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RESEARCH ARTICLE

Perennial C4 grasses increase root biomass and carbon in sown temperate pastures

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ABSTRACT
The addition of perennial warm-season C4 grasses to perennial pastures, may contribute to carbon sequestration, in addition to increasing production and stabilising seasonal variations. We quantified root biomass in three pasture mixtures after 3 years of growth: a conventional mixture of *Festuca arundinacea*, *Trifolium repens* and *Lotus corniculatus*, the conventional mixture + *Paspalum notatum* and the conventional mixture + *Paspalum dilatatum*. Root biomass and content of carbon were higher at 0–10 cm than at 10–30 cm depth for both summer and winter sampling dates in all samples. Mixtures with *Paspalum* had higher root biomass than the conventional mixture in summer. No differences were observed between the two species of *Paspalum* in root biomass or carbon. These results show that the inclusion of *Paspalum* species in these systems may potentially increase carbon soil carbon, although further research is required to evaluate the effect of other management practices.

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Functional types; *Paspalum notatum*; *Paspalum dilatatum*; roots; sustainability

Introduction

Soil organic carbon is an important component of the global cycle of carbon, constituting approximately 70% of the organic carbon in the biosphere (FAO 2001). Soil organic carbon is one of the main determinants of agricultural productivity, since it is closely associated with soil fertility, structure and ability to retain water. Its abundance affects and is affected plant productivity (Jobbágy and Jackson 2000). Vegetation in natural and agricultural systems has an important role in carbon sequestration in soil ecosystems (Rasse et al. 2005). This effect is central when the contribution to climate change of the balance of greenhouse effect gases is considered. It is then essential to know carbon stocks and their accumulation rates to calculate the carbon footprint of livestock grazing (Picasso et al. 2014; Modernel et al. 2016). Particularly, grassland ecosystems

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are the main biomass producers in temperate regions in the world (Bernhardt-Römermann et al. 2011). For different types of soils in Uruguay, Durán (1998) reported between 117 and 202 tons per hectare of organic carbon at one metre of depth, the highest values corresponding to Vertisols. The percentage of biomass and carbon allocation to belowground structures is about 60%, on average, for these ecosystems (Céspedes et al. 2012). Jackson et al. (1996) found that in grasslands of temperate regions, 83% of the roots are concentrated in the first 30 cm of soil where more intense accumulation and loss processes occur.

Some species possess structures for vegetative propagation that also work as resistance and storage organs and accumulate during adverse seasons. This is the case of grasses with rhizome structures which also have an extensive root system (Vázquez Yanes et al. 1997). Cespitose grasses have a better development at greater depths and therefore under these species, carbon stocks may show lower stratification in the soil.

Sown pastures in temperate regions of South America are usually comprised by a few C3 grass and legume species, offering a relatively high biomass production in winter in order to provide forage for livestock in the season of the lowest forage availability of native grasslands. The main limitation of these conventional pastures is their low ability to maintain productivity during the summer and consequently, early warm-season weed colonisation affects their long-term productivity (Tejera et al. 2015). Increasing functional diversity in these pastures by including C4 species, would improve biomass stability over the year as niches do not overlap between C3 and C4 grass species (Díaz and Cabido 2001; Perelman et al. 2007; Bresciano et al. 2014). Moreover, this could improve soil cover during the whole year, decreasing soil erosion and providing other ecosystem services (EEM, 2005; Fornara and Tilman 2008; Tejera et al. 2015) such as increasing the retention of and water and nutrients and stabilising carbon stocks over the time (Lal 2004). Two C4 perennial grasses native to Uruguay have been traditionally proposed to complement biomass production in the pastures during summer (Tejera et al. 2015), *Paspalum dilatatum,* a cespitose species with an erect growth habit (Venuto et al. 1991) and *Paspalum notatum,* which has horizontal rhizomes and a prostrate growth habit (Lombardo 1984). The rhizomes of *P. notatum* are about 2–5 mm in thickness, resistant to cattle trampling (Fachinetto et al. 2012). These two species also have a relatively large root growth (Burson and Watson 1995; Mueller et al. 2013).

