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RESEARCH ARTICLE

Soil carbon dioxide (CO_2) fluxes in permanent upslope pasture and downslope riparian buffers with varying vegetation

Jerry Celumusa Dlamini[1,2,3] | Eyob Habte Tesfamariam[3] | Robert Dunn[2] | J. Evans[4] | Jane Hawkins[2] | Martin Blackwell[2] | Adrian Collins[2] | Laura Cardenas[2]

[1]Department of Soil, Crop and Climate Sciences, University of the Free State, Bloemfontein, South Africa

[2]Sustainable Agriculture Sciences, Rothamsted Research, North Wyke, Okehampton, Devon, UK

[3]Department of Plant and Soil Sciences, University of Pretoria, Hatfield, South Africa

[4]Computational and Analytical Sciences, Rothamsted Research, West Common, Harpenden, Hertfordshire, UK

Correspondence
Jerry Dlamini, Department of Soil, Crop and Climate Sciences, University of the Free State, Bloemfontein, 9300 South Africa.
Email: DlaminiJC@ufs.ac.za

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Abstract

Background: Riparian buffers are primarily implemented for their water quality functions in agroecosystems. Their location in the agricultural landscape allows them to intercept and process pollutants from immediately adjacent agricultural land. Vegetated riparian buffers recycle soil organic matter, which elevates soil carbon (C), which upon processing, processes and releases carbon dioxide (CO_2). The elevated soil C and seasonally anoxic environments associated with riparian buffers promote denitrification and fermentation, further increasing soil CO_2 production.

Aim: Against this context, a replicated plot-scale experiment was established at North Wyke, UK, to measure the extent of soil CO_2 emissions in permanent pasture served by grass, willow, and woodland riparian buffers, as well as a no-buffer control.

Methods: Soil CO_2 was measured using the static chamber technique in conjunction with soil and environmental variables between June 2018 and February 2019.

Results: Cumulative soil CO_2 fluxes were in the descending order: woodland riparian buffer; 11,927.8 ± 1987.9 kg CO_2 ha^{-1} > no-buffer control; 11,101.3 ± 3700.4 kg CO_2 ha^{-1} > grass riparian buffer; 10,826.4 ± 2551.8 kg CO_2 ha^{-1} > upslope pasture; 10,554.6 ± 879.5 kg CO_2 ha^{-1} > willow riparian buffer; 9294.9 ± 1549.2 5 kg CO_2 ha^{-1}. There was, however, no evidence of significant differences among all treatments of the current study.

Conclusions: Despite the lack of significant differences, the results from our short-term study show that the woodland riparian buffer had relatively larger soil CO_2 emissions than the remainder of the other riparian buffers and the upslope pasture it serves. Our short-term findings may be useful in developing soil CO_2 mitigation strategies through careful selection of riparian buffer vegetation and may be useful in calibrating mechanistic models for simulating such emissions from similar agro systems.

KEYWORDS
novel grass, permanent pasture, riparian buffers, willow, woodland

1 | INTRODUCTION

Riparian buffer strips are best management practices for protecting freshwater ecosystems from various pollutants, including nitrogen (N), phosphorus (P), pesticides, and herbicides, emanating from agricultural lands (Jacinthe et al., 2015; Tonderski, 1996; Valkama et al., 2019). On top of providing various environmental and ecosystem services, the juxtaposition of riparian buffer strips in an agricultural landscape allows them to abate and process pollutants through several processes, including mineralization and denitrification (Jaynes & Isenhart, 2014; Naiman & Decamps, 1997).

FIGURE 1 A schematic diagram of the replicated experimental plots and their location at NorthWyke, United Kingdom.

Against the context of soil and water conservation benefits, through their vegetation, riparian buffer strips recycle organic matter (OM), elevating soil organic carbon (C; Blazejewski et al., 2009), which accelerates carbon dioxide (CO_2) production through C-mineralization and microbial respiration in soils (Tufekcioglu et al., 2001). For instance, Franzluebbers et al. (2000), Harrison-Kirk et al. (2013), and Lundquist et al. (1999) reported that an increase in soil organic carbon (SOC) increases C mineralization, thereby resulting in subsequent CO_2 emissions from soils. This implies that although a remarkable amount of atmospheric C in riparian buffer vegetation is sequestered in the vegetative component via photosynthesis, the soil component can be a significant source of CO_2 through increased microbial respiration (Capon et al., 2013). A few authors have raised concerns about CO_2 emissions from vegetated riparian zones, which could invalidate their C sequestration potential (Vidon et al., 2016) and their soil and water conservation roles (Mitsch et al., 2001; Sabater et al., 2003). Atmospheric CO_2, some of which is sourced from soils, is one of the major greenhouse gases and impacts global warming (Ray et al., 2020).

Despite the role of CO_2 in the greenhouse gas effect and the potential role of riparian buffers in CO_2 emissions, the understanding of the functional traits driving soil respiration CO_2 emissions in riparian buffer zones (De Carlo et al., 2019; Soosaar et al., 2011) in comparison with emissions and drivers in adjacent agricultural land remains elusive and poorly quantified (Jacinthe et al., 2015). Our study aims to (1) identify short-term soil and environmental drivers of soil CO_2 from soil respiration in permanent pasture and downslope riparian buffers with varying vegetation, and (2) quantify short-term soil CO_2 emissions from soil respiration in permanent upslope pasture and downslope riparian buffers with varying vegetation.

