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Garlic yield after decomposition and nutrient release of cover crops under no-tillage and conventional tillage

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ABSTRACT: Garlic (*Allium sativum*) is normally grown under conventional tillage (CT) with soil being excessively mixed by plowing and harrowing operations that degrade soil structure, increase production costs, and increase environmental contamination. Alternatively, cover crops can be grown and their residues placed on soil surface, enabling garlic to be grown under no-tillage (NT) system. However, for subtropical climate there is little information on the impacts of tillage systems and cover crop species, particularly of their decomposition process and nutrients release, on garlic nutritional status and yield. This study aimed to evaluate garlic yield, and the decomposition rate and nutrient release from aboveground residues of cover crops cultivated in CT and NT methods, in a subtropical climate. Pearl millet (*Pennisetum glaucum*), bean (*Phaseolus vulgaris*) and sunn hemp (*Crotalaria ochroleuca*) were cultivated as cover crops previous to garlic, under CT or NT, for two consecutive years in the same area. The highest dry matter yield and nutrient release by cover crops were observed for millet and sunn hemp. The highest accumulations of P and K were observed in millet residue. Total garlic yield averaged 16.2 Mg ha^{-1} yr^{-1} and was affected neither by tillage method nor by cover crop species. The yield of marketable garlic was higher when soil was covered with bean residue in NT. Yield of non-marketable garlic was higher under CT in the first year, when high precipitation occurred shortly before harvest. The highest residue decomposition and nutrient release rates were observed under CT, in the three cover crop species. No-tillage increases marketable yield of garlic and the residence time of cover crop residues. We recommend cultivation in NT systems using cover crops, thus increasing marketable garlic yield and nutrient cycling.

Keywords: *Allium sativum*, nutrient cycle, nutrient availability, soil fertility.

INTRODUCTION

Garlic (*Allium sativum*) is normally grown under conventional tillage, with plowing and harrowing operations that expose soil surface to the direct impact of raindrops and degrades soil aggregates, consequently leading to water erosion. Water, soil, and nutrients are lost (Barbosa et al., 2021; Grando et al., 2023), reducing nutrient availability and garlic yield (Nearing et al., 2017; Poesen, 2018). Alternatively, cover crops such as millet (*Pennisetum glaucum*), bean (*Phaseolus vulgaris*) and sunn hemp (*Crotalaria ochroleuca*) can be grown previously to garlic crop. Aboveground residues can be deposited on soil surface, and garlic planted in furrows so that cover crop reduce or prevent water erosion, which is particularly relevant in subtropical regions where rainfalls are frequent and intense (Cardoso et al., 2012; Wolschick et al., 2021). This can increase the nutrient availability to garlic, increasing yield and, consequently, profitability on farms.

Besides soil cover, cover crops uptake nutrients from soil and incorporate them into the aboveground tissue. Latter, this deposited residue onto soil surface can maintain or increase carbon and organic matter levels (Melo et al., 2016; Kuneski et al., 2023), which is desired because organic matter is a source of nutrients, such as nitrogen (N), phosphorus (P), and sulfur, among others (Gmach et al., 2020). It can also complex toxic elements, such as aluminum (Al). In addition, after decomposition, nutrients such as N, P and K can be released into the soil (Giacomini et al., 2003). Growing garlic will then absorb part of the nutrients, which can be diagnosed through leaf analysis, improving the yield (Hahn et al., 2020). However, nutrient amount accumulated and residue biochemical composition differ between cover crop species (Brunetto et al., 2011; Weiler et al., 2022). This impact the decomposition rate and the nutrients amount released to the soil, which is not sufficiently known in garlic crops in southern Brazil, which are normally located in high-altitude regions, with low temperatures and frequent rainfall. This also affects the residue decomposition rate (Weiler et al., 2019).

Our hypothesis is that (a) soils managed in conventional tillage (CT) have a higher residue decomposition rate, increasing garlic yield; and (b) soils managed in a no-tillage (NT), by having greater protection from the soil surface due to the presence of surface residue, will have greater marketable garlic yield. This study aimed to evaluate whether garlic production is affected by CT or NT, as well as the decomposition and nutrient release in cover crop species grown in a subtropical climate.

MATERIALS AND METHODS

Experimental area

Experiment was conducted during the two consecutive years of 2019 and 2020, in the same area, in the municipality of Caçador (latitude -26.816764, longitude -50.996680), state of Santa Catarina (SC), southern Brazil. Local climate was classified as humid subtropical (Cfb) (Alvares et al., 2013), characterized by mild temperatures. Air temperature and precipitation data, obtained at a meteorological station located one kilometer from the experiment, are shown in figure 1. Soil was classified as Typic Hapludox (Soil Survey Staff, 2014) or *Nitossolo Bruno Distrófico* (Santos et al., 2013), and had the following properties in the 0.00-0.10 and 0.10-0.20 m layers, respectively: clay = 520 and 530 g kg^{-1}; pH(H_2O) (1:1 ratio) = 6.1 and 6.0; organic matter (Walkley and Black, 1934) = 35.5 and 33.7 g kg^{-1}; P (Mehlich-1 extractor) = 9.4 and 9.2 mg dm^{-3}; K (Mehlich-1 extractor) = 257.3 and 192.5 mg dm^{-3}; Ca^{2+} (KCl 1 mol L^{-1} extractor) = 7.5 and 7.6 cmol$_c$ dm^{-3}; Mg^{2+} (KCl 1 mol L^{-1} extractor) = 3.7 and 3.7 cmol$_c$ dm^{-3}; Ca-Mg-K saturation at CTC = 79.3 and 76.9 %.

Accumulated precipitation from June to November was 327 mm in 2019 and 456 mm in 2020 (Figure 1). In 2019, lower precipitation was recorded from June to August, but 17 days of rain occurred in October before the garlic harvest. In 2020, rainfall volumes were low in October and November.

