Article

# Contribution of carbon and nitrogen to the soil by residues of alternative forage crops

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## Abstract

A greater diversity of forages in autumn-winter increases the input of carbon (C) and nitrogen (N) into the soil in the harvest residues. The objective of the study was to evaluate the potential contribution of C and N to the soil in alternative and traditional forage residues during the autumn-winter cycle. The experiment evaluated the dry matter (DM) yield, quantity of residues and C/N ratio in 11 forage species. The traditional crops oats, barley, triticale, wheat, berseem clover and annual ryegrass contributed less harvest residues (365 to 612 kg ha$^{-1}$) and of lower quality, with values of the C/N ratio of 23.5 to 42.8. Alternative crops canola, beet, brassicas, radish and chickpea contributed more residues (432 to 2 958 kg ha$^{-1}$), with higher N contents (18.5 to 32.6 g kg$^{-1}$) and lower values of the C/N ratio (11.4 to 20). Alternative crops with thickened roots such as beet, brassica and radish improved the quantity and quality of harvest residue contribution, with a potential C capture capacity similar to traditional crops. However, only Winfred brassica and Graza radish obtained DM yields (10 094 to 11 636 kg ha$^{-1}$) similar to or greater than those observed in the control cereals Cuauhtémoc oats (11 161 kg ha$^{-1}$) and AN105 triticale (9 644 kg ha$^{-1}$). A greater diversity of forages can improve in quantity and quality the contribution of harvest residues to the soil.

**Keywords:** C/N ratio, dry matter, traditional crops, yield.

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# Introduction

In the Comarca Lagunera, the production of forage to feed dairy cattle is carried out intensively under irrigation with perennial crops such as alfalfa and three cycles of annual crops of corn, sorghum and autumn-winter cereals. The main winter cereal is oats, while in spring and summer, two crops of corn or sorghum are obtained (Santamaría *et al*., 2006), all produced with a conventional tillage system. Alfalfa is important in crop rotation in the region because it produces quality forage and contributes to the accumulation of labile C and N, as well as improving the use of N by the following annual species in crop rotation (Chen *et al*., 2019; Zhou *et al*., 2019). However, considering that annual crops are established with conventional tillage, with at least one plow pass in the year and one or two harrow passes before sowing each crop, the transition period from perennial crop to sowing annual crops is critical because losses of organic carbon occur in the soil.

According to Chen *et al*. (2019), these losses can reach up to 30% in annual crops with conventional tillage compared to reduced tillage. The addition of agricultural residues to the soil is a practice that is carried out with the aim of improving the physical and chemical properties of the soil and providing nutrients, but for these nutrients to be absorbed by plants, a transformation process called mineralization must occur. During the mineralization process, various factors such as soil organisms, temperature, moisture, texture, soil type, and C and N concentrations are involved in the decomposition of crop residues (Monsalve *et al*., 2017). Additionally, the biochemical composition of the residues influences in an important way since several studies describe the quality of the residues by the content of N and C and the quality criterion that they commonly use to predict the mineralization is the C/N ratio of the residues (Trinsoutrot *et al*., 2000).

In the production of annual forages in the region, the amount of harvest residues incorporated into the soil is limited because the largest proportion of the aerial part is harvested in forage crops. In addition, residues of oats, corn and sorghum are considered of low quality for the soil because they have high values of the C/N ratio (31.4 to 56.4). These levels of the C/N ratio indicate that a process of immobilization of C and N in the soil probably occurs, decreasing the availability of N for the use of the following crops in the rotation (Lynch *et al*., 2016; Singh *et al*., 2021). To improve the management of harvest residues, it is important to increase the quantity and quality of organic residues contributed to the soil through greater diversification of forage crops. Zhou *et al*. (2019) found that a high diversity of species increases the quality of plant residues with a decrease in the C/N ratio, which indirectly favors the accumulation of carbon in the soil.

In this regard, alternative crops such as canola, beet, chickpeas and forage brassicas showed a potential yield of DM similar or greater than that of traditional species (oats, wheat and triticale), while their nutritional composition was higher, with crude protein contents of 196 to 281 g kg$^{-1}$ (Reta *et al*., 2008). The high content of N in the forage of alternative crops (31.36-44.96 g kg$^{-1}$) (Reta *et al*., 2008) compared to those observed in traditional crops (17.47-22.4 g kg$^{-1}$) (Reta *et al*., 2018; Sánchez-Duarte *et al*., 2019) suggests that their residues may be of higher quality, with the potential to improve the availability of N in crop rotation, in addition to favorably affecting the accumulation of C in the soil. The objective of the study was to evaluate the potential contribution of C and N to the soil in alternative and traditional forage residues during the autumn-winter cycle.