2 | MATERIALS AND METHODS

2.1 | Site description

The experimental site is Rothamsted Research, North Wyke, Devon, UK (50°46′10″N, 3°54′05″ E; Figure 1). The site is at an altitude of 177 m asl, has a 37-year (from 1982 to 2018) mean annual precipitation of 1033 mm, and mean annual temperature of 10.1°C (Orr et al., 2016). The slope is 8° and soils belong to the Hallsworth series (Clayden & Hollis, 1985), a dystric gleysol (FAO, 2006), with a stony clay loam topsoil comprising of 15.7%, 47.7%, and 36.6% of sand, clay, and silt, respectively (Armstrong & Garwood, 1991), overlying a mottled stony clay, derived from Carboniferous Culm rocks. Below the topsoil layer, the sub-soil is impermeable to water, resulting in seasonal waterlogging; most excess water moves by either surface or sub-surface lateral flow (Orr et al., 2016).

2.2 | Experimental design and treatments

The experiment was laid out as three blocks of four plots with four treatments replicated three times on the 12 plots (Figure 1). The four treatments comprised three different riparian buffer strip vegetation (grass, willow, and woodland riparian buffers) and a no-buffer control, each with a permanent upslope pasture (Figure 1). Each plot was 46 m in length and 10 m wide; the main upslope pasture (area "a" in Figure 1) being 34 m in length (340 m^2) and the buffer strip being 12 m (120 m^2; areas "b" and "c" in Figure 1). Areas "b" were planted with one of the three different riparian vegetation types (10 × 10 m). Area "c" was an untouched strip of existing vegetation measuring 2 × 10 m (Dlamini et al., 2022).

To hydrologically isolate each plot, a plastic-lined and gravel-filled trench was installed to a depth of 1.40 m to avoid the lateral flow of water and associated pollutants, including nutrients. The upslope plot was managed as a three-cut silage crop, with a permanent pasture dominated by ryegrass (*Lolium perenne* L.), Yorkshire fog (*Holcus lanatus* L.), and creeping bentgrass (*Agrostis stolonifera* L.). N (as NH_4^+-N; Nitram), P (as P_2O_5; triple superphosphate), and potassium (K; as K_2O; muriate of potash) were previously split-applied into three silage cutting events, with annual rates of 180 (split: 80, 50, 50), 140 (split: 100, 25, and 15), and 290 (split: 80, 100, and 80 and autumn: 30) kg ha^{-1}, respectively. During the current study, fertilizer was applied all at once in the upslope pasture and no-buffer control at rates of 50, 15, and 80 kg ha^{-1} for N, P, and K, respectively, which were initially recommended by routine soil analysis. Fertilizers were only applied to the upslope pasture, with no fertilization occurring in the riparian buffer strips. Further details for the treatments are described below:

1. No-buffer strip controls: plots without the 12 × 10 m buffer strips. The area of land described as a no-buffer control was always managed precisely as what is described for the permanent upslope pasture (Dlamini et al., 2022).
2. Grass buffer strips: Novel grass buffer strips (*Festulolium loliaceum* cv. Prior)—The novel grass was planted in areas "b" at the end of 2016 at a seeding rate of 5 kg ha^{-1}, a recommended seeding rate for the species in the Devon area. The novel grass hybrid was developed to be a dual-use grass species that provides efficient forage production and could help mitigate flooding by increasing water infiltration (Macleod et al., 2013). During the current study, the 3-year-old hybrid grass was about 80-cm tall and had never been cut since planting in 2016 (Dlamini et al., 2022).
3. Willow buffer strips: Bio-energy crop—five willow cultivars, namely, Cheviot, Mourne, Hambleton, Endurance and Terra Nova (all *Salix* spp.); the first three being newly developed cultivars and the latter being older ones. Whips of willow approximately 30 cm in length were inserted to flush into the ground in May 2016 at a population of 200 plants per 10 × 10 m area, a recommended planting density for willow plants in the Devon area. The willow cultivars were chosen from the National Willow Collection based at Rothamsted Research, Harpenden site, based on their suitability to grow in the wet clay-rich soils of the Devon site. They were also chosen based on their high capacity for pollutant uptake and their wide use for soil bioremediation (Aronsson & Perttu, 2001). During the current experiment, the 3-year-old willow trees were about 3-m tall and had not been cut since planting in 2016 (Dlamini et al., 2022).
4. Woodland buffer strips: Deciduous woodland—six species, namely, pedunculate oak (*Quercus robur* L.), hazel (*Corylus avellana* L.), hornbeam (*Carpinus betulus* L.), small-leaved lime (*Tilia cordata* Mill.), sweet chestnut (*Castanea sativa* Mill.) and wych elm (*Ulmus glabra* Huds.) were planted in the woodland buffer strip areas. Five individual plants (each 40 cm in height and bare rooted) of each species were planted 1.6 m apart in rows 2-m apart in December 2016 in the 10 × 10 m riparian buffer area, with 1.5 m tall protection tubes used to remove the risk of browsing by wild herbivores (e.g., deer). Planting was done at a density of 3000 plants ha^{-1}, a recommended planting density for the Devon area. The woodland species were chosen based on their ability to respond well to coppicing. The choice was also based on financial incentives for planting woodland along riparian buffer zones, as well as its potential for water quality improvement (Sydes & Grime, 1981). The buffer choice was also fitted with the local agri-environment payment scheme available at the time (Countryside Stewardship) for a riparian buffer zone, so it would be something that farmers with watercourses would be able to financial incentive to plant these trees in their riparian buffer areas. The 3-year-old woodland trees were 1.6 m tall during the current experiment and had never been cut since planting in 2016 (Dlamini et al., 2022).

Area "c" is the requirement for cross-compliance in England whereby farmers with watercourses must adhere to Good Agricultural and Environmental Condition (GAEC) rule 1; establishment of buffer strips along watercourses (DEFRA, 2019). All of the areas within the 10 × 10 m (10 m width is a GAEC recommended N fertilizer application distance away from surface waters)-managed riparian buffer strips were sprayed with glyphosate to remove the existing vegetation in spring 2016. The grass buffer strips were cultivated, and the seed was sown as described above, while the willow and woodland buffers had the trees planted within the swathe of dead grass.