Treatments and experimental design

Each plot measured 4.5 × 22 m (99 m^2) and consisted of three beds. Central bed was considered the useful area. Garlic was grown in an arrangement of five rows per bed, with a spacing of 9 cm between plants, 22.5 cm between rows, and 50 cm between beds, totaling 333 thousand plants ha^{-1}. The experimental design was a randomized blocks, in a 3 × 2 factorial scheme, with four replicates. Treatment factors consisted of a combination of three species of cover crops cultivated before garlic and two soil tillage methods. Cover crops were pearl millet (*Pennisetum glaucum*) cultivar BRS 1501, bean (*Phaseolus vulgaris*) cultivar BRS Estilo, and sunn hemp (*Crotalaria ochroleuca*); at a seed rate of 50, 50, and 10 kg ha^{-1}, respectively. Cover crops were sown on 12/26/2018 and 12/22/2019.

After a growing period of 127 days in 2019 and 131 days in 2020, cover crops were shredded into fragments of approximately 5 cm with a mechanical brush cutter and managed according to the treatments. In CT, residues from cover crops were incorporated through plowing into the 0.00-0.20 m layer. In the NT, residues from cover crops remained on the soil surface for 45 and 48 days until garlic was planted on 06/10/ 2019 or 06/14/2020, respectively. In NT, garlic was planted without tilling the soil, with only furrows formed using a direct planting machine with a cutting disc and furrower-fertilizer. In CT, garlic was planted after plowing and harrowing operations, followed by the formation of raised beds with a rototiller. Fertilizers were applied as 50 kg ha^{-1} of N (20 kg ha^{-1} at planting and 30 kg ha^{-1} at topdressing 30 days after planting), 87 kg ha^{-1} of P and 166 kg ha^{-1} of K. In NT, fertilizers were applied in furrow, while in the CT, they were applied to the entire area and incorporated in the 0.00-0.20 m soil layer. Garlic cultivar in both years was 'Chonan'. Garlic crops were irrigated by sprinklers at a frequency and quantity determined according to data on soil moisture obtained by tensiometers installed at 0.20 and 0.40 m depth.

Dry matter production of cover crops

After shredding the cover crops, the residue was sampled at three random points within each plot. A 0.25 m^2 area, delimited by a metal frame and randomly placed in the plot, was used for this evaluation. Plant material was cut at ground level, dried in an oven with forced air circulation at 65 ± 5 °C until constant mass, and subsequently weighed. Plants were ground in a Willey mill (Tecnal, R-TE-650/1, Brazil). In the 2020 season, part of the residue obtained was properly stored for subsequent decomposition assessment.

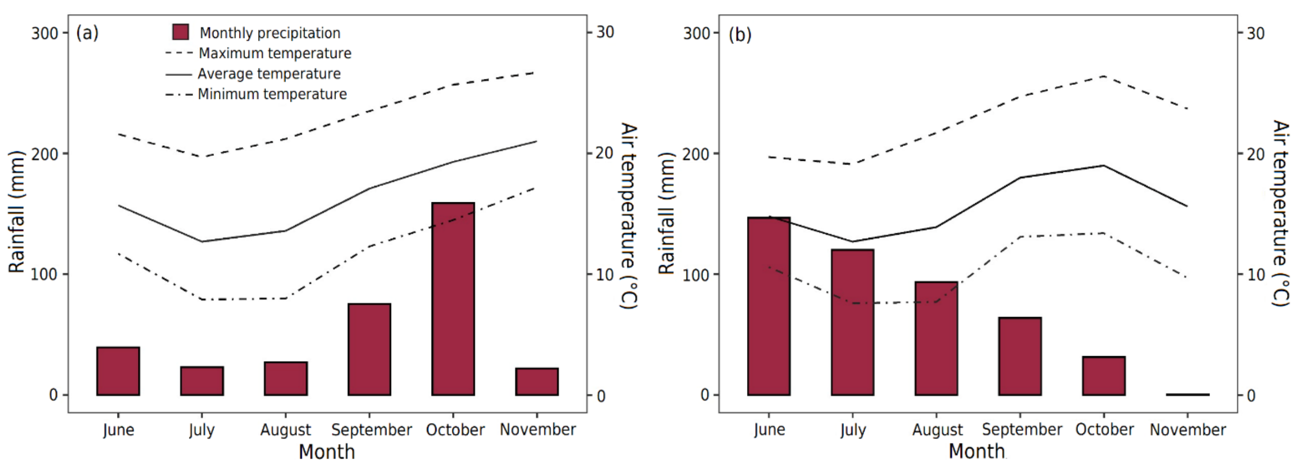

Figure 1. Monthly rainfall and maximum mean, and minimum temperatures during the garlic crop cycle in the experimental area in 2019 (a) and 2020 (b) crop seasons, in southern Brazil.

Cover crop residue decomposition (litterbags)

In the second year of the experiment (2020), the decomposition and nutrient release rate from cover crop residues were evaluated. For this, at the day of shredding, cover crops were collected and further chopped into 5-cm fragments. Twenty grams of residue were added to litterbags (Keuskamp et al., 2013) of 2-mm mesh opening and 0.20 × 0.20 m dimension, representing the residue deposition of 5 Mg ha^{-1} of dry matter (DM). Eighteen litterbags for each of the three cover crops were placed on the soil surface in one plot cultivated under NT, while in CT method, 18 litterbags in one plot were buried to a depth of about 0.10 m. Subsequently, three samples were taken per tillage method, at 48, 84, 115, 134, 158, and 189 days after the initial deposition of the litterbags, corresponding to planting (S0), V4, V8, V11, R3, and the garlic harvest (R5) (Rosa, 2015), respectively. In each sampling, the litterbags were opened, and soil residues were manually removed with a brush. The material was dried in a forced air circulation oven at 65 ± 5 °C, until it reached a constant weight. Subsequently, the residues were ground in a Willey mill (Tecnal, R-TE-650/1, Brazil) and reserved for further analysis.

Garlic leaf sampling

To assess the nutritional status of garlic plants, ten young leaves (4th leaf completely expanded) were collected in each plot to differentiate the plants visually (Hahn et al., 2020). Leaves were washed in distilled water, and dried in a forced air circulation oven at 65 ± 5 °C, until they reached a constant weight and, subsequently, were ground in a Willey-type mill.

