee, FL, USA) by using one-way analysis of variance (ANOVA) to test the effects of treatments and time, independently. The statistical significance ($p < 0.05$) of the mean difference between treatments was determined by using the Tukey Honestly Significant Difference test.

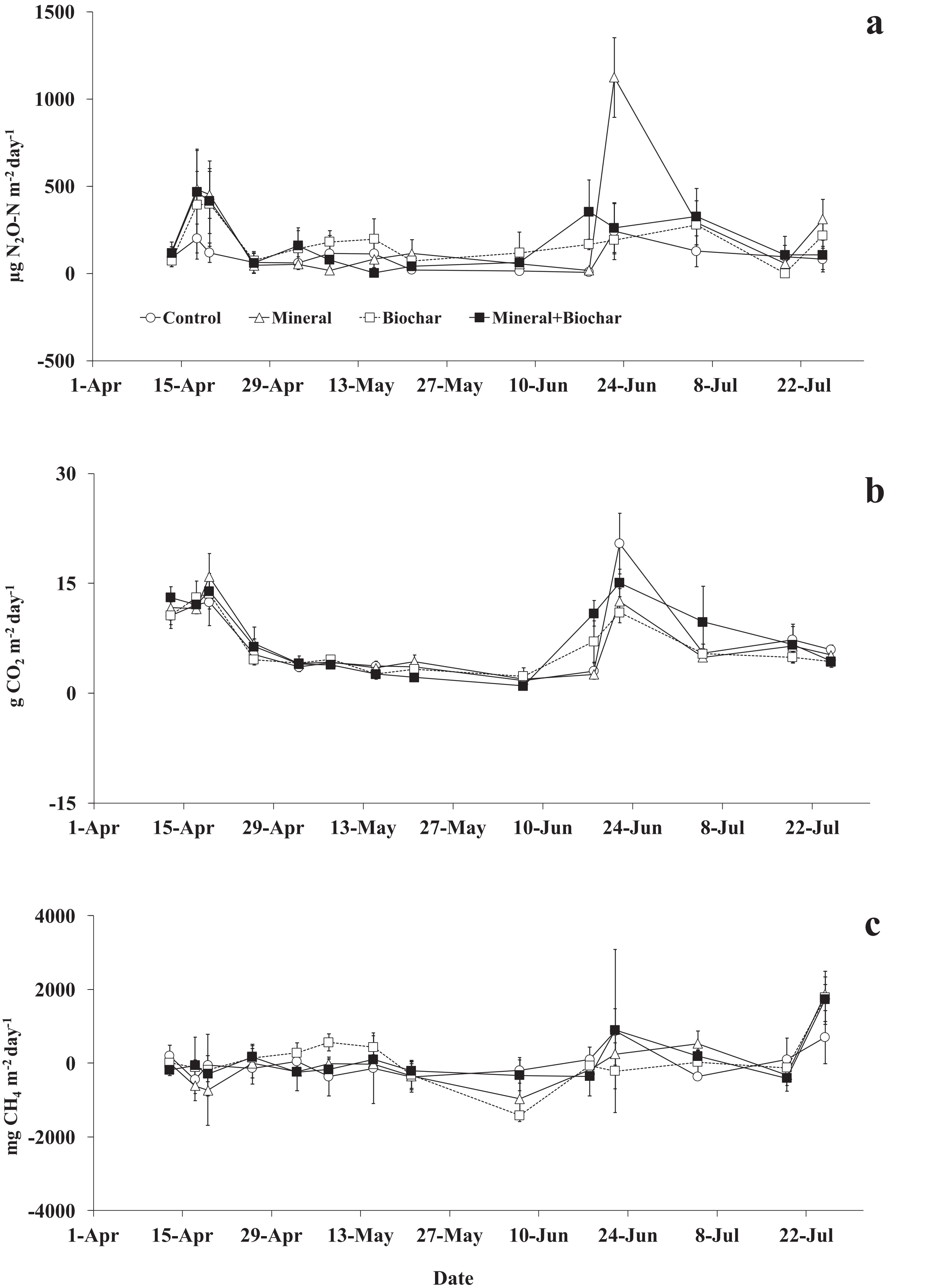

Fig. 2 Fluxes of nitrous oxide (A), carbon dioxide (B), and methane (C) after the application of each treatment in cardoon crop. Vertical bars represent standard deviation ($n = 4$)