2.2.1 | Sampling design

Each plot consisted of the main crop area with one chamber and either a control (no-buffer) area with a single chamber or a buffer area (sown with one of three riparian buffer vegetation covers) that had two chambers (upper and lower). The three no-buffer control plots in the experiment had a chamber box situated at a similar position on the slope to where the buffer strip boxes were, but they were still part of the fertilized crop area (Figure 1).

2.3 | Field measurements and laboratory analysis

2.3.1 | CO_2 measurements

Field sampling and lab analysis

CO_2 fluxes were measured using the static chamber technique (Chadwick et al., 2014; De Klein & Harvey, 2012). The polyvinyl chloride (PVC) chambers were square frames with lids (40 cm width × 40 cm length × 25 cm height) with an internal base area of 0.16 m^2. Thirty-three chamber collars were inserted to a depth of 5 cm below the soil surface using a steel base, and installation points were marked using a hand-held global positioning system (Trimble) so that they could be precisely replaced after removing them during agronomic practices, that is, silage cutting. In the willow and woodland riparian buffer strips, chambers were installed in-between two rows, while in the upslope pasture, no-buffer strip control, and grass riparian buffer strips, chambers were installed in pre-determined positions (Figure 1). More specifically, the chambers were positioned as follows: (1) in area “a,” there was one chamber near the upslope margin of the plot (subsequently referred to as area “a” top chamber); in the no-buffer strip control plots, there was an additional chamber near the lower margin of the plot (called area “a” bottom chamber); (2) in area “b,” there were two chambers, one near the upper and one near the lower margins of the buffer strip (subsequently referred to as area “b” upper and lower chambers, respectively). Gas sampling was conducted periodically from June 2018 to February 2019, between 10:00 a.m. and 1:00 p.m., using 60-mL syringes and pre-evacuated 22-ml vials fitted with butyl rubber septa. A gas sampling plan was developed at the beginning of the experiment with biweekly samplings after fertilizer application and less frequently (i.e., once or twice a month) afterward, making up 18 sampling events for the whole experimental period (Dlamini et al., 2022). On each sampling occasion, gas samples were collected at four-time intervals (0, 20, 40, and 60 min) from three random chambers to account for the non-linear increase in gas concentration with deployment time and to assess the quality of the calculated flux (Grandy et al., 2006). The linearity sampling chambers were randomly changed all the time during sampling events and were regardless of treatment or position in the field. The remaining chambers were sampled terminally at 40 min after closure (Chadwick et al., 2014). Additionally, 10 ambient gas samples were collected adjacent to the experimental area: five at the start and five at the end of each sampling event. CO_2 concentrations were measured using a Perkin Elmer Clarus 500 gas chromatograph (Perkin Elmer Instruments) fitted with an electron capture detector after applying a 5-standard calibration.

Determination and calculation of CO_2 flux

As suggested by Conen and Smith (2000), soil CO_2 fluxes were calculated based on the rate of change in concentration (ppm) within the chamber, which was estimated as the slope of a linear regression between concentration and chamber closure time. Daily CO_2 fluxes were computed using the Livingston and Hutchinson (1995) model. Cumulative soil CO_2 fluxes were estimated by calculating the area under the gas flux curve after linear interpolation between sampling points (Mosier et al., 1996).

2.3.2 | Soil analysis and meteorological measurements

Soil pH (within-lab precision [RSD]: 0.015) was measured in water (1:2.5 soil: water) (Jenway pH meter), and soil OM was determined using the loss on ignition technique (Wilke, 2005). Composite soil samples (0–10 cm), made up of four random sub-samples, were collected monthly within a radius of 1 m of each chamber using a soil corer with a semi-cylindrical gouge auger (2–3 cm diameter; Poulton et al., 2018). Total oxidized N (comprised of nitrite [NO_2^-] and nitrate [NO_3^-] N, the former considered to be negligible) and ammonium (NH_4^+-N) (within-lab precision [RSD%]: 7.2%) were quantified by extracting field-moist 20 g soil samples using 2 M KCl; 1:5 soil: extractant ratio, and analysis performed using an Aquakem analyzer (Thermo Fisher Scientific). On every gas-sampling occasion, composite soil samples (0–10 cm) made of four random sub-samples were collected within a radius of 1 m from each chamber using the soil corer described above for gravimetric soil moisture determination. Dry bulk density (BD) was determined at the start of the experiment next to each chamber using the core-cutter method (Amirinejad et al., 2011) and used to convert the gravimetric moisture determined during each of the gas sampling events into percent soil water-filled pore spaces (WFPS). Average daily precipitation was acquired from data measured at hourly intervals by an automatic weather station courtesy of the Environmental Change Network at Rowden, NorthWyke (Lane, 1997; Rennie et al., 2020).

