Revista
Brasileira de
Ciência do Solo

Division - Soil Use and Management | Commission - Land Use Planning

Residual biomass quality index: a tool for conservation agriculture

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ABSTRACT: One of the pillars of a no-tillage system is the addition of adequate amounts of residue to keep the soil continuously covered. Cover crops are a tool for supplying the demand for the permanence of residues on the soil surface and releasing nutrients to the soil. However, there is no index that relates these two factors and can reconcile the maximum permanence of crop residues in the soil with the maximum N supply via N mineralization of such residues. This study aimed to assess the effect of different cover crops on the decomposition rate of residues and N release, using the residual biomass quality index (RBQI) to evaluate cover crop systems. The study was conducted in a long-term experiment in a *Latossolo Vermelho* (Ferralsol, Oxisol) under no-tillage in the two agricultural years 2017/18 and 2018/19. The experiment was in a split-plot factorial scheme with eight winter cover crops and three N rates in randomized blocks with three replications. The cover crop systems were black oat (O), common vetch (V), forage radish (R), white lupine, rye, annual ryegrass, oat + vetch (O+V), and oat + vetch + radish (O+V+R). The N rates applied to the corn in succession were 0, 90, and 180 kg ha^{-1}. The decomposition rate, remaining dry mass (RDM) on the soil surface, N release rate, and N accumulated release (NAR) were assessed using litterbags. Considering NAR and RDM evaluated for up to 105 days, the N release index (NRI) and remaining dry mass index (RDMI) were determined, and the residual biomass quality index (RBQI) was obtained using the product of these variables. The consortia O+V+R and O+V resulted in a decomposition rate and N release rate closer to the rates observed for oats and rye. The NAR was similar to that observed for Fabaceae species, and the RDM was similar or superior to that found for black oat. With these characteristics, the systems in the O+V+R and O+V consortia presented the highest values of RBQI, ranging from 0.61 to 0.90, indicating that RBQI is a potential indicator for choosing cover crop systems that promote greater sustainability of the no-tillage system. The use of N fertilizer in corn did not change the rates of decomposition and N release from the residues of cover crops.

Keywords: cover crops, consortium, decomposition, nitrogen.

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Received: November 09, 2022
Approved: March 30, 2023

How to cite: Cassol C, Conceição PC, Amadori C, Haskel MK, Freitas LA, Tomazoni AR. Residual biomass quality index: a tool for conservation agriculture. Rev Bras Cienc Solo. 2023;47:e0220150.
https://doi.org/10.36783/18069657rbcs20220150

Editors: José Miguel Reichert and Luciano da Silva Souza.

INTRODUCTION

The use of soil cover crops has great potential for increasing the sustainability of production systems (Rigon et al., 2020). This potential varies according to the species included in the production system and as a function of dry mass (DM) addition, nutrient cycling, decomposition, and release of nutrients, mainly nitrogen (N), as well their effects on soil's physical, chemical, and biological properties.

Decomposition process and nutrient release of cover crops are dynamic, mediated by the action of microorganisms, and associated with the quality of the vegetable material, such as the contents of N, cellulose, and hemicellulose, as well as lignin/N and C/N ratio (Tian et al., 1995; Kumar and Goh, 2003; Weiler et al., 2022). When associated with climatic conditions, they control the decomposition rate of cover crops in the field (Acosta et al., 2014; Thapa et al., 2022). Another factor that might differentiate the decomposition rate for the same species in different years is the amount of dry matter in the labile pool (Doneda et al., 2012), which presents greater ease of decomposition and might vary depending on the plant growth phase (flowering or maturation) that is managed (Carvalho et al., 2015). Besides that, N fertilization in the subsequent commercial crop is also an important factor, in which the method of fertilizer application (surface, incorporated or subsurface) and the timing of application can also modify the decomposition rates and nutrients release (Costa et al., 2016), as well as the amounts of soil N, which can alter the chemical composition of the tissues.

Residue decomposition of different species, such as those from Fabaceae or Poaceae may have different effects on soil protection and commercial crop yield, which may negatively or positively affect the cultivation system (Aita et al., 2014). When cover crops with a high C/N ratio are used, decomposition occurs more slowly and normally with microbial N immobilization. On the other hand, the use of winter cover crops with a low C/N ratio, such as Fabaceae or Brassicaceae species, causes rapid N release and decomposition of residues, leaving the soil exposed at the beginning of summer cultivation (Ziech et al., 2015). Hence, it is important to properly choose the type of cover crop that will precede commercial crops to obtain a balance in providing these essential ecosystem services for the sustainability of the production system.

Provision of ecosystem services for soil protection through the permanence of cover crops residues on the soil surface and N release for commercial crops can be obtained with a mixture of different cover crop species in different edaphoclimatic conditions (Aita and Giacomini, 2003; Aita et al,. 2004; Lawson et al., 2013; Brust et al., 2014; Baraibar et al., 2017; Wendling et al., 2017; Drost et al., 2020; Lacey et al., 2020; Reiss and Drinkwater, 2020), taking advantage of the interspecific synergies between species. However, there are no indices that assess the supply balance of these ecosystem benefits, and there are only indices that correlate the chemical characteristics of the cover crops with the rate of N release (Tian et al., 1995; Kumar and Goh, 2003), where the authors integrate the effects of the C/N ratio, lignin, and polyphenols to create a residual biomass quality index (PQRI) and predict N release.