Nutrient determination in garlic plant tissue and cover crops

Parts of the garlic leaves, original cover crop residues and removed litterbag-residues, were subjected to sulfur digestion in a digestion block. The resulting extract was distilled in a micro-Kjeldahl distiller (Tecnal, TE-0363, Brazil) and subjected to titration with sulfuric acid 0.025 mol L^{-1} (Tedesco et al., 1995) for determining the nitrogen concentration. Another part of the tissue was subjected to nitric-perchloric digestion (HNO_3:$HClO_4$ - 3:1 v/v) (Miller, 1998). Phosphorus concentration was determined by UV-visible spectrophotometry (Bell Photonics, 1105, Brazil) at 882 nm (Murphy and Riley, 1962). Potassium concentration was determined using a flame photometer (PerkinElmer, AA200, Norwalk, USA). A third part of the cover crop residues, as well as those added and removed from the decomposition bags at sampling times, were subjected to wet oxidation in a sulphochromic solution - $K_2Cr_2O_7 + H_2SO_4$ (Walkley and Black, 1934) for carbon determination.

Garlic yield

Garlic bulbs were harvested from one linear meter of the plot's central bed. After harvesting, the plants were subjected to a 40-day curing period in a warehouse. Marketable bulbs were classified into the following categories: #2 (<32 mm), #3 (32-37 mm), #4 (37-42 mm), #5 (42-47 mm), # 6 (47-56 mm), and #7 (>56 mm), according to ordinance No. 242, of September 17, 1992 of MAPA (Luengo et al., 1999). Bulbs with secondary growth (over-sprouted) or damaged were considered non-marketable.

Soil sampling and nutrient analysis

Five days after planting and on the day of garlic harvesting, soil samples were collected in the 0.00-0.10 and 0.10-0.20 m layers. Soil was air-dried until constant weight. Phosphorus and K were extracted by Mehlich-1 (Mehlich, 1953) and quantified by plasma emission spectroscopy (ICP-OES). Total carbon was determined by oxidation with K dichromate (Walkley and Black, 1934) and then multiplied by 1.724 to obtain the organic matter content (Silva, 2009).

Statistical analysis

Response variables of garlic yield and nutrient content were subjected to analysis of variance (ANOVA). The factors ‘cover crops’, ‘soil tillage method’, and ‘year of cultivation’ were evaluated, as well as their interactions. Normality of residues was tested using the Shapiro-Wilk test and compared using the Tukey test ($p<0.05$). All analyses were performed in the R statistical environment (R Development Core Team, 2022), using the “agricolae” (Mendiburu, 2021) and “Rmisc” (Hope, 2013) packages for descriptive statistical analysis and the “ggplot2” (Wickham, 2021) package for graphic composition.

Dry matter decomposition rates (kDM), N (kN), P (kP), and K (kK) and the remaining mass of DM, N, P, and K (A) were calculated based on the single-compartment regression model adjusted to observed values (Jenny et al., 1949). The model has the following equation: DM, N, P, and K = $Ae^{(-kt)}$, in which: DM, N, P, and K are the remaining amounts of DM and nutrients (% DM, N, P, and K added) after a period of time t, in days; A is the initial amount of dry matter or nutrient; k is the residue decomposition constant. With the value of k, the half-life time ($T_{1/2}$) was calculated, which expresses the period necessary for half of the residue to decompose or for half of the nutrients contained in the residue to be released.

RESULTS

Nutrient in garlic leaves

Nutrient contents in garlic leaves were influenced by soil tillage method, cover crop species, and cultivation year (Figure 2). Nitrogen content in garlic leaves was higher in plants grown under CT than NT (Figure 2a), and in the 2020 harvest compared to 2019 (Figure 2b). The highest P content in leaves was observed in garlic plants grown in the CT, after sunn hemp (Figure 2c). The highest K content was observed in plants grown under CT, after millet (Figure 2e), from the 2019 harvest (Figure 2f).

Garlic yield

Garlic total mean yield was 16.2 Mg ha^{-1} yr^{-1} and was not affected by the soil tillage method or cover crop species (Figures 3a and 3b). However, the total yield was 10 % higher in the 2019 harvest (Figure 3c). There was an interaction between cover crop species and soil tillage method for marketable production (Figure 3d), demonstrating that bean cover crop and NT favored garlic yield, on average 15.6 % in relation do CT. The highest yield of non-marketable garlic was in CT in 2019 (Figure 3f). In this year, the highest rainfall was observed in the month of October, which preceded the harvest (Figure 1a).

Dry matter production by cover crops and nutrient accumulation

Soil tillage method did not affect the dry matter (DM) production of cover crops (Figure 4a), but there was variation in the production of different cover crops (Figure 4b). Millet and sunn hemp had a mean DM production 3.4 times greater than bean. Accumulation of N (Figure 4d), P (Figure 4e), and K (Figure 4f) in DM was 19, 4, and 29 kg ha^{-1} yr^{-1} for bean; 115, 20, and 224 kg ha^{-1} yr^{-1} for millet; and 132, 14, and 170 kg ha^{-1} yr^{-1} for sunn hemp, considering DM production of 2.4, 8.8, and 7.5 Mg ha^{-1} yr^{-1}, respectively. Millet showed a high capacity for P, K, and C accumulation (Figure 4c), compared to bean and sunn hemp.

Dry matter decomposition and nutrient releases

Cover crop DM decomposition (k) was faster in the CT (Table 1), with an increase of 35 % in this system, in addition to reducing the half-life ($T_{1/2}$) of the three cover crops