2.4 | Statistical analysis

The data were analyzed using linear mixed models (LMMs) in Genstat 20 (VSN International). LMMs were used to determine whether cumulative soil CO_2 fluxes or any measured soil variables (BD, pH, NH_4^+, total oxidized nitrogen (TON), WFPS, and OM) differed with treatment. The random structure of each model (accounting for the structure of the experiment) is *block/plot*. The fixed structure (accounting for treatment effects) is *area /(treatment crop × buffer area)*. The structure gives the following four tests: (1) *treatment area*-tests for any difference between the main crop versus control area versus buffer, (2) *treatment area . treatment crop*—tests for differences between grass, willow, and woodland riparian buffers, (3) *treatment area . buffer area*—tests for the difference between upper and lower chambers within the riparian buffers with differing vegetation, and (4) *treatment area . treatment crop . buffer area*—tests for interaction between riparian buffer type and distance, that is, whether the buffers' upper and lower area differs

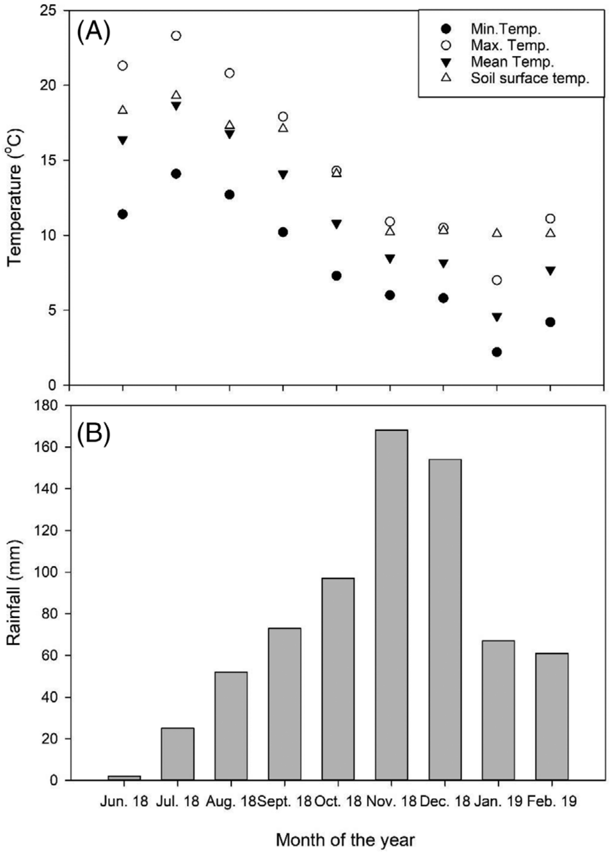

FIGURE 2 Monthly (A) minimum, maximum, and soil surface temperatures, and (B) rainfall during the site during the experimental period

depending on the riparian buffer vegetation (or vice versa). LMMs were also used to assess the relationship between cumulative soil CO_2 fluxes and measured soil variables.

Pearson's correlation coefficient (*r*) was used to indicate the strength of relationships between soil and environmental factors and cumulative soil CO_2 fluxes. This was tested more formally in the LMMs described above. If the LMMs indicated that treatment differences were present, the least significant differences (LSD) were calculated to determine which specific pairs of treatments resulted in the significant differences in cumulative soil CO_2 fluxes. All graphs were generated using SigmaPlot (Systat Software Inc.).

3 | RESULTS

3.1 | Meteorological characteristics

The minimum temperature ranged from 2.2°C (January 2019) to 14.1°C (July 2018), while the maximum temperature ranged from 7.2°C (January 2019) to 23.3°C (July 2018). The mean temperature ranged from 4.6°C (January 2019) to 18.7°C (July 2018). Soil surface temperature ranged from 10.1°C (January 2019) to 19.3°C (July 2018; Figure 2A). Monthly rainfall ranged from 2 to 168 mm, and the total rainfall during the experimental period was 699 mm. The highest rainfall of 168 mm was received during November 2018, while the lowest (2 mm) was received in June 2018 (Figure 2B).

3.2 | Soil and environmental variables

Soil BD ranged between 1.09 ± 0.04 and 1.21 ± 0.05 g cm^{-3}, with the highest BD of 1.21 ± 0.05 g cm^{-3} occurring in the no-buffer strip control and the upslope pasture having a similarly high value (Table 1). This was significantly different from the willow and woodland riparian buffer strip treatments but not the riparian grass buffer strip (*LSD* = 0.14). Soil pH ranged between 5.4 ± 0.17 and 5.5 ± 0.20, and there was no evidence of significant differences (*LSD* = 0.4) between the treatments. The highest concentration of soil OM occurred in the woodland riparian buffer (14.1% ± 0.53%), which was, however, not significantly different from the grass (13.0% ± 0.53%) or willow (13.9% ± 0.53%) riparian buffers but did show evidence of a difference to the no-buffer strip control (10.1% ± 0.69%) and the upslope pasture (9.4% ± 0.29%; *LSD* = 1.9; Table 1).

3.3 | Soil mineral N dynamics

Figure 3 shows the soil N concentrations determined during sampling days. Figure 3A shows that soil TON concentrations during the sampling period were similar between all treatments during the first sampling event before the first silage cut and fertilizer application. During the first sampling day after fertilizer application, an increase in soil TON concentration was detected in all the treatments. The most considerable increase of about 10-fold was detected in the no-buffer control treatment, which showed between 5- and 18 times higher TON concentrations than the vegetated riparian buffer treatments. Following this, peak soil TON concentrations decreased to pre-fertilizer application levels for grass, woodland, and willow riparian buffer treatments. However, they stayed elevated for a more extended period for the no-buffer control treatment and the upslope pasture, which reached similar levels. The most considerable soil TON was observed from the no-buffer control, which was, however, not significantly different from the upslope pasture but did show evidence of a difference to the remainder of the treatments (Table 1). As shown in Figure 3B, the soil NH_4^+-N concentrations during the experimental period behaved the same way as soil TON, except that there was no increase in NH_4^+-N in the grass buffer treatment at the sampling time immediately after fertilizer application. The no-buffer control yielded the largest soil NH_4^+-N significantly, compared to all the other treatments (Table 1).

3.4 | Soil WFPS

Soil WFPS started <70%, following the same trend throughout the experimental period. The largest WFPS peak in all the treatments was observed at the end of November 2018, with the highest value observed from the upslope pasture during the peak (Figure 4A). Soil

TABLE 1 Means (± standard error) of some soil physical and chemical properties of the upslope pasture and the downslope riparian buffer strips during the experimental period. Upslope pasture: $n = 12$, no-buffer control: $n = 3$, grass, willow, and woodland riparian buffer: $n = 6$.