The inclusion of perennial native C4 grasses also has a special interest in a sustainable agricultural intensification scenario. An increase in diversity in pasture systems is expected to promote their stability in terms of biomass production during the year (Skinner et al. 2006; Tejera et al. 2015) and must be considered in order to contribute to sustainability. There is evidence that the inclusion of C4 species in forage mixtures of grasses and legumes may increase carbon sequestration in soils (Fornara and Tilman 2008) and modify its distribution reaching greater depths in the profile (Bonin et al. 2013; Mueller et al. 2013).

In order to evaluate the ecological sustainability and environmental impact of grazing livestock systems, it is necessary to consider, not only the aerial biomass but also the biomass and carbon contained in belowground structures. An increase in root biomass production is a much relevant objective to increase the rate of carbon sequestration (Kell 2011). At the local and regional levels, there are a few studies evaluating root biomass in grazed native pastures (Pucheta et al. 2004; Altesor et al. 2006; Piñeiro et al.

2006; 2009, 2010; Paruelo et al. 2010; Lopez et al. 2015, 2016). However, to our knowledge, no previous study has reported the contribution of perennial native grasses to belowground biomass in sown pastures in the soil conditions of Uruguay. The aim of this study was to evaluate the effect of the inclusion of C4 grasses in a conventional pasture on root biomass and accumulated carbon. Overall, we hypothesised that the inclusion of *Paspalum* species in the conventional mixtures would increase root biomass and carbon in the mixture given their deeper rooting system. Also, we expected mixtures with *P. notatum* to have higher root biomass and carbon in the top soil due to its rhizomes.

Materials and methods

This study was carried out at Centro Regional Sur Experimental Station of the Facultad de Agronomía, Universidad de la República, located in Joanicó, Canelones (34°36′S 56° 13′W), on Typical Vertisols soils (Altamirano et al. 1976; IUSS 2007). A complete randomised block design with three replicates was used. Each experimental unit had an area of 0.96 ha. Treatments were different forage mixtures: (a) a conventional mixture of *Festuca arundinacea* Schreb (cv. Quantum), *Trifolium repens* L. (cv. Zapicán) and *Lotus corniculatus* L. (cv. INIA Draco), (b) the conventional mixture + *P. notatum* Flüggé (cv. Pensacola) (CMPn) and (c) the conventional mixture + *P. dilatatum* Poir. (Australian commercial seed) (CMPd). Warm-season grasses were sown in December 2009; seed density was 19.5 kg ha^{-1} for *P. dilatatum* and 15 kg ha^{-1} for *P. notatum*. Plots were fertilised at 100 kg ha^{-1}, 7–40–0, N:P_2O_5:K_2O. The density of *Paspalum* plants achieved three months after sowing was 8 plants m^{-2} for *P. dilatatum* and 114 plants m^{-2} for *P. notatum*. The cool-season grass and the legumes were sown in April 2010 at a distance between rows of 0.17 m; seed density was 10 kg ha^{-1} for tall fescue, 1.5 kg ha^{-1} for white clover and 12 kg ha^{-1} for birdsfoot trefoil. Plots were fertilised again at the same initial dose. A high density of sown species was obtained and it was maintained throughout the study period (see Tejera et al. 2015). All plots were put under strip grazing when the height of forage reached 20 cm and cattle were removed when it was reduced to 10 cm. Belowground sampling was conducted in two seasons: summer (December 2012, third summer of the pastures) and winter (August 2013, forth winter of the pastures). The first 30 cm of soil were sampled since this is the area where a greater proportion of roots is usually found (Jackson et al. 1996). Two randomly distributed 14 × 14 × 30 cm soil cores with vegetation were extracted per plot.

In the laboratory, each sample was separated into two soil portions with root structures: the top one (from the surface with vegetation to 10 cm in depth) and the deeper portion (from 10 to 30 cm). Each sample portion was weighed and then roots and rhizomes were separated from soil (belowground or root biomass), using a dispersing solution of 5 g L^{-1}sodium hexametaphosphate during 24 h. Biomass was dried for 48 h at 70°C, and then weighed and ground. Roots were sieved through two sieves: a 2 mm one and a 0.5 mm one. Carbon content was determined by organic carbon oxidation with potassium dichromate ($K_2Cr_2O_7$) in a sulfuric medium using external heat (1 h at 150 °C) in order to facilitate oxidation (Mebius 1960). Carbon was determined by colorimetry at 600 nm wave length. A standard curve was adjusted with glucose. Biomass and accumulated carbon values in legumes were not discriminated, since their biomass contribution was relatively low and similar between treatments (mean 15%, Tejera et al. 2015).