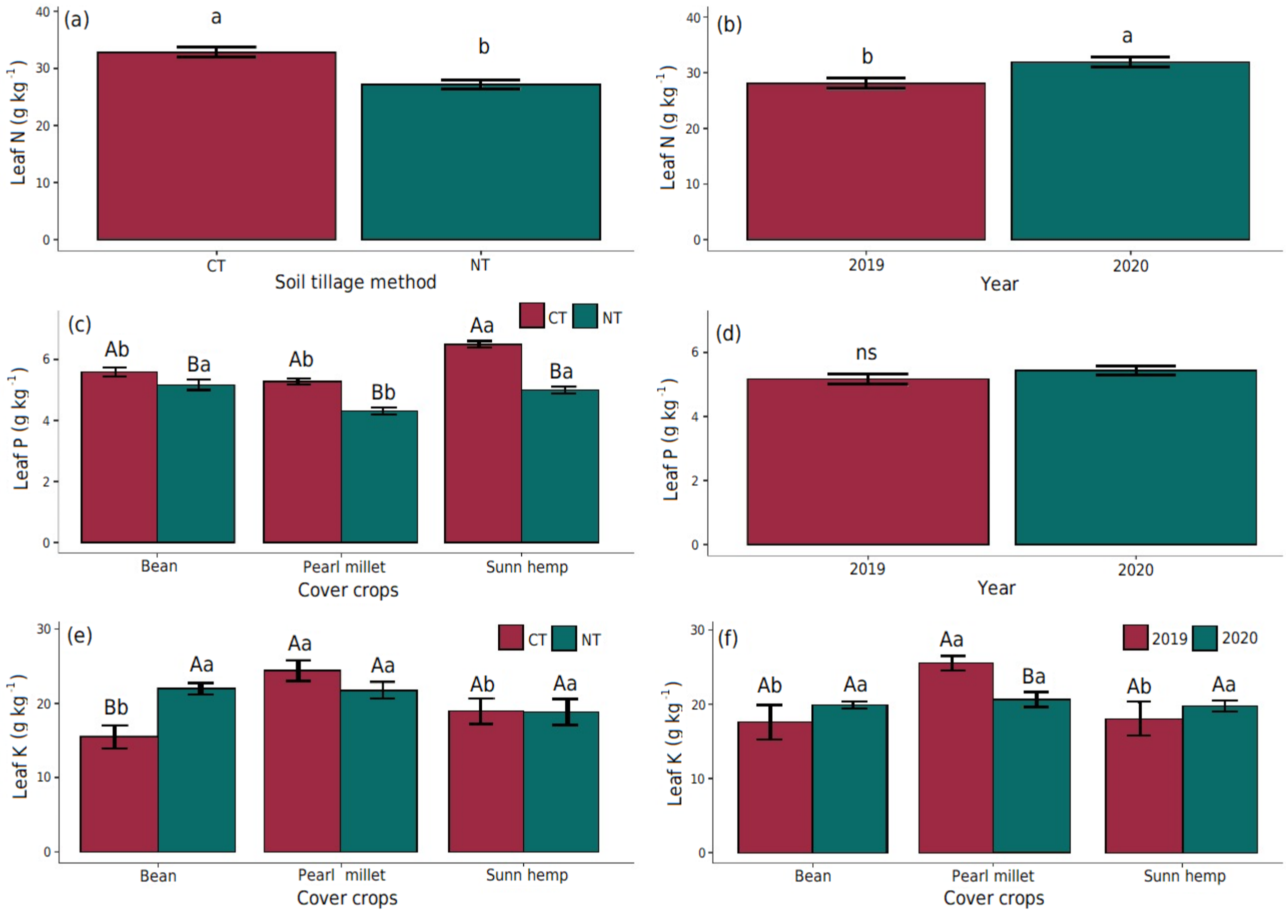

Figure 2. Contents of N (a, b), P (c, d), and K (e, f) in garlic leaves grown under CT (conventional tillage) and NT (no-tillage) with residues of bean (*Phaseolus vulgaris*), pearl millet (*Pennisetum glaucum*) and sunn hemp (*Crotalaria ochroleuca*) in southern Brazil during the 2019 and 2020 crop seasons. Panels (a, b, d) portray the fitted bars considering the effect of soil tillage method (a) and crop season (b, d), once interaction was non-significant ($p<0.05$). Panels (c, e, f) portray the fitted bars considering the interaction of the soil tillage method and cover crop (c, e) and the crop season and cover crop (f). Equal lowercase letters do not differ from each other using the Tukey test ($p<0.05$) (a, b, d). Equal uppercase letters for soil tillage system (c, e) and year (f) or lowercase letters for cover crop species (c, e, f) do not differ from each other using the Tukey test ($p<0.05$); ns: not significant.

by 26 %, in relation to NT. Sunn hemp residue showed the highest decomposition rate, regardless of the soil tillage method. Half-life of residue-N was longer in millet, with an increase of 98 days in NT compared to CT. The CT method increased the N release rate by an average of 69 %, reducing the half-life by 40 %. Half-life of P showed an interval between CT and NT of 28 and 20 days for millet and sunn hemp, respectively. However, K was the nutrient with the highest release rate, with 50 % of the nutrient released to the soil in an interval of 16 and 19 days, regardless of the crop or soil tillage method.

Residues decomposition from cover crop species was faster in the CT system (Figure 5). Potassium was completely released from DM into the soil in the first 50 days of evaluation. Bean crop accumulated and released smaller nutrient amounts due to the lower DM production (Figure 5).

The mean C/N ratios of cover crops in the two cultivation systems were 64.8, 40.8, and 28.7 for bean, millet, and sunn hemp, respectively (Table 2). Cover plant species with a higher C/N ratio showed lower rates of DM decomposition, as well as a lower rate of N and P nutrient release, except for K (Figure 6). Furthermore, the NT presented a residual amount of DM after 189 days of evaluation 1.3, 1.3, and 2.7 times higher for bean, millet, and sunn hemp, respectively, compared to the CT system.