Parameter	Upslope pasture	No-buffer control	Grass buffer	Willow buffer	Woodland buffer	Max. LSD
Bulk density (BD;g cm^{-3})	1.21 ± 0.028	1.21 ± 0.05	1.09 ± 0.041	1.20 ± 0.041	1.19 ± 0.041	0.14
pH	5.5 ± 0.2	5.5 ± 0.20	5.4 ± 0.17	5.5 ± 0.17	5.4 ± 0.17	0.4
Organic matter (OM; % w/w)	9.4 ± 0.3	12.9 ± 0.7	10.1 ± 0.5	13.9 ± 0.5	14.1 ± 0.5	1.9
Water-filled pore spaces (WFPS; %)	66.1 ± 4.3	61.0 ± 6.3	56.5 ± 5.1	63.0 ± 5.1	69.1 ± 5.1	14.3
NH_4-N (mg kg^{-1} dry soil)	12.4 ± 0.8	17.9 ± 1.8	2.34 ± 0.6	7.4 ± 1.9	3.5 ± 0.5	5.1
TON (mg kg^{-1} dry soil)	11.6 ± 0.9	14.7 ± 3.2	1.8 ± 0.3	5.1 ± 0.9	4.2 ± 0.5	4.7

Abbreviation: LSD, least significant differences.

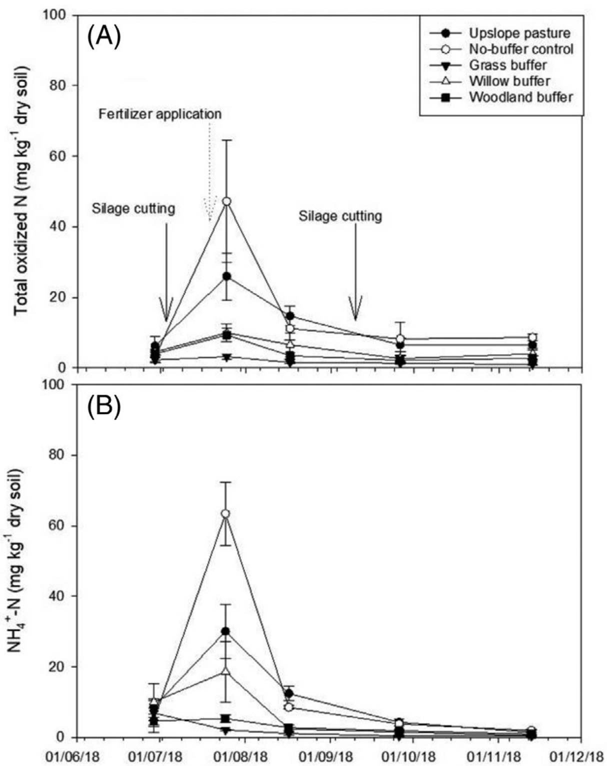

FIGURE 3 Soil TON (A) and NH_4^+-N (B) dynamics for the upslope pasture and the downslope riparian buffers with different vegetation treatments during the experimental period; data points and error bars represent the treatment means (upslope pasture: $n = 12$, no-buffer control: $n = 3$, grass, woodland, and willow buffer: $n = 6$) and standard error (SE) during each sampling event.

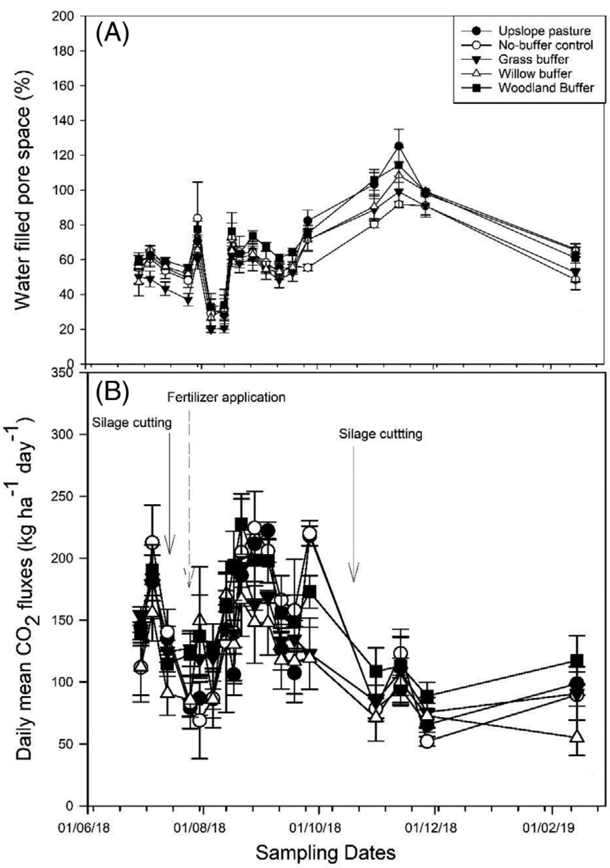

FIGURE 4 Daily soil water-filled pore spaces (WFPS) (A) and carbon dioxide (CO_2) (B) fluxes in the upslope pasture and downslope riparian buffers. Data points and error bars represent the treatment means (cropland: $n = 12$, no-buffer control: $n = 3$, grass, woodland, and willow buffer: $n = 6$) and SE during each sampling day.

WFPS ranged from 56.5% ± 5.10% to 69.1% ± 5.10%, with the highest value measured in the woodland riparian buffer strip (69.0% ± 5.10%), which was, however, only significantly different (*LSD* = 14.3) to the grass riparian buffer strip treatment (Table 1).