In a conceptual model, the higher the residual biomass quality index (RBQI), better the balance of the cover crop system regarding N release and the permanence of residues on the soil. The ideal system would have maximum N release and maximum remaining dry matter. In this way, using the RBQI to assess the supply balance of such ecosystem benefits will amplify these benefits in the production system.

The RBQI also contributes to the production systems being able to raise their quality, through the no-tillage participatory quality index (PQI), which has been used in Brazil to assess the level of adoption of conservation practices by farmers and to qualify the production system according to the regional reality (Nunes et al., 2020; Telles et al., 2020; Possamai et al., 2022). The persistence of straw in the soil is one of the index's indicators that have the highest correlation with the PQI.

We propose the RBQI to classify cover crop systems in terms of balance between N release and the permanence of residues on the soil surface. Our hypothesis is that the use of cover crops in consortia results in higher RBQI value than single crops, increasing with species diversity. This study aimed to assess the effect of different cover crops on the decomposition rate of residues and N release, using the RBQI to evaluate cover crop systems.

MATERIALS AND METHODS

Experimental site and design

The study was conducted in a long-term experiment located at the experimental station of the Federal Technological University of Paraná, Dois Vizinhos, Paraná State, Brazil (25° 42′ 52″ S and 53° 03′ 94″ W, 530 m altitude). The regional climate is humid subtropical (Cfa, Koppen's classification system) with an annual precipitation of 2010 mm (Vieira et al., 2018). The local soil is *Latossolo Vermelho* (Santos et al., 2018), equivalent to Ferralsol (IUSS Working Group WRB, 2015), and Oxisol (Soil Survey Staff, 1999), with clay texture (773 g kg^{-1} clay, 224 g kg^{-1} silt, and 3 g kg^{-1} sand). The initial soil chemical properties in the 0.00-0.20 m soil layer were: pH ($CaCl_2$) = 5.3; pH SMP index = 6.4; organic matter = 40.8 g kg^{-1}; P (Mehlich 1) = 4.3 mg dm^{-3}; K^+ = 0.2 cmol$_c$ dm^{-3}; Ca^{2+} = 6.0 cmol$_c$ dm^{-3}; Mg^{2+} = 2.8 cmol$_c$ dm^{-3}; H+Al = 3.8 cmol$_c$ dm^{-3}; Sum of bases = 9.0 cmol$_c$ dm^{-3}; cation exchange capacity (CEC) = 12.8 cmol$_c$ dm^{-3}; and base saturation = 70 %.

The experiment was initiated in 2010 and has been cultivated in no-tillage with a succession of winter cover crops and corn (*Zea mays* L.), with the application of two rates of mineral N (0 and 180 kg ha^{-1}) on corn. However, in the two agricultural years evaluated, 2017/18 and 2018/19 (May to February), an intermediate rate was also applied, 90 kg ha^{-1} N. Therefore, the experiment was in a split-plot factorial scheme with eight winter cover crops and three N rates, in randomized blocks with three replications.

The treatments in the main plots included eight winter cover crop systems: black oats (O) (*Avena strigosa* Schreb.) sowing at a density of 90 kg ha^{-1}, common vetch (V) (*Vicia sativa* L.) at 40 kg ha^{-1}, forage radish (R) (*Raphanus sativus* L.) at 15 kg ha^{-1}, white lupine (*Lupinus albus* L.) at 100 kg ha^{-1}, rye (*Secale cereale* L.) at 50 kg ha^{-1}, and annual ryegrass (*Lolium multiflorum* Lam.) at 50 kg ha^{-1}, as well as the consortia of black oat + vetch (O+V) at 60+40 kg ha^{-1}, and oat + vetch + radish (O+V+R) at 60+30+10 kg ha^{-1}. In the subplots (5 × 15 m), three rates of mineral N (0, 90, and 180 kg ha^{-1}) were manually applied to corn using urea (46 % N).

Cover crops were mechanically sown with a space of 0.17 m between rows, without fertilization, in May (02/05/2017 and 22/05/2018) after total area desiccation. The chemical management of the cover crop occurred 126 and 105 days after sowing, for 2017 and 2018, respectively, with an application of herbicide (glyphosate at 576 g ha^{-1}). The corn was sown 30 and 8 days after the chemical management of cover crops for 2017 and 2018, respectively. Nitrogen fertilization was manually performed 33 days after corn sowing (DACS) according to the treatment rates.

Biomass parameters

Biomass production was determined by collecting all the biomass in two random points in each subplot, in an area of 0.25 m^2 measured by a metallic frame, 115 and 87 days after sowing, in 2017 and 2018, respectively. Some of the cover crops were at the flowering stage, such as oat, rye, and lupine, while radish was at the end of flowering and, vetch and ryegrass did not reach this stage. In the consortium treatments, botanical species were separated, determining the participation of each species in the total biomass production (Table 1). Samples were dried in a forced-air circulation oven at 55 °C until constant weight (48-72 h) to determine DM production.