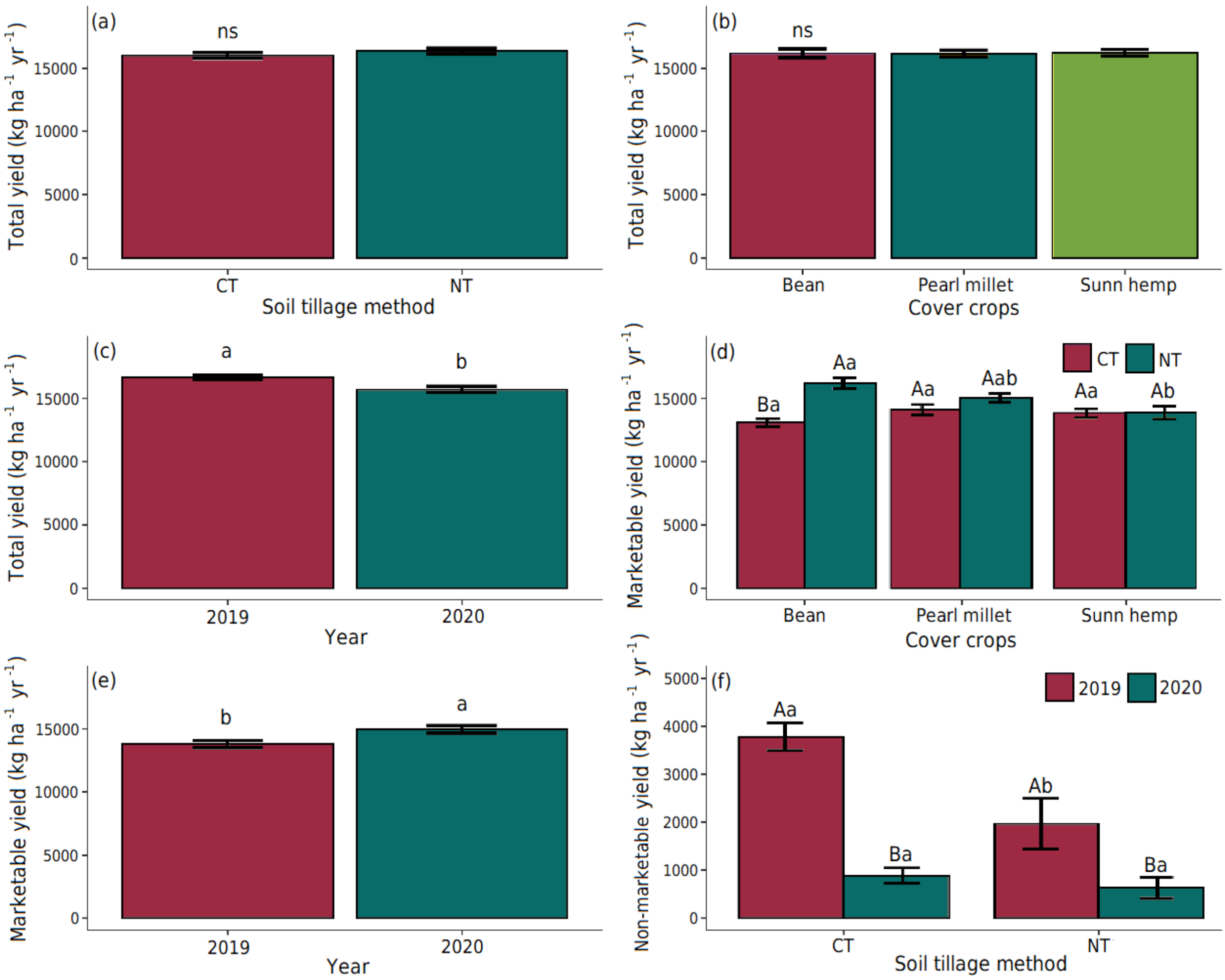

Figure 3. Garlic total yield (a, b, c), marketable yield (d, e) and non-marketable yield (f) grown under CT (conventional tillage) and NT (no-tillage) with residues of bean (*Phaseolus vulgaris*), pearl millet (*Pennisetum glaucum*) and sunn hemp (*Crotalaria ochroleuca*) in southern Brazil, during the 2019 and 2020 crop seasons. Panels (a, b, c, e) portray the fitted bars considering the effect of soil tillage method (a), cover crop (b) and crop season (c, e), once interaction was non-significant ($p<0.05$). Panels (d, f) portray the fitted bars considering the interaction of soil tillage system and cover crop (d) and the crop season and soil tillage method (f). Equal lowercase letters do not differ from each other using the Tukey test ($p<0.05$) (a, c, e). Equal uppercase letters for soil tillage method (d) and year (f) or lowercase letters for cover crops (d) and soil tillage method (f) do not differ from each other using the Tukey test ($p<0.05$); ns: not significant.

DISCUSSION

Nutrient content in garlic leaves

The highest contents of N and P were observed in garlic leaves grown in CT method, when compared to the NT (Figures 2a and 2c). Nitrogen foliar content in CT was above the critical level of 26 g kg^{-1} proposed by Hahn et al. (2020) for garlic, when grown in a subtropical climate. Phosphorus content in leaves was within the sufficiency range of 5.2 - 6.3 g kg^{-1} proposed by Cunha et al. (2016). However, the K content was below the sufficiency range of 29.7 - 36.4 g kg^{-1}. The highest nutrient contents observed in garlic grown in CT can be attributed to soil mixing, which stimulates the mineralization of organic N and P (Kristensen et al., 2000), thus increasing availability to plants. It is important to observe before planting garlic, phosphate fertilizer (87 kg P ha^{-1}) was applied. However, soil mixing exposes P to a greater number of functional groups of inorganic reactive particles, enhancing adsorption, which reduces availability. Therefore, it is possible a large part of the P absorbed by the plant comes from other sources, including decomposing plant residues. Despite the lower accumulation and release of P by the bean crop (4 kg ha^{-1}), the leaf contents in garlic were higher in relation to millet in the NT. This leads us to consider that the amount of P released by the cover crop has a smaller