3.5 | Variability of soil CO_2 fluxes

Out of the 18 total sampling events in the current study, it is in only nine events where the daily soil CO_2 fluxes were found to be significant amongst treatments, with the woodland riparian buffers having predominantly large fluxes. At the commencement of the experiment, CO_2 fluxes were <160 kg ha^{-1} day^{-1} in all the treatments, with the largest of 153.4 ± 7.4 kg CO_2 ha^{-1} day^{-1} recorded in the grass riparian buffer treatment. At the second sampling event, soil CO_2 fluxes peaked up 212.7 ± 30.3 kg CO_2 ha^{-1} day^{-1} in the no-buffer control treatment, which, however, spiraled down to 69.1 ± 30.7 kg CO_2 ha^{-1} day^{-1} in the same treatment but remained larger in the rest of the treatments. At

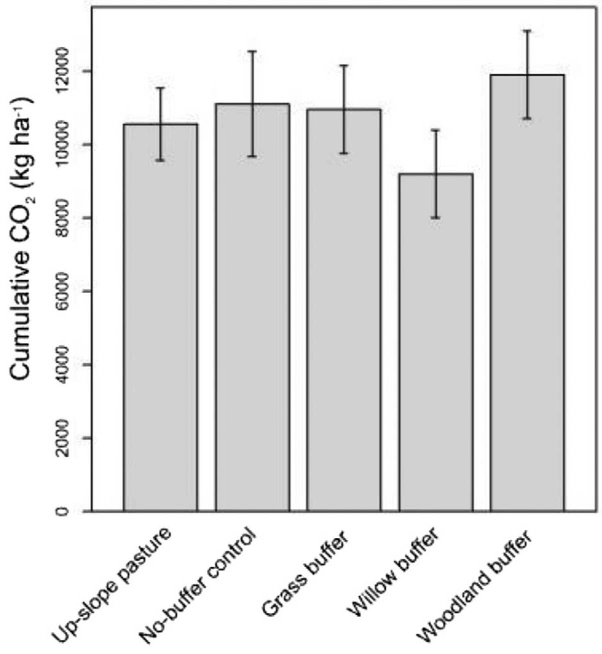

FIGURE 5 Cumulative CO_2 emissions for the whole experimental period from the permanent upslope pasture and different downslope buffer vegetation. Error bars represent 95% confidence intervals (cropland: $n = 12$, no-buffer control: $n = 3$, grass, woodland and willow buffer: $n = 6$). Vertical lines are 95% confidence intervals.

the end of August 2018, we observed a second peak with the largest flux of 228.1 ± 93.1 kg CO_2 ha^{-1} day^{-1}. Afterward, soil CO_2 fluxes in all treatments had a downward spiral until the end of the experiment (Figure 4B). We observed that significant correlations between daily soil CO_2 fluxes and daily rainfall during sampling events 3 ($r = 0.3$; $p = 0.033$), 4 ($r = 0.21$; $p = 0.026$), 10 ($r = 0.11$; $p = 0.027$), 15 ($r = 0.026$; $p = 0.0001$), and 16 ($r = 0.12$; $p = 0.003$). We also recorded significant correlations between daily soil CO_2 fluxes and soil temperature on sampling events 4 ($r = 0.7$; $p = 0.0001$), 8 ($r = 0.59$; $p = 0.042$), 11 ($r = 0.89$; $p = 0.0001$), and 17 ($r = 0.67$; $p = 0.001$).

3.6 | Variability of cumulative soil CO_2 emissions

The current study showed no treatment differences in cumulative soil CO_2 emissions (Figure 5). Soil CO_2 emissions followed the descending order of: woodland riparian buffer; 11,899 ± 1197 kg CO_2 ha^{-1} > no-buffer control; 11101.3 ± 1435 kg CO_2 ha^{-1} > grass riparian buffer; 10,954 ± 1197 kg CO_2 ha^{-1} > upslope pasture; 10,554.6 ± 989 kg CO_2 ha^{-1} > willow riparian buffer; 9196 ± 1197 kg CO_2 ha^{-1}.

3.7 | Relationships of cumulative CO_2 and explanatory variables

There was no evidence of any significant linear relationships between cumulative soil CO_2 emissions and any of the measured soil and environmental variables (Table 2, Figure 6). Although not significant, we observed an increase in cumulative soil CO_2 emissions with every increase in soil pH, WFPS, and OM, and a decrease in cumulative soil CO_2 emissions with every increase in soil BD, NH_4^+-N, and TON (Figure 7).

TABLE 2 *p*-values for the slope of the fitted line of the model for carbon dioxide (CO_2) and measured soil variables.

Variable	Intercept	Standard error intercept	Slope	Standard error slope	*p*-value
BD	14779	5052	−3463	4190.7	0.42
pH	8399	8325	417.1	1515.9	0.79
NH_4	10939	1047	−33.0	60.2	0.59
TON	10887	1064	−26.2	58.3	0.66
WFPS	9993	2756	10.7	41.1	0.81
OM	10262	2023	35.4	155.0	0.82

4 | DISCUSSION

4.1 | Soil and environmental variables and soil CO_2 fluxes

Soil moisture is well documented as one of the significant drivers of soil CO_2 fluxes by several authors, particularly Reth et al. (2005), Dlamini et al. (2020), Ray et al. (2020), and Adams et al. (2021). Similar to the previous authors, expansive soil CO_2 fluxes in all the treatments followed immediately after increases in soil WFPS, particularly in the first 4 months of the current study. The previous authors, particularly Dlamini et al. (2020) reported that denitrification, induced by high soil moisture conditions, is carried by facultative anaerobes, producing free energy, N gas (N_2), and CO_2, as a result of electron transfer between NO_3^- and C. This process is known to be dependent on soil C-supply and accounts for about 37% of CO_2 produced in the soil respiration system (Rastogi et al., 2002). Also, Ray et al. (2020) found that CO_2-producing soil respiration increased with soil moisture following rainfall events, similar to observations of the current study where on a number of events, we found significant correlations between daily rainfall and soil CO_2 fluxes. The previous author credited such CO_2 increase after rainfall and subsequent soil moisture increase to stimulated microbial activities, including soil respiration.