Table 1. Participation of each species in total dry mass production and accumulated N in the consortium cover crop systems in the agricultural years 2017/18 and 2018/19

Cover crop species	Dry matter			N content		
	2017/18	2018/19	Mean	2017/18	2018/19	Mean
	%					
O+V+R						
Oat (O)	58	53	56	44	37	40
Vetch (V)	19	16	18	32	27	30
Radish (R)	23	30	27	24	36	30
Total	100	100	100	100	100	100
O+V						
Oat (O)	80	72	76	64	58	61
Vetch (V)	20	28	24	36	42	39
Total	100	100	100	100	100	100

The dynamics of decomposition and N release by the cover crops were assessed using litter bags (Bocock and Gilbert, 1957) with a 1 mm nylon mesh, measuring 0.2 × 0.2 m and covering a soil area of 0.04 m^2. The litter bags were filled with cover crop dry biomass standardized with 0.10 m length size, in a proportional amount according to the DM production of each species and each subplot, using equation 1:

$$\text{DM/litter bag} = (\text{DM kg ha}^{-1}/10{,}000\ \text{m}^2) \times 0.04\ \text{m}^2 \qquad \text{Eq. 1}$$

In each subplot, eight litter bags of equal mass were prepared, seven of which were placed between lines immediately after corn sowing. One litter bag was stored as a control (time zero). Prior to litter bag fixation, the residues on the soil surface were removed laterally to allow direct contact with the soil.

Litter bags were evaluated at 15, 30, 45, 60, 75, 90, and 105 DACS for both years. In each evaluation, the litter bags were cleaned to remove adhered soil and handled carefully to avoid contamination in the residue sample. The litter bag content was dried in a forced-air circulation oven at 55 °C until constant weight to determine the remaining dry mass (RDM), according to mass loss, and then analyzed for organic carbon concentration (Yeomans and Bremner, 1988) and total N content (Silva, 2009).

The N accumulated release (NAR) of the litter bag residues was calculated by the difference in the N accumulated at time zero in relation to the other periods of evaluation using equation 2.

$$\text{NAR} = \text{NI} - \text{NRt} \qquad \text{Eq. 2}$$

in which: NAR is the N accumulated release (kg ha^{-1}); NI is the initial N at time zero (kg ha^{-1}); and NRt is the N remaining at the time of each assessment (kg ha^{-1}).

The decomposition and N release rates are expressed as a percentage of the initial DM and initial N content, respectively. To calculate the half-life, the data were adjusted to a mathematical model with simple exponential decay, with three parameters, as described by Wieder and Lang (1982), using equation 3.

$$y = y0 + ae^{(-k*x)} \qquad \text{Eq. 3}$$

in which: y is the amount of residue over time (days); y0 is the amount of RDM after 105 days (kg ha^{-1}); a is the amount of decomposed DM after 105 days (kg ha^{-1}); k is the decomposition constant (g g^{-1}); and x is the number of days. With the k value, the half-life time was estimated ($T_{1/2}$) in relation to the decomposed DM in the period of 105 days (a) using equation 4:

$$T_{1/2} = \ln(2)/k, \text{ with } \ln(2) = 0.693 \text{ and } T_{1/2} = 0.693/k \qquad \text{Eq. 4}$$

Data were tested for normality according to Lilliefors test, and when necessary, data were transformed (log x or √x), then submitted to the analysis of variance (ANOVA) (F-test $p<0.05$) considering a split-plot factorial scheme. Means were compared using the Scott-Knott test ($p \leq 0.05$) assisted by the GENES computer program (Cruz, 2016).

Residue quality index

To indicate the cover crop system with the best characteristics to be inserted into the production system, we propose the residue quality index (RBQI) based on the remaining dry mass index (RDMI) on the soil surface and the N release index (NRI) after chemical management and for a certain time during commercial crop development. Such an index classifies the cover crop systems on a scale from 0 to 1; that is, a higher RBQI value indicates a better balance of the cover crop system between N release and permanence of residues on the soil surface. The RBQI of the soil cover crops was obtained using equation 5.

$$\text{RBQI} = \text{NRI} \times \text{RDMI} \qquad \text{Eq. 5}$$

To obtain the NRI, we defined the highest NAR value among the evaluated systems as 100 %, that is, the ideal cover crop system in relation to the processes that occurred at 105 DACS (Equation 6).

$$\text{RNRI} = \text{NARsis} / \text{NARmax} \qquad \text{Eq. 6}$$

in which: NARsis is the release of the cover crop system evaluated at 105 days (kg ha^{-1}) and NARmax is the greatest release among the systems under evaluation (kg ha^{-1}).

Similarly, to obtain the RDMI, the greatest amount of RDM was defined among the systems under evaluation as 100 %, that is, the ideal system, regarding the processes occurring at 105 DACS (Equation 7).

$$\text{RDMI} = \text{RDMsis} / \text{RDMmax} \qquad \text{Eq. 7}$$

in which: RDMsis is the amount of RDM in the system under evaluation at 105 days (kg ha^{-1}) and RDMmax is the greatest amount of RDM among the evaluated systems (kg ha^{-1}).