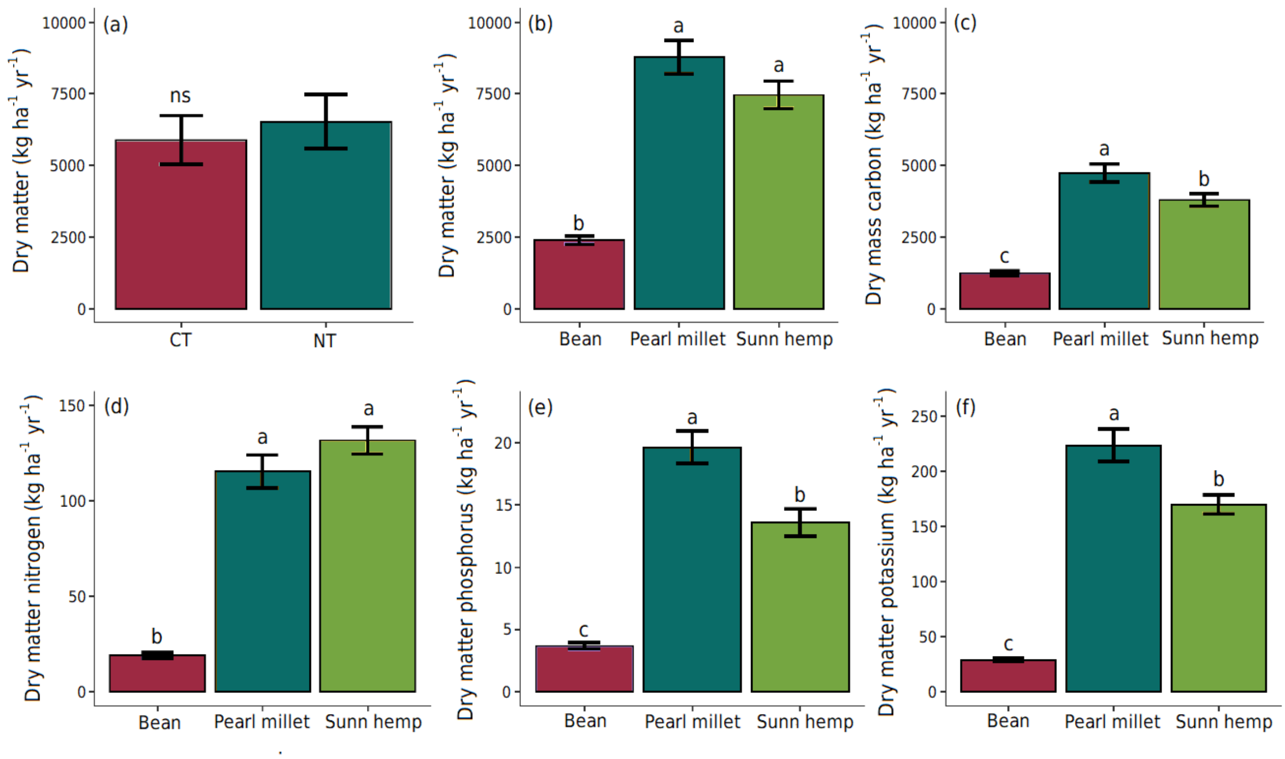

Figure 4. Dry matter production (a, b) and accumulation of C (c), N (d), P (e), and K (f) in the biomass of bean (*Phaseolus vulgaris*), pearl millet (*Pennisetum glaucum*) and sunn hemp (*Crotalaria ochroleuca*) grown under CT (conventional tillage) and NT (no-tillage) in southern Brazil during the 2019 and 2020 crop seasons. Panels (a, b, c, d, e, f) portray the fitted bars considering the effect of soil tillage method (a) and cover crops (b, c, d, e, f), once interaction was nonsignificant at alpha 5 %. Values were composed of averages of the 2019 and 2020 crop seasons. Equal letters do not differ from each other using the Tukey test ($p<0.05$) (a, b, c, d, e, f); ns: not significant.

impact when compared to soil tillage method on nutrient availability. This conclusion is corroborated when evaluating P levels in the soil, which are affected by soil tillage system and cultivation year, but not by cover crops.

Garlic yield

The largest yield of marketable garlic was observed in soil with bean residue in the NT (Figure 3d). Traditionally, in the southern region of Brazil, garlic is grown in succession to bean. Therefore, directly planting garlic in bean residues continues to be suggested. Total garlic yield was only affected by the cultivation year, with no effect from the soil tillage method or cover crops (Figure 3c). Meteorological conditions observed in the first year of garlic cultivation favored greater non-marketable production (Figure 3f), due to the greater volume of rainfall in the month before harvest (Figure 1). This occurs because excess soil moisture, combined with less solar radiation, causes greater garlic oversprouting (Wu et al., 2016). Based on our findings, in years of high rainfall volume, the NT can be a key to improving marketable garlic yields; once for garlic growers, high yield does not necessarily mean high profitability when a market quality classification must be observed. In addition, choosing the correct garlic cultivar with a short cycle may reduce garlic oversprouting.

Soil tillage method or cover crops did not affect total garlic yield (Figures 3a and 3b). This can be explained because areas cultivated with garlic are normally subjected to fertilization to maintain nutrient levels at or above a critical level. This is necessary because garlic has a small root system, which can decrease the likelihood of nutrient absorption (Khokhar, 2023). In addition, garlic has high productivity. Therefore, maintaining adequate nutrient levels in the soil is always necessary.

Table 1. Parameters of the adjustment models to the measured values of dry matter, remaining N, P, and K, and half-life in treatments with cover crops under CT (conventional tillage) and NT (no-tillage) in southern Brazil, in the 2020 crop season

Cover Crop	Soil tillage method	Dry Matter			N			P			K		
		k	$T_{1/2}$	R^2	k	$T_{1/2}$	R^2	k	$T_{1/2}$	R^2	k	$T_{1/2}$	R^2
Bean	CT	0.0059	118	0.90**	0.0058	121	0.88**	0.0323	125	0.90**	0.0367	19	0.81**
Bean	NT	0.0046	152	0.84**	0.0034	197	0.58**	0.0318	119	0.74**	0.0450	16	0.96**
Pearl millet	CT	0.0063	110	0.85**	0.0058	119	0.76**	0.0432	103	0.87**	0.0414	18	0.88**
Pearl millet	NT	0.0045	155	0.90**	0.0032	217	0.55**	0.0407	131	0.87**	0.0413	17	0.90**
Sunn hemp	CT	0.0100	69	0.83**	0.0097	72	0.76**	0.0465	70	0.77**	0.0467	16	0.89**
Sunn hemp	NT	0.0073	95	0.94**	0.0063	111	0.87**	0.0422	90	0.83**	0.0427	17	0.85**

CT: Conventional tillage; NT: No-tillage; $T_{1/2}$: half-life time in days; k: decomposition rate per day; $T_{1/2}$ parameters calculated from the equation $X = Ae^{(-kt)}$. **Statistically significant by the Tukey test (p<0.01).