## Materials and methods

The research was carried out in the autumn-winter cycles 2017-2018 and 2018-2019 in the La Laguna Experimental Field (CELALA, for its acronym in Spanish) of the National Institute of Forestry, Agricultural and Livestock Research (INIFAP, for its acronym in Spanish), located in the municipality of Matamoros, Coahuila, Mexico (103° 13’ 42” west longitude and 25° 31’ 41” north latitude, at an altitude of 1 100 masl). The soil used was one with a loam-clay texture without salinity problems, with a depth greater than 1.8 m and a pH of 8.14. In the 0-30 cm stratum, the soil had an organic matter content of 1.41% and concentrations of NH4-NO3 and P of 11.05 mg kg$^{-1}$ and 5.16 mg kg$^{-1}$, respectively.

In the two growing cycles, soil preparation consisted of fallowing, harrowing and leveling the land. Before sowing, the experiment was traced and each experimental plot was fertilized with granulated ammonium sulfate and monoammonium phosphate, at a rate of 50 kg N and 80 kg $P_2O_5$ ha$^{-1}$, respectively. Subsequently, between the cuts and after the cuts, a nitrogen fertilization dose of 250 kg ha$^{-1}$ was completed. Fertilizers were applied and incorporated manually. Sowing of all crops was done manually in dry soil on September 15, 2017, and October 12 in 2018. Eleven forage species were evaluated in 17 treatments based on alternative and traditional crops with the capacity to regrow and adapt to the autumn-winter production cycle in the region.

The traditional crops and cultivars used were the following: of oats (*Avena sativa* L.), varieties Cuauhtemoc and Karma; of barley (*Hordeum vulgare* L.), varieties Cántabra and Narro 95; of triticale (*x Triticosecale Wittmack*), varieties Río Nazas and AN 105; of wheat (*Triticum aestivum* L.), varieties Salamanca and AN 265; of berseem clover (*Trifolium alexandrinum* L.), cultivar Multicut; of annual ryegrass (*Lolium multiflorum* Lam.), Tetraploid Oregon. The alternative species and cultivars evaluated were the following: of chickpea (*Cicer arietinum* L.), porquero chickpea variety; of canola (*Brassica napus* L.), spring cultivar Ortegón and winter cultivar Riley; of beet (*Beta vulgaris* L.), cultivar Starmon; of brassicas, cultivar ‘Winfred’ (*Brassica oleracea* L. x *Brassica rapa* L.) and cultivar Hunter (*Brassica rapa* L. x *Brassica napus* L.); of forage radish, cultivar Graza (*Raphanus sativus* L. x *Brassica oleracea* L., *Raphanus maritumus* L.). The crops ‘Winfred’ brassica, ‘Hunter’ brassica and ‘Graza’ radish were only evaluated in the 2018-2019 cycle.

The experimental area was irrigated by a system of PVC plastic pipes with gates. The volume of water applied in each plot was measured, adjusting the water flow in the gates of the pipes installed for irrigation and considering the irrigation time in each experimental plot. Irrigation was applied on the same day of sowing with an irrigation sheet of 150 mm; eight days later, a light irrigation with a 60 mm sheet was applied. During the production cycle, six supplemental irrigations were applied with a total sheet of 75 cm in oats, triticale, wheat, clover and Hunter brassica, while in barley, Winfred brassica and Graza radish, five supplemental irrigations with a sheet of 63 cm were applied.

The nitrogen fertilization dose (250 kg ha$^{-1}$) was also completed, with 55 kg ha$^{-1}$ at 33 das, 90 kg ha$^{-1}$ after the first cut in each species between 77 and 112 das, and 55 kg ha$^{-1}$ before the second cut between 112 and 135 das. The experimental design used was one of randomized complete blocks with four repetitions, in each of which the 17 treatments were randomly distributed. Each of the 68 experimental plots consisted of 20 furrows 0.18 m apart and 6 m long. At harvest, fresh forage and DM yields were determined. The useful plot to determine forage yield was 14.4 $m^2$, harvesting 16 central furrows of 5 m in length.