Therefore, in a conceptual model, the higher the RBQI, the better the balance of the cover crop system regarding N release and permanence of residues in the soil (Figure 1). Based on this assumption, four RBQI levels were defined. The cover crop systems with high RBQI (over 0.75) usually corresponded to the species that presented high residue permanence and high N release; medium RBQI (from 0.5 to 0.75) for the systems with medium to high N release and permanence of residues; low RBQI (from 0.25 to 0.5) for the systems that presented an intermediate combination of NRI and RDMI; and very low RBQI (below 0.25) was ascribed to the system that combined very low and low N release and residue permanence, as well as systems that presented high N release but low residue permanence, and those that promoted low N release but high residue permanence (Figure 1).

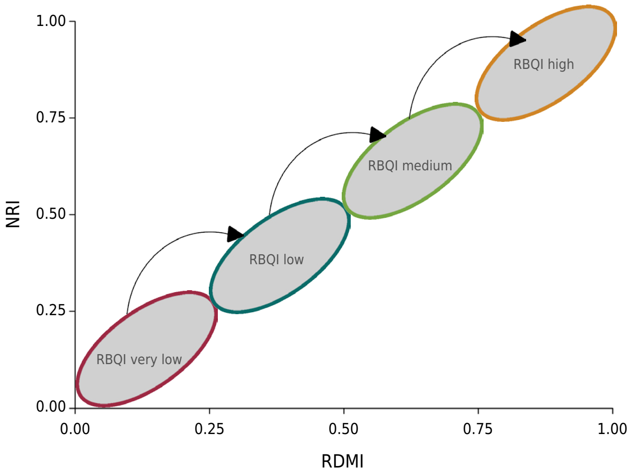

Figure 1. Conceptual model for the residual biomass quality index (RBQI) of cover crop systems of cover crop systems, with the nitrogen release index (NRI) and the remaining dry mass index (RDMI).

RESULTS AND DISCUSSION

Decomposition rate and remaining dry mass

In the 2017/18 agricultural year, the systems containing ryegrass, vetch, and lupine presented the highest decomposition rates and, consequently, the lowest relative RDM. The differences in rates occurred at 30 days for ryegrass, which presented the highest decomposition rate with 52 % RDM, differing from the other systems by up to 60 DACS (Table 2).

At 75 DACS, systems with Fabaceae species presented a decomposition rate similar to that of ryegrass with values below 50 % of RDM, which represented less than 1.0 Mg ha^{-1} DM for these systems. The other systems presented 59 % maintenance at 75 DACS, which represented 3.9 Mg ha^{-1} residue for oats and the consortia, the highest amount among the systems under evaluation.

The high decomposition rate of ryegrass might be related to the low C/N ratio usually verified for Poaceae species and the half-life time of the labile pool. Ryegrass is a long cycle crop and considering the regional climate conditions, at the moment of evaluation it’s not reach the flowering stage. At 105 DACS, the ryegrass and Fabaceae species systems presented 35 % RDM, approximately 0.8 Mg ha^{-1} DM. The systems with oat, O+V, O+V+R, rye, and radish presented 59 % RDM, corresponding to approximately 3.1 Mg ha^{-1} for oat and consortia, systems with the highest amounts of RDM among the cover crop systems.

In the 2018/19 agricultural year, the highest decomposition rates were observed for vetch and radish, with the maintenance of only 45 % residue in the evaluation occurring at 30 DACS, representing 0.7 Mg ha^{-1} DM. The lowest decomposition rates occurred in the consortium systems and oat with 64 % maintenance, representing 3.4 Mg ha^{-1} DM in the consortium systems (Table 3).

At the end of the 105 days, vetch and radish presented 28.5 % maintenance with 0.45 Mg ha^{-1} DM, whereas the systems with oat, consortia, lupine, rye, and ryegrass presented the lowest decomposition rates with 37 % RDM, representing 1,32 Mg ha^{-1} for oat, rye, and lupine, and 2.0 Mg ha^{-1} DM in the consortium systems, the highest amounts among the systems tested.

Although lupine is a Fabaceae species, its RDM amount over time in the 2018/19 agricultural year was higher than that of oat, rye, ryegrass, radish, and vetch, possibly linked to the higher initial production of DM (higher stem/leaf ratio) and the final decomposition rates (45-105 DACS) similar to those verified for the Poaceae species. Therefore, the order obtained according to the permanence of residue in the soil considering the mean of both years was O+V+R > O+V > oat > rye > lupine > radish > vetch > ryegrass.

The decomposition rate presented different kinetics between cover crops in different years. Over half (56 %) of the decomposition observed during the evaluation period (105 days) occurred in the first 30 days of 2017/18. In the agricultural year 2018/19, 69 % of the decomposition was observed up to 30 DACS, which reached 88 % decomposition at 45 DACS.