Dry matter production by cover crops and nutrient releases

The greater DM production of millet and sunn hemp provided the greatest accumulations of nutrients (N, P, and K) (Figure 4). Millet presented the highest DM production (8.8 Mg ha^{-1}), accumulating 115, 20, and 224 kg ha^{-1} yr^{-1} of N, P, and K, respectively. The larger quantities of millet and sunn hemp residues can increase soil surface protection, dissipating the kinetic energy of raindrops. This reduces the likelihood of soil aggregate degradation, preventing water erosion, which is desirable as it prevents soil and nutrient loss (Almeida et al., 2016; Wolschick et al., 2021). Furthermore, nutrients absorbed and accumulated in the tissue, such as N, P, K and other nutrients, can return to the soil after deposition and decomposition of residues (Giacomini et al., 2003; Weiler et al., 2019). Part of the C in tissues may return to the soil, increasing organic matter levels (Kuneski et al., 2023), while another part may be released into the atmosphere as CO_2. Decomposition rate in the subtropical climate, as in our study, presented lower DM half-life (Table 1) compared to semi-arid (Pereira et al., 2023) or tropical Brazilian regions (Mangaravite et al., 2023). This reinforces the importance of studies in different regions with diverse climatic conditions to improve the knowledge of litter decomposition and its influences on nutrient cycling.

The DM decomposition rate and N and P release are influenced by the C/N ratio of the cover crops, with residues with a higher C/N ratio (Table 2), showing a higher percentage of permanence at the end of the evaluation period (Figures 6a, 6b and 6c). Therefore, the lowest coefficient of mineralization values in bean and millet are related to the higher C/N ratio compared to sunn hemp (Table 1). This occurs due to the lack of N available to the microbial biomass that participates in decomposition (Thapa et al., 2022). The higher value of C/N ratio for cover crops compared to the values presented in the literature (Rosolem et al., 2004; Boer et al., 2007; Rondon et al., 2007; Soratto et al., 2012; Raphael et al., 2016; Xavier et al., 2017) occurred because the management of cover crops was conducted at the end of their cycle, allowing the beginning of decomposition of the more labile fractions, with lower C/N ratio and lignin content (Weiler et al., 2019).

Higher decomposition rates and release of N, P, and K in bean, millet, and sunn hemp residues were observed using the CT method. Residue in NT has less contact with soil (Thapa et al., 2022), which reduces the decomposition rate and, consequently, the residue colonization by microorganisms tends to be lower. Furthermore, most of the residues on the soil surface in NT remain dry due to solar radiation, which can reduce decomposition. On the other hand, in CT the contact area of the residue with the soil is larger and the

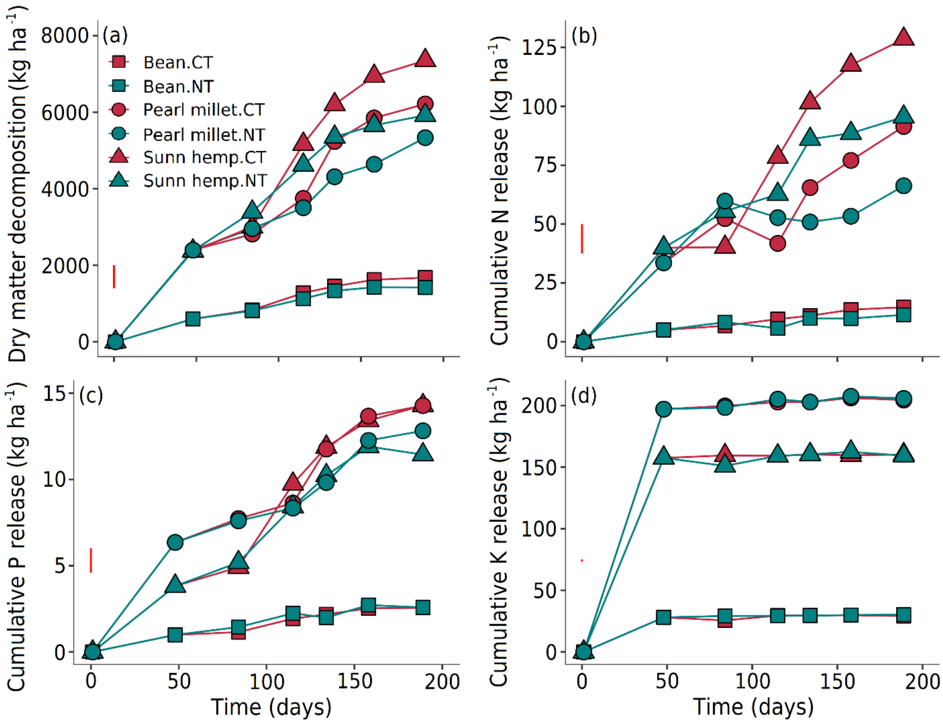

Figure 5. Dry matter decomposition (a) of cover crop residues and accumulated release of N (b), P (c), and K (d) under CT (conventional tillage) and NT (no-tillage) in southern Brazil, during a 189-day, in the 2020 crop season. Red vertical line represents the minimum significant differences (MSD) at 5 % significance.

residue remains with a higher water content, which increases the decomposition speed (35 %, on average) and the release of nutrients.

After being absorbed by the plant, N is incorporated into organic compounds, just as P is a component of phospholipids, nucleic acids, and other compounds (Ferreira et al., 2014; Taiz et al., 2015). Therefore, the release of N and P in plant dry matter is slower. Initially, the more soluble forms of N and P are released when the residue comes into contact with water. Subsequently, the release of nutrients from less soluble fractions depends on the activity of microorganisms (Ferreira et al., 2014).

Potassium proved to be a nutrient highly accumulated by millet (Figure 4f), but also quickly available, with a maximum half-life of 19 days, regardless of the evaluated crop or adopted soil tillage method (Figure 5d). This occurs because K is not part of biomolecules of plant tissue (Taiz et al., 2015; Salume et al., 2020) and is in the ionic form K^+ and highly soluble; therefore, it is quickly released into the soil solution after the occurrence of rain and the beginning of the decomposition process (Boer et al., 2007). When available to plants, K causes positive effects, helping to alleviate biotic and abiotic stresses (Mahiwal and Pandey, 2022).