In order to characterise environmental conditions in the site, average temperature (°C), precipitations (mm) and meteorological frost events were obtained from records from a local weather station (INIA Las Brujas, Canelones). The first sampling date took place after a spring with above than average rainfall; the second sampling date took place after a winter with below than average rainfall and above than an average number of frost events (Table 1).

Two different approaches were used to analyse biomass and carbon stock variables. The first approach was a repeated measure analysis considering the two sampling seasons in the model (model 1). In this case, a general linear mixed model was used, assuming heterogeneous variances by treatment. Block, treatments, sampling season and their interaction were considered as fixed effects. The error term associated to treatment and block effect was considered as random. The second approach analysed separately the two sampling season and considered the effect of sampling depth on the response variables (model 2). For each season, treatment effects, depth and their interaction were analysed using a linear mixed model, with treatment, depth and the interaction considered as fixed effects and assuming heterogeneous variance by treatment. In order to compare biomass and carbon averages, orthogonal contrasts were laid out between the conventional mixture and the average of both treatments with *Paspalum,* and between the two *Paspalum* treatments, also assuming heterogeneous variances between treatments. Statistical processing was performed using SAS software with the Mixed Procedure.

Results

According to model 1, no season × forage mixture interaction was observed for any variable (P values ranging from .11 to .98). Season affected total root biomass ($P = .03$) and total root carbon ($P = .02$), biomass and carbon in the 010 cm layer ($P < .01$ and $P = .01$, respectively). The values for summer were higher than those for winter in all the cases (Table 2).

Forage mixture affected root biomass ($P = .04$) in the 0–10 cm layer and total root biomass ($P = .05$) but no differences were found in the 10–30 cm layer (Figure 1(a)). The mixtures with *Paspalum* in the 0–10 cm layer had higher root biomass than the

Table 1. Monthly average temperature (°C), precipitation (mm) and meteorological frost events (number of days), and historical averages.

	Spring	Summer	Autumn	Winter
Temperature (°C)				
2011–2012	16	22	17	10
2012–2013	17	23	17	12
Average (1970–2013)	16	22	17	11
Precipitation (mm)				
2011–2012	78	82	84	123
2012–2013	133	136	120	37
Average (1970–2013)	97	93	98	83
Frost events (days)				
2011–2012	1	0	0	12
2012–2013	0	0	0	9
Average (1970–2013)	0	0	0	1

Note: Spring (September to November), summer (December to February), autumn (March to May), winter (June to August).

Table 2. Mean root biomass and carbon (kg ha^{-1} DM ± s.e.) at 0–10 cm, 10–30 cm and total in the summer and winter.

Variable	Depth (cm)	Summer	Winter (kg ha^{-1})
Root biomass	0–10	10802 ± 2825A,a	5242 ± 2077B,a
	10–30	1937 ± 484n.s.,b	2940 ± 1481n.s.,b
	0–30	12739 ± 1249A	8182 ± 1222B
Root carbon	0–10	3004 ± 820A,a	1935 ± 701B,n.s.
	10–30	670 ± 177n.s.,b	874 ± 374n.s.,n.s.
	0–30	3674 ± 372A	2809 ± 446B

Notes: Different letters indicate significant differences between seasons (Summer and Winter) for each depth (uppercase), corresponding to model 1 and between depth (0–10, 10–30) for season (lowercase), corresponding to model 2.