DM content was obtained in a 0.72$m^2$ sample taken at random from the sample used for DM yield measurements. For this, two of the central furrows of each plot of 2 m in length were sampled. The sampled plants were dried at 60 °C in a Shel Lab forced air oven Model FX28-2 until reaching a constant weight. DM yield was determined by multiplying the fresh forage yield by the DM content of each plot. In the 2017-2018 cycle, three harvests were carried out in the cereals in the booting stage, five harvests were carried out in ryegrass and berseem clover in the vegetative stage; canola and beet were harvested three times also in the vegetative stage, while chickpeas were harvested only once in the flowering stage.

In the 2018-2019 cycle, the cereals were harvested twice in the booting stage; chickpeas were harvested only once in the stage of flowering and formation of pods; while in the rest of the species, the harvests were carried out in the vegetative stage, with two harvests in brassicas, beet, radish and canola, while ryegrass and berseem clover were harvested on four and three occasions, respectively. After the harvest of all crops, on March 20, 2018, corresponding to the first cycle and on March 26, 2019, of the second cycle, the harvest residue was collected at two sampling points on an area of 0.25 $m^2$ (0.5 x 0.5 m) taken at random in each experimental plot, where the root (20 cm depth) and organ residues of the aerial part were included. In each sample, the soil was sieved, separating the plant residues, which were then washed to remove the adhered soil.

The samples were dried in a Shel Lab forced air oven Model FX28-2 at 60 °C until reaching a constant weight, and subsequently, the weight of the dry matter was obtained. The dry forage samples were ground in a Wiley mill (Thomas Scientific Swedesboro, NJ USA) with a 1 mm mesh. A quartering of the ground sample was carried out in order to obtain a representative subsample of each plot in all the harvests carried out and subsequently, the sieving process was carried out using a 100 µm sieve. To determine the contents of C and N by the dry combustion method, between 10 and 15 mg of forage were weighed with an OAHUS PA224C analytical balance, previously dried at room temperature and sieved at 100 µm. The samples were calcined in the Elemental Analyzer (Thermo Fisher Scientific Model Flash 2000) at 950 °C using oxygen as an oxidizing agent (AOAC, 2005).

Meteorological data were obtained from a climate station located at the experimental site. Climate conditions in the two years of the study were similar in average temperatures, with higher rainfall in September 2018, which delayed the establishment of the second cycle until October 12, 2018 (Table 1). Due to this situation, together with the fact that some species were only evaluated during the second cycle, statistical analyses of the variables obtained were performed by year. Analyses of variance ($p \leq 0.05$) were performed for the total forage DM yield data and for the contents of N and C, C/N ratio and DM yield, N and C in the residues (aerial part and roots). The protected Fisher's least significant difference test ($p \leq 0.05$) was used to compare the means. The analysis of the information was carried out with the statistical program SAS (SAS Institute, 2011).

**Table 1. Monthly temperature, rainfall and evaporation during the development of forage species in two production cycles in Matamoros, Coahuila, Mexico.**

| Month | Cycle | Temperature (°C) | | | Rainfall | Total evaporation (mm) |
|---|---|---|---|---|---|---|
| | | Mean of maximums | Mean of minimums | Mean | | |
| September | 2017-2018 | 39.6 | 18 | 26.2 | 118.6 | 159.4 |
| | 2018-2019 | 36.8 | 17.8 | 24.7 | 309.8 | 124 |
| October | 2017-2018 | 35.2 | 11 | 23.6 | 35.5 | 113.8 |
| | 2018-2019 | 35.2 | 10.5 | 21.8 | 40.7 | 110 |
| November | 2017-2018 | 36 | 4.5 | 19.9 | 0 | 77.5 |
| | 2018-2019 | 32.6 | -0.1 | 17.1 | 2.9 | 93 |
| December | 2017-2018 | 30.2 | -3.5 | 14.6 | 46.9 | 64.5 |
| | 2018-2019 | 32.2 | -1 | 14.7 | 17.2 | 79.5 |
| January | 2017-2018 | 30.1 | 0.5 | 14.1 | 0 | 82.9 |
| | 2018-2019 | 31.9 | 3.5 | 15.5 | 3.5 | 84.8 |
| February | 2017-2018 | 35.8 | 9.6 | 21.3 | 13.3 | 120.3 |
| | 2018-2019 | 39.3 | 5.5 | 20.7 | 0 | 139 |
| March | 2017-2018 | 380 | 10.5 | 23.1 | 0 | 183.1 |
| | 2018-2019 | 37.6 | 6.5 | 22 | 0.6 | 175.6 |