Table 1 Cumulative and yield-scaled greenhouse gas emissions by treatment ($n = 4$)

Treatments	N_2O (g N ha^{-1})	N_2O (% N applied)	CO_2 (kg ha^{-1})	CH_4 (kg ha^{-1})	GWP (kg CO_2-eq. ha^{-1})	Yields (kg DM ha^{-1})	Yield-scaled GWP (kg CO_2-eq. kg^{-1})
Control	119 ± 46^{c}		8542 ± 335^{a}	178 ± 329^{b}	$45{,}063 \pm 20147^{b}$	7864 ± 739^{b}	5.7 ± 2.3^{b}
Mineral	327 ± 47^{a}	1.31 ± 0.19^{a}	7809 ± 624^{a}	479 ± 92^{a}	$107{,}846 \pm 10664^{a}$	9189 ± 508^{ab}	11.9 ± 1.4^{a}
Biochar	240 ± 46^{b}		7276 ± 841^{a}	448 ± 335^{a}	$83{,}383 \pm 17008^{b}$	7626 ± 1214^{b}	12.0 ± 3.4^{a}
Mineral+ biochar	210 ± 51^{b}	0.84 ± 0.20^{b}	8501 ± 857^{a}	561 ± 319^{a}	$79{,}954 \pm 19766^{b}$	$14{,}168 \pm 6328^{a}$	10.2 ± 4.6^{a}

GWP, global warming potential in CO_2-equivalents obtained by the conversion factors of 265 for N_2O and 28 for CH_4; *DM*, dry matter

Values presented with different superscripts within columns are significantly different ($p < 0.05$) by Tukey's test

3 Results and Discussion

3.1 Greenhouse Gases from Soil

The daily fluxes of N_2O increased significantly ($p < 0.05$) in amended treatments (mineral, biochar, and mineral+biochar) relative to the treatment control (Fig. 2A). A similar trend was observed in these treatments during the remaining measurement period. A first peak was observed on April 13–19 (400–490-μg N_2O-N m^{-2} day^{-1}) (Fig. 2A). Then, the N_2O fluxes decreased in all treatments, followed by a second peak on June 18 (200–1100-μg N_2O-N m^{-2} day^{-1}). Comparative to the control treatment, the application of mineral and biochar treatments increased significantly ($p < 0.05$) the N_2O fluxes. In most measurement dates, the N_2O fluxes from the mineral+biochar treatment were significantly ($p < 0.05$) reduced in comparison with the mineral treatment. The cumulative N_2O emission from the mineral treatment was significantly higher ($p < 0.05$) than those from all the other treatments (control, biochar, and mineral+biochar), while no significant difference ($p > 0.05$) was found among biochar and mineral+biochar treatments (Table 1). In fact, the cumulative N_2O emission from the mineral+biochar treatment, expressed as absolute values or as percentage of N applied, was significantly ($p < 0.05$) reduced in 36% in comparison with the mineral treatment (Table 1).

As reported in Table 1, the cumulative N_2O emissions from the biochar treatment increased significantly ($p < 0.05$) relative to the control treatment, which may be related with the N content (1.9 g N kg^{-1}) of the biochar used. Results of the present work are in contrast with previous studies (Cayuela et al. 2014; Liu et al. 2019), which showed that biochar played significant roles in mitigating N_2O. The C/N ratio, pyrolysis conditions, biochar and N fertilizer application rates, soil texture, and pH were suggested to be the main factors which can mitigate N_2O emission due to biochar addition (Kookana et al. 2011). In addition, biochar reduced N_2O emissions by the following mechanisms: (i) large specific surface area and strong sorption capacity (NH_4^+ and NO_3^-) by decreasing inorganic N pool and then inhibiting nitrification and denitrification processes (Cayuela et al. 2014) and (ii) increase of soil aeration, due the high oxygen concentration in the biochar, will inhibit the denitrification process (Ameloot et al. 2016).

The daily fluxes of CO_2 did not differ significantly ($p > 0.05$) among treatments and followed a similar trend in the remaining measurements. A first peak was observed on April 13–19 (12–16-g CO_2 m^{-2} day^{-1}) and a second one on June 22 (11–15-g CO_2 m^{-2} day^{-1}) (Fig. 2B). No significant difference ($p > 0.05$) of cumulative CO_2 emissions was observed between treatments (Table 1).