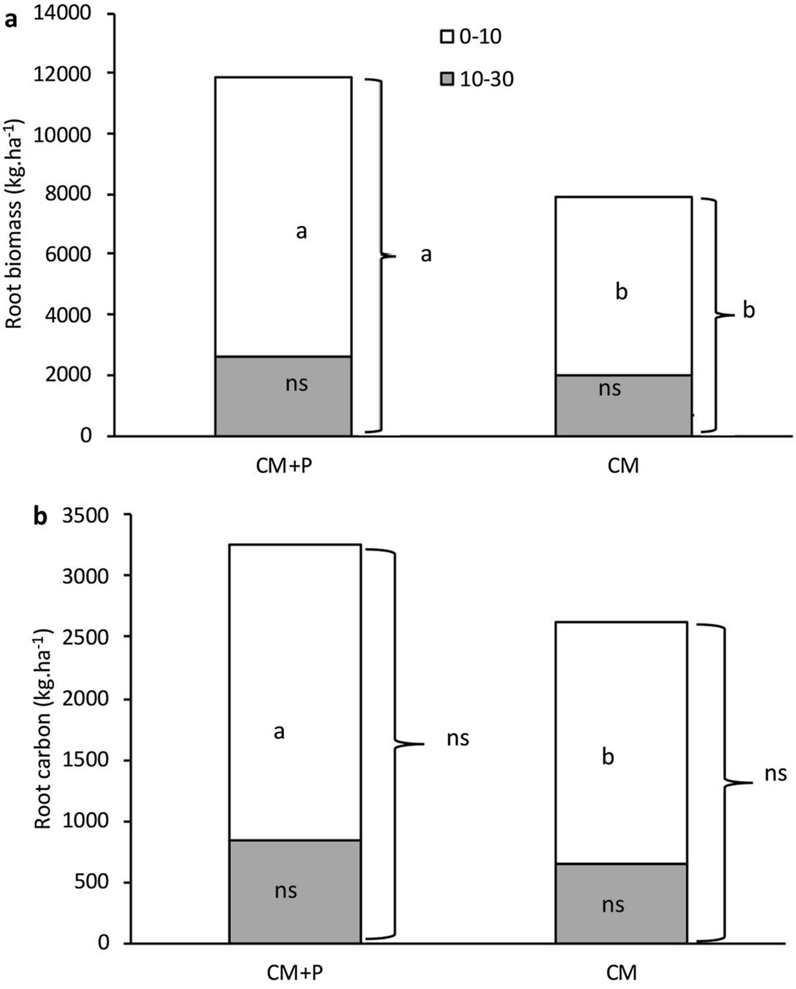

Figure 1. Root biomass (kg ha^{-1} DM ± s.e.) (a) and root carbon (kg ha^{-1} DM ± s.e.) (b), in forage mixtures of grasses and legumes (CM, conventional mixture) versus the mixture with Paspalum (CP + P). Different letters indicate significant differences between forage mixtures for each depth and total profile ($P \leq .05$).

conventional mixture averaged over the two seasons. For root carbon, forage mixture was significantly different only in the 0–10 cm layer and higher for mixtures with *Paspalum* (Figure 1(b)).

According to model 2, in summer, the depth and forage mixture had an effect on the biomass ($P < .001$, $P = .02$, respectively), and no depth × forage mixture interaction was detected. Biomass was higher in the top layer (Table 2) and in the mixture with *Paspalum* ($P < .01$) (Figure 2(a)). Depth affected root carbon in summer ($P = .001$), with higher values in the top layer (Table 2). In winter, depth was the only significant effect ($P = .02$) for root biomass. In winter no factor affected carbon ($P > .05$, Table 2 and Figure 2(b)).