## Results and discussion

### C/N ratio in residues

The harvest residues of traditional crops such as small grain cereals and annual ryegrass had higher values ($p \leq 0.05$) of C/N ratio (22.6 to 42.8) compared to those obtained by the alternative crops canola, beet, brassicas and porquero chickpeas (11.4 to 20). Only the C/N ratio of berseem clover (11.2 to 15) was similar to that observed in alternative crops (Table 2). According to the values indicated by Lynch *et al*. (2016), in the two cycles of the study, all cereals had high values (>25) in the C/N ratio, except for Cuauhtémoc oats and the two barley cultivars during the 2017-2018 cycle (Table 2). These species were also characterized by their low N contents (8 to 14.6 g kg$^{-1}$).

Other studies indicate that these levels of N and C/N cause the process of temporary immobilization of N of the soil solution by microorganisms to occur in the soil, which delays the mineralization of the N contained in the residues (Alghamdi *et al*., 2022) and this occurs because the N requirements of soil microorganisms are not covered by harvest residues (Gezahegn, 2017). C/N values in residues of alternative species (canola, beet, brassicas, radish, chickpeas and berseem clover) (Table 2) were similar to those observed in other studies conducted with hairy vetch (9-9.9), red clover (10.3 to 14.5), forage radish (15.1 to 15.7), canola (24) (Finney *et al*., 2016); peas (9), clover (13) (Pereira *et al*., 2017); spinach (9.6) (Frerichs *et al*., 2022); lentil, chickpeas, pigeon pea (17.7-19.5) (Singh *et al*., 2021); peas (18) and forage radish (8) (Alghamdi *et al*., 2022).

**Table 2. Carbon (C) and nitrogen (N) contents and the C/N ratio in the harvest residues of conventional and alternative crops evaluated in the autumn-winter cycles 2017-2018 and 2018-2019.**

| Crop | 2017-2018 | | | 2018-2019 | | |
|---|---|---|---|---|---|---|
| | N (g kg$^{-1}$) | C (g kg$^{-1}$) | C/N | N (g kg$^{-1}$) | C (g kg$^{-1}$) | C/N |
| Traditional crops | | | | | | |
| Cuauhtémoc oats | 16 e | 376.7 abc | 23.5 b | 13.8 d | 368 bcd | 27.5 cd |
| Karma oats | 14 fgh | 401.9 a | 28.6 a | 12.1 de | 343 ef | 29.1 c |
| Narro 95 barley | 24.5 b | 353.2 c | 14.5 d | 12.7 de | 349 def | 27.8 cd |
| Cántabra barley | 14.5 fg | 342.8 c | 23.6 b | 13.3 d | 376 b | 28.3 c |
| Río Nazas triticale | 12.6 h | 358.8 bc | 28.6 a | - | - | - |
| AN105 triticale | 13.4 gh | 346.3 c | 25.9 ab | 8 f | 332 fg | 42.8 a |
| AN265 wheat | 14 fgh | 357.9 bc | 25.6 b | 9.9 ef | 339 efg | 34.9 b |
| Salamanca wheat | 14.6 efg | 376 abc | 25.9 ab | 13.5 d | 304 h | 22.6 de |
| Berseem clover | 26.2 a | 392.9 ab | 15 d | 33.4 a | 373 bc | 11.2 h |
| Annual ryegrass | 15.4 ef | 373.7 abc | 24.4 b | 14.5 d | 380 b | 26.3 cd |
| Alternative crops | | | | | | |
| Ortegón canola | 22.8 c | 357.7 bc | 15.7 d | 18.8 c | 318 gh | 17 fg |
| Riley canola | 24.7 b | 348 c | 14.1 d | 31.6 a | 361 bcde | 11.4 h |
| Beet | 18.5 d | 366.5 abc | 20 c | 21.5 c | 382 b | 17.7ef |
| Winfred brassica | - | - | - | 32.6 a | 377 b | 11.6 h |
| Hunter brassica | - | - | - | 30.1 ab | 350 cdef | 12 gh |
| Graza radish | - | - | - | 18.5 c | 303 h | 17.2 f |
| Porquero chickpeas | 23.8 bc | 372.9 abc | 15.7 d | 27.6 b | 415 a | 15.1 fgh |

Means with the same letter in columns are not statistically different (LSD≤ 0.05).