Table 2. Ratio of C/N, half-life time ($T_{1/2}$), decomposition rate, initial dry mass (DM), and remaining dry mass (RDM) of cover crops in the agricultural year 2017/18 for cover crop systems and N rates (0, 90, and 180 kg ha^{-1})

Cover crops	C/N ratio	$T_{1/2}$	Days after corn sowing						
			15	30	45	60	75	90	105
			Decomposition rate						
		day	%						
Oat	30 a**	37	87 ^{ns}	72 a*	68 a*	64 a*	62 a**	54 a**	49 a**
O+V	28 a	44	88	74 a	70 a	65 a	61 a	55 a	50 a
O+V+R	25 b	35	85	70 a	65 a	61 a	58 a	51 a	46 a
Ryegrass	19 c	17	69	52 b	49 b	44 b	40 b	37 b	34 b
Rye	26 b	32	80	71 a	66 a	61 a	55 a	52 a	48 a
Vetch	13 d	44	77	66 a	62 a	58 a	48 b	42 b	37 b
Radish	21 c	41	78	70 a	68 a	62 a	57 a	52 a	48 a
Lupine	15 d	169	81	70 a	68 a	66 a	44 b	39 b	33 b
CV (%)	14.8		10.9	17.6	16.4	16.9	13.4	16.3	18.7
N rates									
0	22 ^{ns}	35	80 b*	68 a*	65 a**	62 a**	54 ^{ns}	48 ^{ns}	43 ^{ns}
90	22	25	79 b	65 b	61 b	56 b	52	48	44
180	22	40	83 a	71 a	68 a	63 a	53	47	43
CV (%)	12.1		7.4	10.2	10.4	13.5	12.4	15.1	15.0
Cover crops	DM		RDM						
	Mg ha^{-1}								
Oat	5.27 a**		4.59 a**	3.8 a**	3.6 a**	3.4 a**	3.3 a**	2.89 a**	2.63 a*
O+V	6.49 a		5.75 a	4.83 a	4.56 a	4.27 a	4.02 a	3.64 a	3.28 a
O+V+R	7.36 a		6.31 a	5.23 a	4.77 a	4.55 a	4.35 a	3.82 a	3.44 a
Ryegrass	1.70 c		1.18 c	0.9 c	0.84 c	0.75 c	0.67 d	0.62 d	0.58 c
Rye	3.23 b		2.57 b	2.26 b	2.14 b	1.96 b	1.76 b	1.68 b	1.56 b
Vetch	2.31 b		1.78 b	1.53 b	1.44 b	1.34 b	1.1 c	0.97 c	0.86 c
Radish	2.96 b		2.31 b	2.07 b	2.01 b	1.85 b	1.7 b	1.54 b	1.43 b
Lupine	2.84 b		2.14 b	1.86 b	1.8 b	1.71 b	1.17 c	1.07 c	0.93 c
CV (%)	4.1		3.9	4.7	4.6	4.5	4.6	5.0	5.2
N rates									
0	4.03 a**		3.33 a*	2.81 ^{ns}	2.55 ^{ns}	2.55 ^{ns}	2.3 a*	2.04 a*	1.81 ^{ns}
90	4.47 a		3.65 a	3.03	2.62	2.61	2.44 a	2.25 a	2.05
180	3.56 b		3.01 b	2.59	2.28	2.28	2.04 b	1.79 b	1.65
CV (%)	2.7		2.9	3.1	3.2	3.6	3.6	4.0	4.1

Means followed by the same letter in the column, within cover crops and rates did not differ statistically in the Skott-Knott test ($p<0.05$). ns: not significant. * and ** significant at $p \leq 0.05$ and $p \leq 0.01$, respectively. DM and RDM data at 15, 30, 45, 60, 75, 90, and 105 DACS were transformed using log x. CV: coefficient of variation. O+V: oat+vetch; O+V+R: oat+vetch+radish.

Table 3. Ratio of C/N, half-life time ($T_{1/2}$), decomposition rate, initial dry mass (DM), and remaining dry mass (RDM) of cover crops in the agricultural year 2018/19 for cover crop systems and N rates (0, 90, and 180 kg ha^{-1})