Previous studies (Fidel et al. 2019; Maucieri et al. 2017; Oo et al. 2018; Yang et al. 2019) reported that biochar could

Table 2 Morphological characteristics of cardoon plants by treatment ($n = 4$)

Treatments	Morphological characteristics H	NS	NPR	NSR	NI	TNI	HLB	SDB	SDT	IL	ID
Control	129 ± 26^{a}	2 ± 1^{b}	4 ± 1^{a}	5 ± 1^{a}	7 ± 2^{a}	13 ± 7^{b}	91 ± 20^{b}	22 ± 4^{b}	10 ± 1^{b}	65 ± 2^{a}	75 ± 1^{a}
Mineral	138 ± 16^{a}	3 ± 1^{ab}	2 ± 1^{b}	1 ± 1^{b}	3 ± 1^{b}	13 ± 1^{b}	102 ± 18^{a}	14 ± 2^{b}	11 ± 1^{ab}	65 ± 1^{a}	72 ± 3^{a}
Biochar	126 ± 7^{a}	3 ± 1^{ab}	3 ± 1^{ab}	1 ± 1^{b}	5 ± 1^{b}	11 ± 1^{b}	102 ± 15^{a}	17 ± 2^{b}	11 ± 1^{ab}	62 ± 3^{a}	73 ± 1^{a}
Mineral+ biochar	152 ± 25^{a}	4 ± 1^{b}	3 ± 1^{ab}	4 ± 3^{a}	8 ± 4^{a}	18 ± 8^{a}	110 ± 17^{a}	27 ± 10^{a}	12 ± 1^{a}	65 ± 2^{a}	77 ± 3^{a}

H Plant height (cm), *NS* number of stems, *NPR* number of primary ramifications, *NSR* number of secondary ramifications, *NI* number of inflorescences, *TNI* total number of inflorescences, *HLB*, height of lower branch (mm), *SDB* stem diameter at the base (mm), *SDT* stem diameter at the top (mm), *IL* inflorescence length (mm), *ID* inflorescence diameter (mm)

Values presented with different superscripts within columns, are significantly different ($p < 0.05$) by Tukey's test

Table 3 Biomass production of cardoon plants by treatment ($n = 4$)

Treatments	Biomass production LDW	SDW	IDW	DW	TFW	TAW
Control	269 ± 116^{b}	231 ± 116^{b}	329 ± 216^{b}	786 ± 511^{b}	50 ± 24^{b}	40 ± 14^{b}
Mineral	317 ± 23^{ab}	205 ± 23^{b}	397 ± 23^{ab}	919 ± 51^{ab}	47 ± 4^{b}	31 ± 7^{b}
Biochar	284 ± 40^{b}	159 ± 40^{b}	307 ± 42^{b}	763 ± 121^{b}	40 ± 4^{b}	36 ± 8^{b}
Mineral+ biochar	402 ± 146^{a}	412 ± 146^{a}	603 ± 248^{a}	1417 ± 633^{a}	75 ± 34^{a}	73 ± 26^{a}

LDW Leaf dry weight (g), *SDW* stem dry weight (g), *IDW* inflorescence dry weight (g), *DW* total plant dry weight (g), *TFW* total flower dry weight (g), *TAW* total achene dry weight (g)

Values presented with different superscripts within columns, are significantly different ($p < 0.05$) by Tukey's test

increase, decrease, or not affect the CO_2 released from the soil, according the rate of biochar applied to the soil. In this study, the cumulative CO_2 emissions from the mineral+biochar treatment were increased, but not significantly, in 9% relative to the mineral treatment (Table 1). The reasons pointed out are (i) the increase of the CO_2-C released from soil due to the labile organic material (by the activation of microorganisms) remained in biochar after pyrolysis and (ii) biochar itself generate CO_2 due to its inherent labile organic material (carbon availability after decomposition of incomplete pyrolyzed carbohydrates) (Luo et al. 2011; Singla et al. 2014). However, it should be noted that cumulative CO_2 emission in the mineral+biochar treatment was similar to those measured in the control treatment, which needs more research for proper evaluation.