Soil temperature is one of the most important factors of soil CO_2 production through respiration (Hou et al., 2014; W. Wang et al., 2019). Similar to the previous authors, in all the treatments of the current study, a majority of the higher CO_2 fluxes coincided with higher atmospheric and soil surface temperatures, and fluxes decreased with decreasing temperatures (Figures 2A and 4B). We also found significant correlations between soil temperature and daily soil CO_2 in numerous sampling events in the current study. The previous authors reported that high soil temperatures drive CO_2-producing soil microbial reactions, including soil respiration.

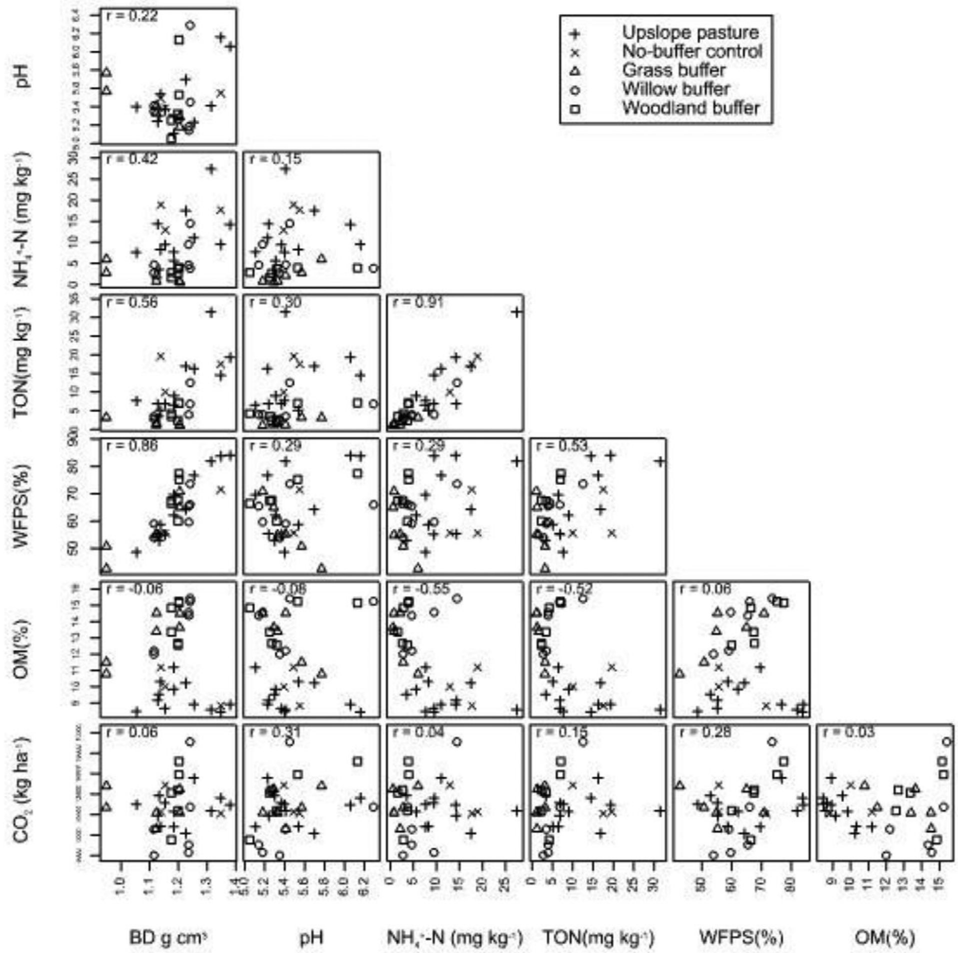

FIGURE 6 Scatterplot showing the relationships between the variables pH, soil NH_4^+-N, soil TON, WFPS%, organic matter (OM), bulk density (BD), and cumulative CO_2 emissions for the permanent upslope pasture and the downslope riparian buffers with different vegetation treatments. *r* = Pearson's correlation coefficient.

4.2 | CO_2 emissions in permanent pastures and different buffers

The woodland riparian buffer had relatively larger cumulative CO_2 emissions than the remainder of the treatments due to its relatively higher soil OM, similar to other authors, particularly Ussiri and Lal (2009) and Setia et al. (2011). The previous authors found that soil OM mineralization in soils results in CO_2 evolution; hence, vegetation that recycles higher OM is most likely to produce higher CO_2. Also, soil NH_4^+-N is known to inhibit soil methane oxidation into CO_2 (Bian et al., 2019; Y. Wang et al., 2014); thus, the higher soil CO_2 was expected in the woodland riparian buffer since the vegetated riparian buffers were not directly fertilized. The values observed in the current study are in line with other authors, particularly Tufekcioglu et al. (2001) and Jacinthe et al. (2015), who reported higher cumulative soil CO_2 values in riparian buffers, compared to immediately adjacent croplands. For example, Jacinthe et al. (2015) found soil CO_2 emissions of 4850 and 8630 kg C ha^{-1} $year^{-1}$ in tree and grass riparian buffers, respectively, and 2560 and 4540 kg C ha^{-1} $year^{-1}$ in their respective immediately adjacent croplands (Table 3) in a humid sub-tropical and cold continental climates, respectively.