Cover crops	C/N ratio	$T_{1/2}$	Days after corn sowing						
			15	30	45	60	75	90	105
			Decomposition rate						
		day	%						
Oat	33 a**	19	74 a**	59 a**	48 a**	44 a**	43 a**	40 a**	39 a**
O+V	22 b	23	79 a	65 a	48 a	46 a	45 a	40 a	38 a
O+V+R	21 b	21	78 a	62 a	45 a	43 a	42 a	40 a	37 a
Ryegrass	32 a	12	61 b	51 b	44 a	41 a	39 a	37 a	35 a
Rye	30 a	13	64 b	54 b	44 a	42 a	41 a	39 a	38 a
Vetch	13 c	11	53 c	45 c	32 b	32 b	29 b	29 b	28 b
Radish	18 b	9	50 c	45 c	38 b	36 b	34 b	32 b	29 b
Lupine	16 c	14	64 b	54 b	45 a	41 a	40 a	38 a	36 a
CV (%)	20.7		8.7	10.6	14.1	15.5	15.5	14.0	17.8
N rates									
0	25 a*	17	65 ^{ns}	58 ^{ns}	44 ^{ns}	41 ^{ns}	39 ^{ns}	38 ^{ns}	36 ^{ns}
90	23 b	16	64	53	42	41	39	36	34
180	22 b	17	67	55	43	40	39	37	35
CV (%)	18.5		9.2	9.3	8.8	9.9	10.1	10.0	13.0
Cover crops	DM		RDM						
	Mg ha^{-1}								
Oat	3.2 c**		2.37 b**	1.89 c**	1.55 c**	1.4 c**	1.36 c**	1.29 c**	1.25 c**
O+V	4.98 b		3.92 a	3.25 a	2.37 a	2.3 a	2.22 a	2.02 a	1.90 a
O+V+R	5.72 a		4.45 a	3.53 a	2.57 a	2.47 a	2.4 a	2.3 a	2.14 a
Ryegrass	2.07 d		1.25 d	1.05 e	0.9 d	0.85 d	0.81 d	0.77 d	0.73 d
Rye	2.99 c		1.92 c	1.63 d	1.32 c	1.26 c	1.22 c	1.16 c	1.15 c
Vetch	1.87 d		0.99 e	0.85 e	0.6 d	0.59 d	0.55 d	0.54 d	0.53 d
Radish	1.24 e		0.62 f	0.56 f	0.47 d	0.45 d	0.42 d	0.4 d	0.36 d
Lupine	4.38 b		2.82 b	2.38 b	1.99 b	1.81 b	1.77 b	1.67 b	1.57 b
CV (%)	8.6		11.3	10.9	28.1	28.9	30.3	27.3	34.7
N rates									
0	3.0 c**		2.09 b**	1.77 b**	1.39 b*	1.28 b**	1.23 b**	1.19 ^{ns}	1.1 ^{ns}
90	3.6 a		2.48 a	2.03 a	1.56 a	1.53 a	1.48 a	1.36	1.3
180	3.3 b		2.32 a	1.87 a	1.46 a	1.37 b	1.33 b	1.25	1.22
CV (%)	4.8		7.4	6.4	14.5	17.1	17.1	18.2	21.7

Means followed by the same letter in the column, within cover crops and rates did not differ statistically in the Skott-Knott test ($p<0.05$). ns: not significant. * and ** significant at $p \leq 0.05$ and $p \leq 0.01$, respectively. DM and RDM data at 15 and 30 DACS were transformed using $\sqrt{x}$. CV: coefficient of variation. O+V: oat+vetch; O+V+R: oat+vetch+radish.

The highest decomposition rate observed in the 2018/19 agricultural year was related to the shorter half-life of the cover crops, which occurred because of the collection of material to fill the litter bags 87 days after sowing in relation to the 105 days that occurred in 2017/18. Associated with this factor, there was greater precipitation (89 mm) at 30 DACS in the year 2018/19 than in the same interval in the year 2017/18 (Figure 2), a condition that is directly related to the increase in microbial activity in the soil (increased soil moisture), which results in increased decomposition and N release. Thus, a period of fast decomposition followed by another slower phase was observed, as Doneda et al. (2012) and Ziech et al. (2015) reported. The first decomposition phase is faster because it depends on the initial soluble C content and the N from the residue, and the second phase is regulated by the concentration of lignin and polyphenols, which are compounds of slow decomposition; therefore, it becomes slower (Aita et al., 2004).

Decomposition rate was not altered as a function of the N rate after its application to the corn crop in both years. In the 2017/18 agricultural year, there was a higher decomposition rate of cover crops with 90 kg ha^{-1} mineral N at 15, 30, 45, and 60 DACS, which means that the effect has already been occurring before the N fertilization at 33 days. The highest decomposition rate is related to the C/N ratio and the $T_{1/2}$ which was lower for cover crops in the treatment with 90 kg ha^{-1}.

Nitrogen release

Nitrogen release rate in the cover crops residues presented similar behavior to that of the decomposition in the two agricultural years, because the nutrient release depends on the decomposition rate (Aita et al., 2014). In the 2017/18 year, the highest N release rates occurred for vetch and radish at 15 DACS (Table 4). In subsequent evaluations (30, 60, and 105 DACS), vetch, lupine, radish, and ryegrass had the highest release rates. At 30 DACS, these systems released 54 % of the added N. At 60 and 105 DACS, the release rate increased to 58 and 71 % of the added N, respectively. The systems with the lowest release rates were consortia, oat and rye, with 40, 57, and 67 %, respectively, of the added N released during the same period.

The systems formed three groups, the lowest releases were verified at 30 DACS for the systems with ryegrass and rye, with 20 kg ha^{-1} N, the intermediate releases were for oat, O+V, and radish (29 to 31 kg N ha^{-1}) and the highest releases for vetch, lupine, and O+V+R (41 to 49 kg N ha^{-1}). At 30 and 60 DACS, there was stabilization in N release, in general, and at 45 DACS the values were equal to the lowest and the intermediate groups. At the end of the 105 DACS, the systems with Fabaceae species and triple consortium had the highest amount of N released, ranging from 53 to 58 kg N ha^{-1}, while the other systems had releases ranging from 28 to 39 kg N ha^{-1}.