Soil mixing provided a significant increase in the cover crops decomposition rate, contributing to a 25 % mean reduction in the half-life for the three evaluated cover crops (Table 1). This occurred because soil mixing causes greater contact between the cover crop biomass and the soil and decomposer microorganisms, which favors the mineralization rate (Carvalho et al., 2009; Lynch et al., 2016). Furthermore, mixing allows greater organic matter mineralization, quickly increasing mineral N in the soil (Balesdent et al., 2000; Kristensen et al., 2000) and stimulating microbiological activity.

Table 2. Chemical characterization of bean (*Phaseolus vulgaris*), pearl millet (*Pennisetum glaucum*) and sunn hemp (*Crotalaria ochroleuca*) residues at the time of litterbags deposition in garlic cultivation in southern Brazil

Variable	Bean	Pearl millet	Sunn hemp
C (%)*	51.8	53.9	50.8
N (g kg^{-1})*	8.0	13.2	17.7
P (g kg^{-1})*	1.5	2.2	1.8
K (g kg^{-1})*	12.1	25.5	22.8
Ca (g kg^{-1})*	16.2	7.8	11.0
Mg (g kg^{-1})*	4.5	3.9	3.7
S (g kg^{-1})*	1.2	1.1	1.2
Mn (mg kg^{-1})*	20.8	57.5	65.8
Zn (mg kg^{-1})*	17.7	29.0	29.7
Cu (mg kg^{-1})*	12.9	19.5	37.3
B (mg kg^{-1})*	18.8	5.0	19.7
C/N ratio	64.8	40.8	28.7

*Total nutrient content. Values represent the average of the 2019 and 2020 crop seasons.

Several benefits are associated with the NT system, such as increased carbon content (Tiecher et al., 2020; Kuneski et al., 2023), greater biological activity (Balota et al., 2014; Fontana et al., 2024), less loss of soil, water and nutrients (Merten et al., 2015; Wolschick et al., 2021) and more efficient nutrient use (Tiecher et al., 2017). However, in agriculture systems, soil erosion contributes to C losses, with sediment transports with a high content of organic fractions (Juřicová et al., 2022). In this case, to achieve soil sustainability, it is essential to maintain soil conservation, using practices that provide soil protection and contribute to high yields. Despite the NT in garlic production being incipient, this technique can provide important results to the garlic sustainability system.

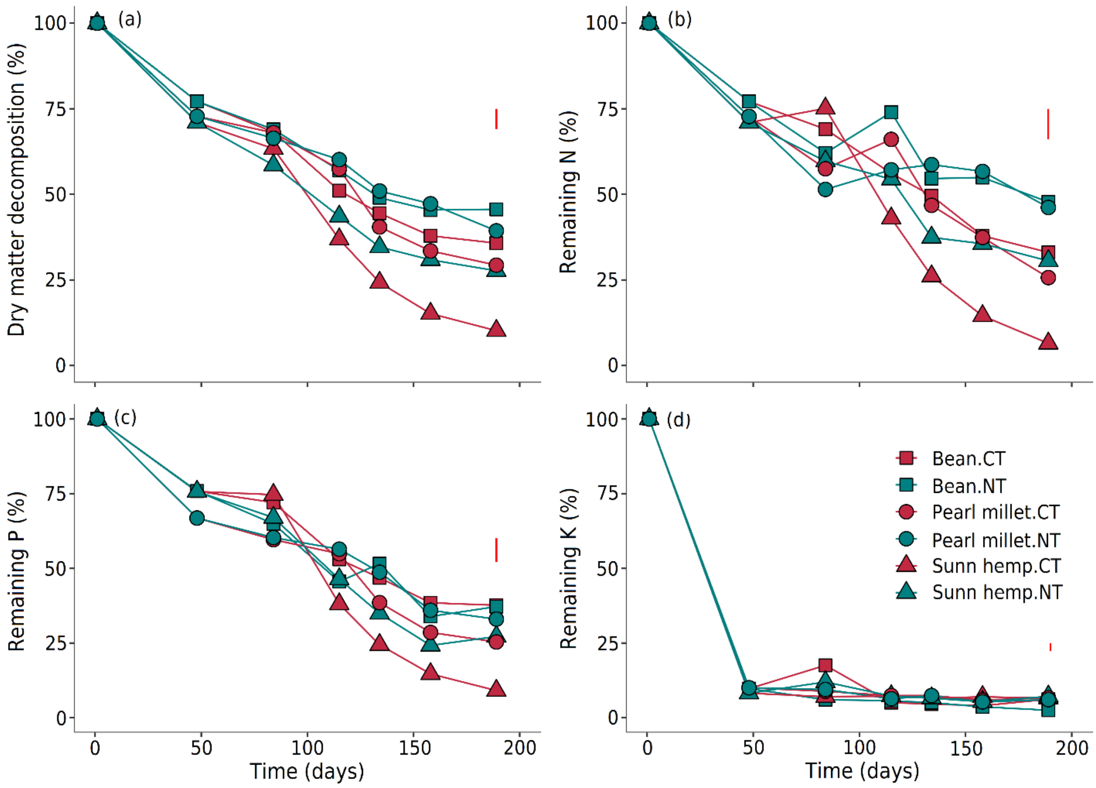

Figure 6. Remaining percentage of dry matter (a) and nutrients N (b), P (c), and K (d) of cover crops under CT (conventional tillage) and NT (no-tillage) in southern Brazil, during a 189-day, in the 2020 crop season. Red vertical line represents the minimum significant differences (MSD) at 5 % significance.

CONCLUSION

Cover crop species and soil tillage method directly affect the accumulation and release of nutrients. Cultivation of millet and sunn hemp intensifies nutrient cycling. Conventional tillage method increases the decomposition rate and release of nutrients in relation to the no-tillage. Garlic cultivation in the no-tillage method increases marketable garlic yield in bean residue, in addition to keeping cover crop residues on the soil surface for longer periods. No-tillage system can be an important choice to improve garlic quality, mainly in rainy crop seasons.

SUPPLEMENTARY DATA

Supplementary data to this article can be found online at https://www.rbcsjournal.org/wp-content/uploads/articles_xml/1806-9657-rbcs-48-e0230134/1806-9657-rbcs-48-e0230134-suppl01.pdf.

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