The residues of these crops, with high N content and low C/N values, had a faster and more intense decomposition and release of N, with maximum values between 42 and 56 days after the onset of decomposition (Singh *et al*., 2021; Alghamdi *et al*., 2022); subsequently, the values decline at 60-90 days (Singh *et al*., 2021). In crops with C/N ratio values greater than 25, Singh *et al*. (2021) found that a slow release of N occurred until 45 days, and then a rapid release occurred at 60 and 90 days.

In the two evaluation cycles, the main difference between the residues of alternative and traditional crops was the higher content of N ($p \leq 0.05$) in the former; while the difference between them in concentration of C was variable, with a tendency to equal or higher contents in alternative crops with respect to traditional crops (Table 2). This has also been observed in other studies where the C/N ratio of several species, such as oats, forage turnip, forage peas and common vetch, was obtained (Doneda, 2010; Murungu *et al*., 2011). In the present study, some variations occurred in the second production cycle, where a higher content of C in porquero chickpeas and lower values in Salamanca wheat and Graza radish were statistically observed ($p \leq 0.05$).

C concentrations in the residues of alternative and traditional crops were similar ($p > 0.05$) (Table 2), which indicates that the ability to sequester C in soil in alternative crops may also be similar to traditional species, depending on the quantity of residues left in the soil and on the rate of mineralization of organic matter. Although alternative crops have the potential for a higher rate of mineralization due to their lower C/N ratio, the amount of C sequestered in the soil after 18 months of incorporation of the residue can be significant, as mineralization usually occurs rapidly in the first two years, and then occurs more slowly (Jenkinson and Rayner, 1977; Mutegi *et al*., 2013). Using a CN-SIM forecast model, Mutegi *et al*. (2013) estimated that 30 years after the incorporation of forage radish residues, it would still be possible to find between 8 and 10% of the material incorporated at a soil depth between 0 and 45 cm. They also found in the same crop that, 18 months after incorporating the residues, the losses of C reached values of 61.4%.

## Potential contribution of dry matter, carbon and nitrogen in residues

### Cycle 2017-2018

Beet statistically exceeded ($p \leq 0.05$) the other species in the amount of DM contributed per hectare in the harvest residues, due to its higher production of DM in the thickened root (2 354 kg ha$^{-1}$) that was left in the soil after harvest. The amount of DM contributed in the residues by the other crops fluctuated from 365 to 612 kg ha$^{-1}$. Among these crops, Ortegón canola and chickpeas stood out, which were higher in quantity of residues than wheat, clover and annual ryegrass (Table 3).

**Table 3. Dry matter yield and amount of harvest residues, nitrogen and carbon contributed by traditional and alternative crops during the 2017-2018 cycle.**

| Crop | Dry matter yield (kg ha$^{-1}$) | Quantity of residues (kg ha$^{-1}$) | | |
|---|---|---|---|---|
| | | Dry matter | Nitrogen | Carbon |
| Traditional crops | | | | |
| Cuauhtémoc oats | 10116 de | 517 cde | 8.3 d | 194.4 bcd |
| Karma oats | 10462 cd | 520 cde | 7.2 de | 205.1 bc |
| Narro 95 barley | 8874 e | 612 b | 15 b | 215.9 b |
| Cántabra barley | 10258 de | 540 bcd | 7.9 d | 185.5 bcde |
| Río Nazas triticale | 11971 ab | 524 bcd | 6.6 de | 188 bcde |
| AN105 triticale | 11164 bcd | 532 bcd | 7.1 de | 183.9 bcde |
| AN265 wheat | 11778 abc | 419 f | 5.8 e | 149.9 ef |
| Salamanca wheat | 11930 abc | 450 def | 6.6 de | 167.8 cdef |
| Berseem clover | 11362 bcd | 401 f | 10.5 c | 157.7 def |
| Annual ryegrass | 12530 ab | 365 f | 5.6 e | 136.5 f |
| Alternative crops | | | | |
| Ortegón canola | 13017 a | 607 bc | 13.8 b | 217.2 b |
| Riley canola | 10056 de | 432 ef | 10.6 c | 149.9 ef |
| Beet | 7366 f | 2354 a | 43.7 a | 864.1 a |
| Porquero chickpeas | 3742 g | 575 bc | 13.7 b | 214.3 b |

Means with the same letter in columns are not statistically different (LSD≤ 0.05).