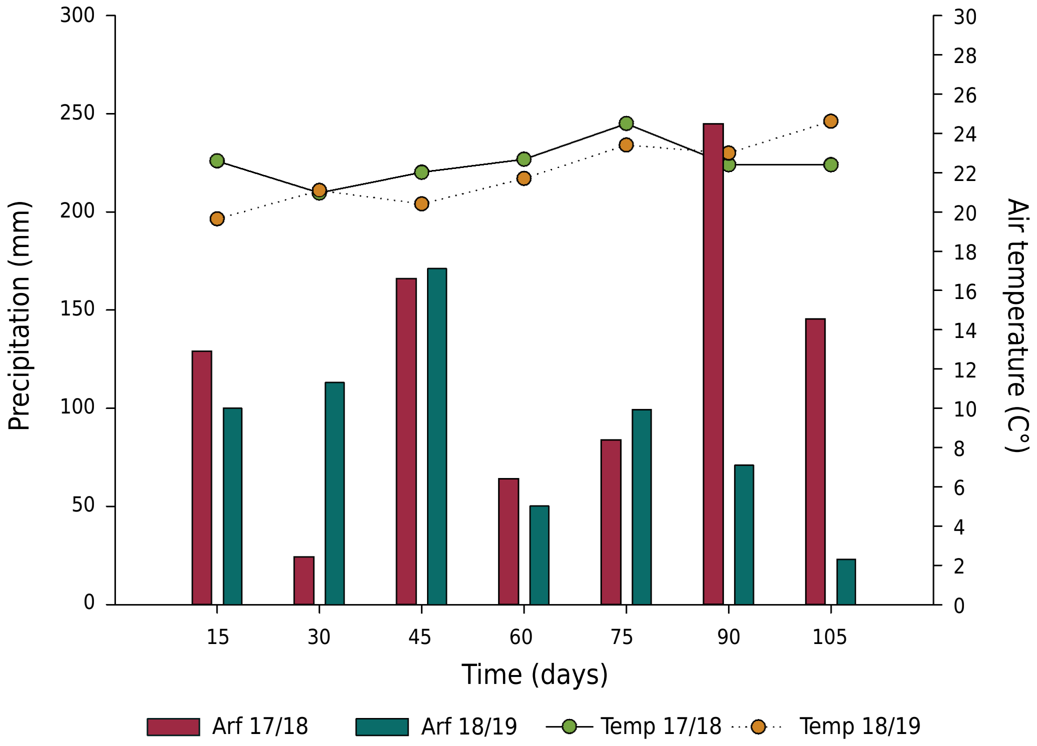

Figure 2. Fortnightly accumulated rainfall (Arf) and mean air temperature (Temp) for the evaluation period of cover crops decomposition in the years 2017/18 and 2018/19.

Table 4. Nitrogen release rate, nitrogen accumulated in the tissues (NAT), nitrogen accumulated release (NAR) by the cover crop residues in the years 2017/2018 for cover crop systems and N rates (0, 90, and 180 kg ha^{-1})

Cover crops	Days after corn sowing							
	0	15	30	45	60	75	90	105
	N release rate							
		%						
Oat	100	70 a**	58 a*	52 b**	51 c**	57 b**	52 a**	53 a**
O+V	100	76 a	67 a	67 a	67 a	67 a	60 a	59 a
O+V+R	100	75 a	59 a	58 b	56 b	55 b	56 a	51 a
Ryegrass	100	67 a	51 b	47 c	47 c	43 c	37 b	35 b
Rye	100	67 a	57 a	49 c	50 c	49 c	50 a	44 a
Vetch	100	53 b	41 b	39 d	42 d	36 c	26 b	23 c
Radish	100	45 b	44 b	40 d	39 d	39 c	35 b	36 b
Lupine	100	62 a	47 b	39 d	41 d	38 c	30 b	24 c
CV (%)		22.5	25.1	17.1	19.0	20.1	32.1	23.5
N rates								
0	100	62 ^{ns}	53 ^{ns}	47 ^{ns}	48 ^{ns}	46 ^{ns}	40 ^{ns}	37 ^{ns}
90	100	64	51	48	45	48	44	42
180	100	68	56	52	53	50	45	42
CV (%)		21.8	23.9	22.8	23.8	28.6	26.5	22.2
	NAT				NAR			
Cover crops	kg N ha^{-1}							
Oat	73 b**	22 ^{ns}	31 a*	35 b**	35 b**	35 b**	35 b**	35 b**
O+V	96 a	23	31 a	32 b	32 b	32 b	39 b	39 b
O+V+R	118 a	30	49 a	49 a	51 a	51 a	52 a	58 a
Ryegrass	35 d	11	17 b	18 b	18 b	19 b	21 b	22 b
Rye	52 c	17	22 b	25 b	25 b	25 b	25 b	28 b
Vetch	71 b	33	41 a	42 a	42 a	44 a	51 a	53 a
Radish	55 c	29	29 a	32 b	33 b	33 b	35 b	34 b
Lupine	77 b	33	43 a	48 a	48 a	50 a	53 a	58 a
CV (%)	37.4	36.8	25.0	44.0	20.1	23.0	44.0	20.2
N rates								
0	72 a**	27 ^{ns}	34 a*	41 a*	35 a**	37 ^{ns}	41 a*	43 a*
90	81 a	28	38 a	43 a	43 a	40	43 a	45 a
180	64 b	20	27 b	34 b	28 b	30	34 b	35 b
CV (%)	24.1	28.6	19.8	32.2	16.0	18.9	32.3	14.2

Means followed by the same letter in the column, within cover crops and rates did not differ statistically in the Skott-Knott test ($p<0.05$). ns: not significant. * and ** significant at $p \leq 0.05$ and $p \leq 0.01$, respectively. NAR data at 15, 30, 60, 75 and 105 DACS were transformed using $\sqrt{x}$. CV: coefficient of variation. O+V: oat+vetch; O+V+R: oat+vetch+radish.