5 | CONCLUSION

The current study's finding shows that the woodland riparian buffers may emit relatively larger soil CO_2 than other riparian buffers and the upslope pasture it serves. Thus, these findings suggest that in the short term the woodland riparian buffers may not be the best choice for water quality services as they may risk trading its water quality functions for CO_2 emissions, but the willow riparian buffer had the lowest emissions. We suggest further long-term investigations on cultivated pasture and riparian buffers that serve them, as this short-term study found no evidence of a statistically significant difference. We also suggest a further investigation with different crops, particularly in sites of different soils and environmental conditions, to validate our findings. Our findings may help develop CO_2 mitigation through careful riparian buffer vegetation selection and calibrating mechanistic

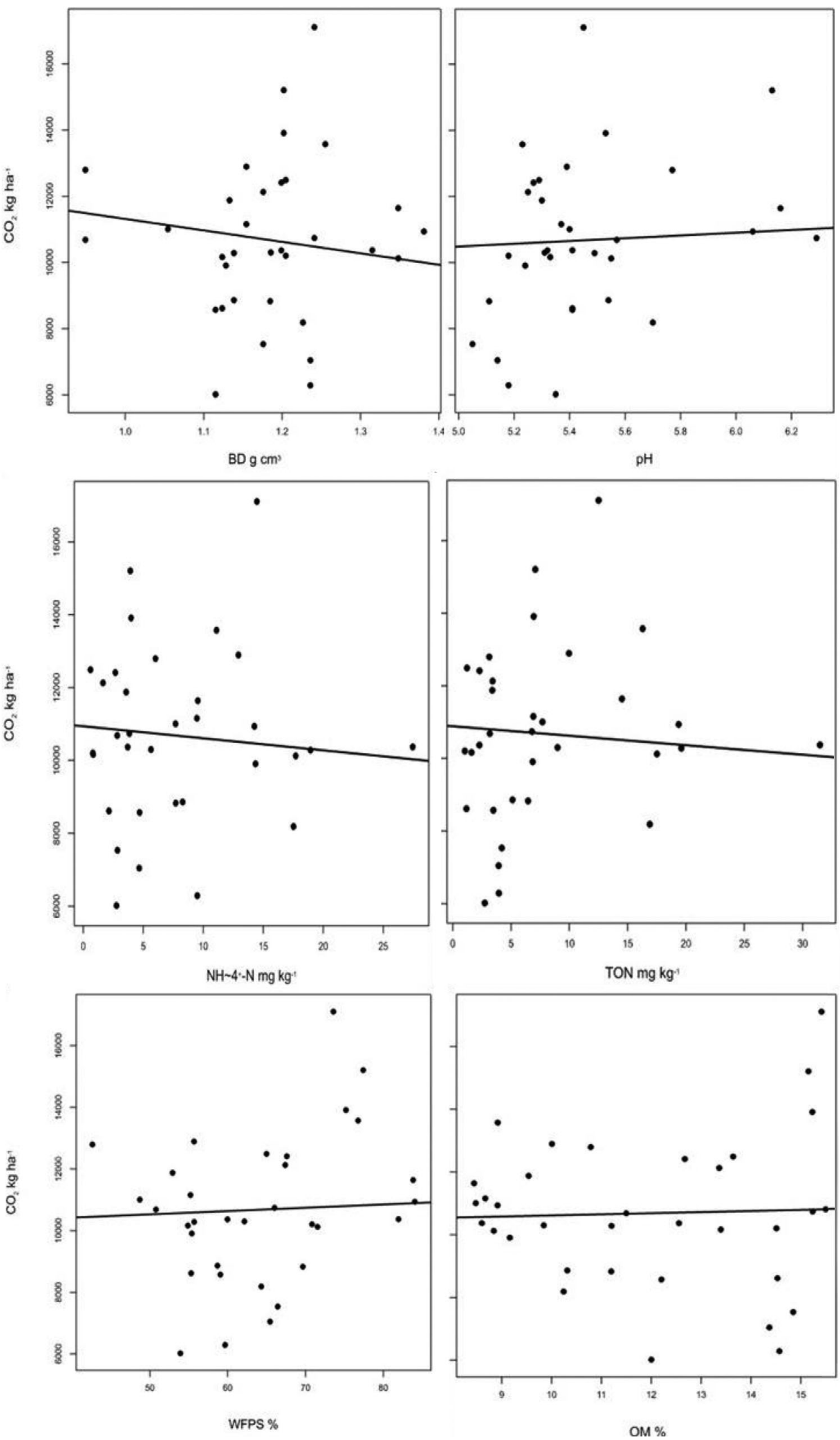

FIGURE 7 Relationships between cumulative CO_2 emissions and each of the explanatory soil variables.

TABLE 3 Some published literature comparing CO_2 emissions between croplands and riparian buffers in comparison to findings of the current study.

Study	Crop type	Riparian buffer vegetation type	CO_2 emissions ($kg\ ha^{-1}\ year^{-1}$)	
			Cropland	Riparian buffer
Jacinthe et al. (2015)	Maize	Forest	2560	4950
Jacinthe et al. (2015)	Maize	Grass	8630	4540
Tufekcioglu et al. (2001)	Maize/soybean	Trees	7692	11,400
Tufekcioglu et al. (2001)	Maize/soybean	Grass	7692	12,758.5
This study	Pasture	No-buffer	10,554.6	11,101.3
This study	Pasture	Grass	10,554.6	10,954
This study	Pasture	Trees	10,554.6	9196
This study	Pasture	Trees	10,554.6	11,899

models that explore CO_2 mitigation measures in cropping systems served by different riparian buffers.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

ORCID

Jerry Celumusa Dlamini https://orcid.org/0000-0003-2968-9553

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