The concentration of C (348 to 373 g kg$^{-1}$) in alternative crops was similar ($p > 0.05$) to the concentrations observed in traditional crops (343 to 402 g kg$^{-1}$) (Table 2); however, beet may contribute a greater amount of C (864 kg ha$^{-1}$) to the soil due to its greater quantity of residues (2 354 kg ha$^{-1}$) compared to traditional crops (365 to 612 kg ha$^{-1}$). Canola and porquero chickpeas contributed amounts of C (150 to 217 kg ha$^{-1}$) similar ($p > 0.05$) to those observed in traditional crops (136 to 216 kg ha$^{-1}$) (Table 3). The potential contribution of N to the soil in the residues of canola and porquero chickpea was higher ($p \leq 0.05$), between 28 and 94.4%, compared to that observed in the controls Cuauhtémoc oats (8.3 kg ha$^{-1}$) and AN105 triticale (7.1 kg ha$^{-1}$); while in beet, the potential contribution of N was higher ($p \leq 0.05$), between 526 and 616%, which is equivalent to amounts between 35.4 and 36.6 kg N ha$^{-1}$ additional to those contributed by traditional crops (Table 3).

## Cycle 2018-2019

The residues of traditional crops reached 385 to 597 kg ha$^{-1}$ of DM, with contributions of 137 to 205 kg ha$^{-1}$ of C and 4.0 to 14.4 kg ha$^{-1}$ of N. Beet, brassicas Winfred and Hunter, and Graza radish contributed to the soil in their residues the largest amounts of N (32.7 to 56.1 kg ha$^{-1}$) and C (564 to 1 168 kg ha$^{-1}$). This behavior occurred due to their higher concentration of N ($p \leq 0.05$) in the residues (18.5 to 32.6 g kg$^{-1}$) (Table 4), in addition to their greater contribution ($p \leq 0.05$) of DM per hectare (1 684 to 2 958 kg ha$^{-1}$), mainly in the thickened roots (Table 4).

**Table 4. Dry matter yield and amount of harvest residues, nitrogen and carbon contributed by traditional and alternative crops during the 2018-2019 cycle.**

| Crop | Dry matter yield (kg ha$^{-1}$) | Quantity of residues (kg ha$^{-1}$) | | |
|---|---|---|---|---|
| | | Dry matter | Nitrogen | Carbon |
| Traditional crops | | | | |
| Cuauhtémoc oats | 11161 abcd | 414 ghi | 5.7 e | 152 gh |
| Karma oats | 10046 cdef | 597 ef | 7.3 e | 205 ef |
| Narro 95 barley | 9784 cdef | 478 ghi | 6 e | 166 fgh |
| Cántabra barley | 10547 bcde | 507 fg | 6.7 e | 188 fg |
| Río Nazas triticale | 9355 def | - | - | - |
| AN105 triticale | 9644 cdef | 499 gh | 4.0 e | 165 fgh |
| AN265 wheat | 12134 ab | 409 hi | 4.1 e | 139 h |
| Salamanca wheat | 9105 ef | 453 ghi | 6.2 e | 137 h |
| Berseem clover | 10093 bcdef | 431 ghi | 14.4 d | 161 gh |
| Annual ryegrass | 12735 a | 385 i | 5.6 e | 146 h |
| Alternative crops | | | | |
| Ortegón canola | 8937 ef | 758 d | 14.2 d | 241 de |
| Riley canola | 8155 f | 747 d | 23.6 c | 271 d |
| Beet | 8828 ef | 2958 a | 54.2 a | 1168 a |
| Winfred brassica | 11636 abc | 1684 c | 54.2 a | 646 b |
| Hunter brassica | 8952 ef | 1852 b | 56.1 a | 655 b |
| Graza radish | 10094 bcdef | 1874 b | 32.7 b | 564 c |
| Porquero chickpeas | 9671 cdef | 606 e | 16.8 d | 252 d |

Means with the same letter in columns are not statistically different (LSD≤ 0.05).