From April 13 to June 18 were observed negative values of CH_4 daily fluxes (− 1417-mg CH_4 m^{-2} day^{-1}) in the amended treatments, with exception of the biochar treatment with positive values observed (280–430-mg CH_4 m^{-2} day^{-1}) between April 26 and May 15. After that, positive values have been observed in all treatments until the end of the measurement period (Fig. 2C). However, cumulative CH_4 emissions were not significantly different ($p > 0.05$) between amended soil treatments (Table 1). Although no significant reduction of CH_4 emissions were observed in this study in biochar-amended soils, increasing biochar incorporation brings soil aeration, promoting CH_4 oxidation rate and consequently increasing soil CH_4 uptake (Brassard et al. 2016). Thus, previous studies (Brassard et al. 2016; Cayuela et al. 2014; Kookana et al. 2011; Liu et al. 2019) reported that GHG emissions may be suppressed over time by using biochar as an amendment.

The GWP, expressed as CO_2-equivalents, was significantly higher ($p < 0.05$) in the mineral treatment than in the other treatments. In addition, the GWP from the mineral+biochar treatment was significantly lower ($p < 0.05$) by 26% relative to the mineral treatment (Table 1). The yield-scaled GWP was not significantly different ($p > 0.05$) among amended treatments, although numerically lower (− 14%) in the mineral+biochar treatment relative to the mineral treatment (Table 1). These results disagree with a recent study (Liu et al. 2019) about the impact of biochar application on yield-scaled greenhouse gas intensity (GHGI), where biochar significantly decrease GHGI by 23–54%, but are in agreement that biochar had no effect on GHGI when no N fertilizer was applied. Thus, biochar amendment had no effect on yield-scaled GWP without the application of N fertilizer but may have the potential to reduce GWP when N fertilizer was applied.

3.2 Cardoon Productivity

The morphological characterization and biomass production are presented in Tables 2 and 3. The plant height (H), number of stems (NS), plant height of lower branch (HLB), inflorescence length (IL), and inflorescence diameter (ID) did not differ significantly ($p > 0.05$) between amended soil treatments (Table 2). The number of secondary ramifications (NSR), number of inflorescences (NI), total number of inflorescences (TNI), and stem diameter at the base (SDB) from the mineral+biochar treatment were significantly higher ($p < 0.05$) when compared with mineral and biochar treatments (Table 2). The leaf dry weight (LDW), inflorescence dry weight (IDW), and total plant dry weight (DW) from the mineral+biochar treatment were significantly higher ($p < 0.05$) by about 50% relative to the biochar treatment (Table 3). Also, the stem dry weight (SDW), total flower dry weight (TFW), and total achene dry weight (TAW) from the mineral+biochar treatment increased significantly ($p < 0.05$) by about 50% relative to mineral and biochar treatments (Table 3).

Previous studies (Cayuela et al. 2014; Han et al. 2019; Nanda et al. 2016; Yang et al. 2019) reported that the application of biochar to soils has shown advantages in the growth of various crop production, namely through the improvement of soil biological activities, nutrients retention, water retention capacity, increase of pH value, and amount of soil organic matter. The soil used in the present study was collected in an agricultural field with high fertility (pH = 5.5, organic matter = 2.6%, high extractable P and K), which may explain the high cardoon productivity in the control treatment and the absence of significant differences ($p > 0.05$) relative to amended treatments. Thus, relatively to mineral N fertilizer itself, the present study reports that biochar combined with mineral N fertilizer seems to had a positive effect on the increase of biomass production (+ 54% than the mineral treatment) (Table 1). However, further long-term field experiments are needed to confirm these inferences.

4 Conclusions

The following conclusions can be obtained from the results of this study:

(1) The application of biochar combined with mineral reduced N_2O emissions by 36% and global warming potential by 26% relative to mineral. However, the cumulative CO_2 and CH_4 emissions as well as yield-scaled global warming potential were not significantly different among mineral and biochar alone or in combination. Furthermore, cardoon production was increased by 50% by the application of biochar combined with mineral fertilizer relative to mineral.

(2) Biochar combined with mineral fertilizer is recommended as a mitigation procedure for agro-environmental purposes, because it reduces the global warming potential and could increase the biomass production of cardoon plants.

Acknowledgments The authors acknowledge the Reviewers for their comments and suggestions.

Funding Information This work was supported by National Funds by FCT - Portuguese Foundation for Science and Technology, under the project UIDB/04033/2020, and projects CYN.STRESS PROJ/CI&DETS/CGD/0011, WASTE2VALUE PDR2020-1.0.1-FEADER-032314, and WASTECLEAN PROJ/IPV/ID&I/019.

Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no conflict of interest.

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