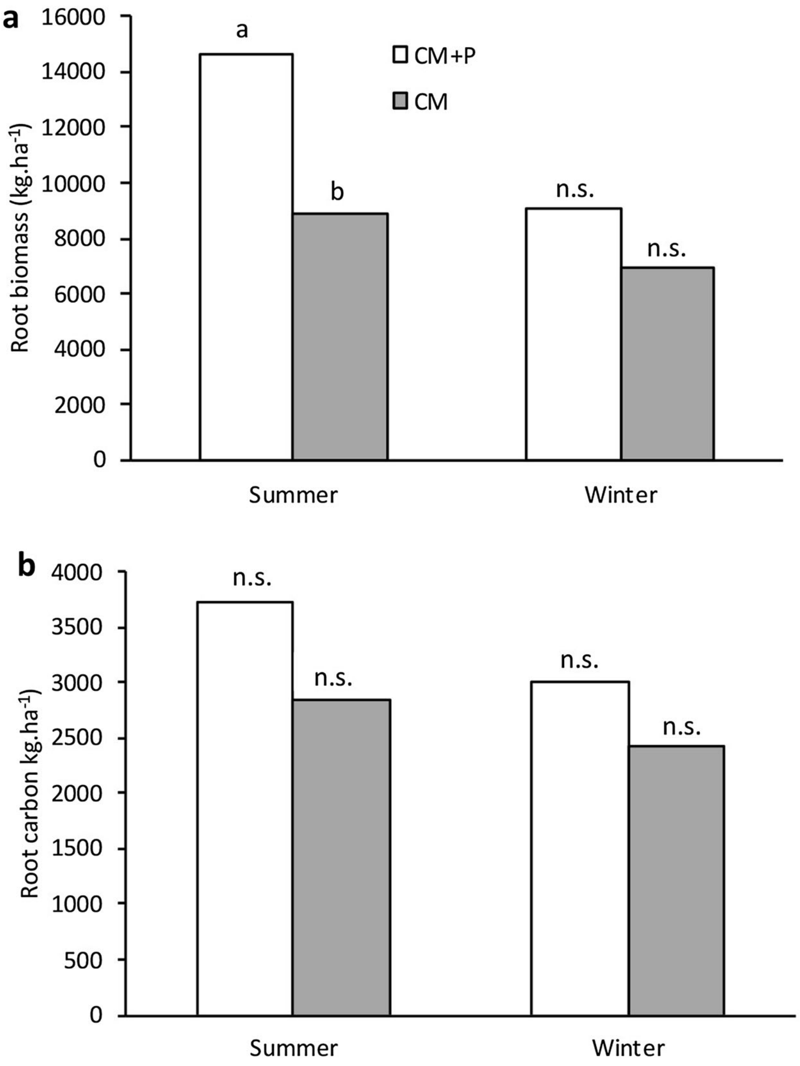

Figure 2. Root biomass (kg ha^{-1} DM ± s.e.) (a) and root carbon (kg ha^{-1} DM ± s.e.) (b), in forage mixtures of grasses and legumes (CM, conventional mixture) versus the mixture with Paspalum (CM + P). Different letters indicate significant differences between forage mixtures for each season ($P \leq .05$).

There was clear stratification in root carbon with higher values in the upper layer for all treatments and seasons. On the other hand, carbon values in the 10–30 cm layer were not different between treatments or seasons. Although in the three mixtures both biomass and carbon were lower in winter, we found a lower seasonal variation in biomass *P. notatum* (20%), while mixture with *P. dilatatum* had much lower root biomass in winter than summer (56% less).

Discussion

In general, our results show that the inclusion of warm season grasses increased root biomass and carbon in the mixtures during certain seasons. We did not find differences between the two *Paspalum* species in root biomass or carbon in any season sampled so the data will be discussed in terms of the effect of the inclusion of *Paspalum* species in general.

Species composition

Although the inclusion of C4 grasses to the conventional mixtures had no effect on total aboveground biomass production in this experiment (Tejera et al. 2015), it increased the contribution of biomass and roots carbon in comparison to the conventional mixture.

During the first years of this experiment (2010–2012), Tejera et al. (2015) recorded that the addition of *Paspalum* sp. increased biomass production in summer, but different growth habits of *P. notatum* and *P. dilatatum* had different effects on the performance of the mixtures. The inclusion of *P. notatum* increased aboveground biomass during the autumn but decreased the performance of the mixture during the winter associated to a reduction in the proportion of the soil covered by *Festuca arudinacea*. We can infer that this effect of *P. notatum* on the mixture could be due its greater competitive ability for the uptake of soil resources. Together with the greater demand by the above-ground structures of *Festuca arudinacea* during its growth period, it may have established a tradeoff between above and belowground productivity due to the higher performance of *P. notatum* in terms of root biomass.