Although to a lesser extent, canola and porquero chickpeas also had a higher ($p\leq 0.05$) contribution capacity of N (14.2 to 23.6 kg ha$^{-1}$) and C (241 to 272 kg C ha$^{-1}$) compared to the traditional crops Cuauhtémoc oats and AN105 triticale (Table 4). The reason for this advantage was also their higher ($p\leq 0.05$) contribution of DM (606 to 758 kg ha$^{-1}$) (Table 4) and higher ($p\leq 0.05$) concentration of N (18.8 to 31.6 g kg$^{-1}$) (Table 2). The amounts of N deposited in the residues of species with thickened roots are similar to the amounts of N reported with species grown for green manure, such as common vetch, hairy vetch, forage peas (34.4 to 65.7 kg N ha$^{-1}$) (Murungu *et al*., 2011; Mattei *et al*., 2018) and oats (30.4 kg ha$^{-1}$) (Reis *et al*., 2014).

The results of the present study indicate that annual autumn-winter crops in forage production systems provide little amount of crop residues (414 to 612 kg ha$^{-1}$), which are of low quality due to their high values of the C/N ratio (23.5 to 42.8). So, these residues are not a significant addition of carbon to the soil, nor do they constitute a contribution of N to the soil for the next crop. Probably, the residues also do not affect the yield of the next crop by immobilization of N, since it has been observed that quantities of straw close to 2 000 kg ha$^{-1}$ did not affect the yield of the next crop (Flores *et al*., 2007; Castagnara *et al*., 2014). Even if the quantity of residues is increased with higher cut heights in autumn-winter cereals, this would not represent a short-term benefit for the production system of the region.

This is because the incorporation of more than 4 000 kg ha$^{-1}$ of oat straw, with a C/N ratio greater than 34, can limit the yield of the corn that is sown immediately afterwards in spring, regardless of the fractional application of N (Castagnara *et al*., 2014). The data from the present study also suggest that crop diversification improves the contribution of organic matter to the soil, with greater quantity and quality of harvest residues, which coincides with what was observed by Zhou *et al*. (2019) in that there is a decrease in the C/N ratio and an increase in the quality of plant residues with a greater diversity of plants.

In the present study, this was obtained mainly with alternative crops with thickened roots, such as beet, brassicas and radish, which had forage yields competitive with those observed in traditional crops (Tables 3 and 4). These alternative crops, in addition to having a lower C/N ratio in their residues (11.6 to 20) (Table 2), can contribute to the soil greater ($p\leq 0.05$) amounts per hectare of dry matter (338 to 714%), carbon (392 to 768%) and nitrogen (951 to 1 355%) compared to traditional crops (Tables 3 and 4). Due to the characteristics of their residues, the continuous sowing of these crops in a long-term period can contribute to conserving or improving the concentration of organic matter in the soils of the region (Smith *et al*., 1992), in addition to increasing the availability of mineral N in the crops of the spring and summer cycles.

In the system of intensive forage production in the region, spring sowing is carried out for a short period after the harvest of autumn-winter crops (30-40 days). Under these conditions, it is likely that the rapid decomposition and release of the N contained in the residues of alternative crops can be used during the early stages of development by the spring crop (corn or sorghum). In this regard, Murungu *et al*. (2011) found that the N released from vetch and pea residues was used by corn as the next crop in the period of 60 to 78 days after incorporation of the residues into the soil.

The amount of N released by the vetch and pea residues contributed 41.3% and 37.5%, respectively, of the total N absorbed by corn. However, in species with low C/N ratio, such as canola and forage brassicas, there may be losses of N after harvest, during the preparation and growth beginnings of spring crops, since the mineralization of the residues of species with similar C/N already occurs 21 days after incorporation into the soil and reaches high values between 42 and 56 days (Pereira *et al*., 2017; Alghamdi *et al*., 2022).

### Dry matter yield potential of species

The decision to incorporate new forage species into the regional crop pattern must be made not only for their ecological benefits, but for their forage production potential. Of the alternative species evaluated, beet, brassicas Winfred and Hunter and Graza radish showed potential benefits by incorporating harvest residues into the soil; however, only Winfred brassica and Graza radish obtained DM yields (10 094 to 11 636 kg ha$^{-1}$) similar or statistically higher than those observed in the control cereals Cuauhtémoc oats (11 161 kg ha$^{-1}$) and AN105 triticale (9 644 kg ha$^{-1}$). This indicates that alternative crops outstanding for their harvest residues are also competitive in the amount of forage production (Table 4).

## Conclusions

A greater diversity of forages in the autumn-winter production cycle with alternative forage species, such as brassica, radish, canola and beet, can contribute to improving the contribution of C and N to the soil in their harvest residues with better quality compared to traditional forages and at the same time to maintain or increase the yield of forage in the production cycle.

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