According to Lal (2004) in humid and cold climates C sequestration would range between 100 and 1000 kg ha^{-1} per year. Following Jones et al. (2009), about 50% of the C partitioned belowground is retained in root biomass, which in our study represents approximately 1680 kg ha^{-1} for three years in mixtures with *Paspalum*, compared to 1317 kg ha^{-1}for the conventional mixture. We could estimate the annual contribution of C accumulation by mixtures with *Paspalum* in 560 kg ha^{-1} year^{-1}, exceeding in 120 kg ha^{-1} year^{-1} the contribution of conventional mixtures. This result would demonstrate the importance of these species in the may have implications for the potential carbon sequestration of pastures (Bonin et al. 2013)

Season

For pastures including only cold-season species (ryegrass-clover) in New Zealand, the highest root biomass was observed in late spring-summer, and the lowest in autumn and winter (Dodd and Mackay 2011; McNally et al. 2015), in our results the increase in root biomass was even higher in summer when adding C4 grasses. Forage mixtures with *Paspalum* showed more biomass (64% more in summer, 32% in winter) and carbon (average 34% higher) in comparison with the conventional mixture (Figure 2). In agreement with what Bonin et al (2013) found, the cycle of root growth occurs in spring and autumn, and as a result, the allocation of resources between the aerial and belowground structures is affected by the season of the year. However, the specific growth habit of a species may affect how this allocation changes. Grasses do not behave equally, *P. notatum* would appear to be less affected that *P. dilatatum* seasonally. Whereas the biomass of root of *P. notatum* presented a low seasonal variation (20% less), *P. dilatatum* showed a major reduction in root biomass in the winter (56%).

In the first centimetres, the growth of belowground structures shows a remarkable seasonal variation because in spring-summer a higher use of root reserves compensates with a higher photosynthesis activity. While in the winter, reserves decrease slowly but there is no compensation due to photosynthesis (Teruel et al. 2000). Throughout this study, precipitations in winter accounted for approximately half of the historical average, which represents a stressful condition. As was stated by Adjku et al. (2013), water is a factor in root growth patterns, together with the occurrence of frosts which was also higher than the number of events recorded in the preceding 10 years. In the deeper soil layer (10–30 cm), the absence of change in biomass and accumulated carbon may reflect the lower variability in terms of both humidity and soil temperature, which would generate less stressful conditions for root structures. Dodd and Mackay (2011) in perennial ryegrass/clover pastures, observed that the relationship between root biomass in the upper and lower soil layer (0–8 and 8–16 cm, respectively) decreased from six times in spring to three times in winter, but these changes in the relationship were mainly due to changes in the upper soil layer.

Depth

Root biomass showed a clear stratification, in agreement with evidences in grasslands and sown pasture systems (Ansin et al. 1998; Piñeiro et al. 2009; Bonin et al. 2013). We found 77% of belowground biomass in the first 10 cm, which is in agreement with other studies in pastures (Formoso 2007; Bonin et al. 2013; Viega et al. 2013) and in natural grasslands in the same region (Pucheta et al. 2004; Lopez Mársico et al. 2015, 2016).

Literature reports suggest that C4 grasses may potentially increase C sequestration deeper in the soil (Bonin et al. 2013; Mueller et al. 2013); however, we did not find significant effects at greater depths.

McNally et al. (2015) suggest that moderately diverse mixtures may potentially increase soil C under grazed pastures through increased root mass inputs and rooting depth. Although this was not observed in this particular experiment, the inclusion of species with contrasting characteristics may have implications for nutrient cycling and C sequestration. Although this aspect has not been studied in pastures of Uruguay, it could be one of the causes of the soil organic matter increase observed in crop-pasture rotations (Picasso et al. 2014).

Potential implications

The inclusion of *P. notatum* and *P. dilatatum* in conventional forage mixtures (with C3 grasses and legumes) increased root biomass and root carbon in the top layer of soil profile. Although we currently cannot estimate how far the estimated carbon values are to the maximum accumulation potential under local conditions, according to Kumar et al. (2006) these results indicate that the inclusion of C4 grasses has potential for a greater contribution to long-term C sequestration. Also, we recorded the effect of the inclusion of C4 grasses under a single management condition; however, more research is needed to better understand how management (eg, fertilisation, irrigation and grazing) can affect underground processes in these ecosystems and their implications.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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