In the 2018/19 agricultural year, the highest N release rates were observed for the systems with radish and vetch, with 56, 63, and 76 % of the added N released at 30, 60, and 105 DACS, respectively (Table 5). The lowest N release rates were observed for the Poaceae species systems, with 19, 32, and 60 % of the added N released during 30, 60, and 105 DACS, respectively. Lupine presented an N release rate similar to the consortia, up to 90 DACS. Subsequently, it became similar to the systems with vetch and radish. However, the consortia presented an intermediary release rate among the systems, with 32, 44, and 63 % of the added N released at 30, 60, and 105 days, with release curves closer to those of the Poaceae species systems.

Table 5. Nitrogen release rate, nitrogen accumulated in the tissues (NAT), nitrogen accumulated release (NAR) by the cover crop residues in the years 2018/2019 for cover crop systems and N rates (0, 90, and 180 kg ha^{-1})

Cover crops	Days after corn sowing							
	0	15	30	45	60	75	90	105
	N release rate							
					%			
Oat	100	87 a**	84 a**	69 a**	71 a**	63 a**	46 a**	45 a**
O+V	100	78 b	70 b	57 b	55 b	55 a	39 b	37 b
O+V+R	100	74 b	66 b	53 b	51 b	43 b	36 b	36 b
Ryegrass	100	87 a	79 a	74 a	74 a	59 a	53 a	48 a
Rye	100	79 b	79 a	64 a	60 b	56 a	45 a	46 a
Vetch	100	60 c	47 c	34 c	34 c	31 c	25 c	23 c
Radish	100	48 d	41 c	34 c	40 c	33 c	26 c	24 c
Lupine	100	74 b	70 b	60 b	58 b	44 b	35 b	28 c
CV (%)		15.1	16.9	18.6	22.8	27.6	21.5	16.9
N rates								
0	100	72 ^{ns}	69 ^{ns}	58 ^{ns}	57 ^{ns}	50 ^{ns}	38 ^{ns}	36 ^{ns}
90	100	73	65	54	55	46	38	36
180	100	75	67	56	53	48	39	35
CV (%)		25.7	21.9	18.8	13.5	18.0	16.3	17.9
	NAT				NAR			
Cover crops				kg N ha^{-1}				
Oat	41 d**	5 d**	7 b**	13 c**	13 b**	17 c**	23 c**	23 d**
O+V	95 b	21 b	28 a	41 b	43 a	43 b	58 a	60 b
O+V+R	111 a	29 a	38 a	52 a	55 a	63 a	71 a	71 b
Ryegrass	26 e	4 d	5 b	7 c	7 b	11 d	12 d	14 e
Rye	44 d	9 c	11 b	17 c	18 b	20 c	24 c	24 d
Vetch	56 c	22 b	29 a	37 b	37 a	38 b	42 b	43 c
Radish	27 e	15 c	17 b	18 c	17 b	19 c	22 c	21 d
Lupine	118 a	32 a	36 a	48 a	51 a	68 a	76 a	85 a
CV (%)	19.1	37.5	45.5	31.0	22.1	12.5	7.6	6.2
N rates								
0	57 b**	15 ^{ns}	19 ^{ns}	24 b*	26 b**	30 b**	37 b**	38 b**
90	70 a	19	23	32 a	32 a	39 a	44 a	45 a
180	67 a	17	22	31 a	32 a	36 a	42 a	45 a
CV (%)	12.6	59.8	57.0	31.8	13.1	8.9	4.9	5.2

Means followed by the same letter in the column, within cover crops and rates did not differ statistically in the Skott-Knott test ($p<0.05$). ns: not significant. * and ** significant at $p\leq0.05$ and $p\leq0.01$, respectively. NAR data at 60 and 75 DACS, and at 90 and 105 DACS were transformed using $\sqrt{x}$ and log x, respectively. CV: coefficient of variation. O+V: oat+vetch; O+V+R: oat+vetch+radish.

The consortium and lupine systems, which presented intermediary release rates, provided higher N release to the corn crop in all periods under evaluation. At 30 and 60 DACS, the accumulated releases of 33 and 47 kg N ha^{-1}, respectively, were similar to those verified for vetch. In subsequent evaluations, vetch interrupted the release, whereas the systems with consortium and lupine increased the amount of N released. Lupine released 85 kg N ha^{-1} at 105 DACS, the highest release among the systems, whereas the consortia released 66 kg N ha^{-1}, which was higher than that of vetch, which released 43 kg N ha^{-1}. The Poaceae and Brassicaceae species systems had the lowest amounts of N released, ranging from 14 to 23 kg N ha^{-1}.

The N release rate of the consortia verified in 2017/18, which was similar to that of the Poaceae species, was different from that found by Aita and Giacomini (2003), who observed that the release curves for the consortia are closer to that of the Fabaceae species, possibly because of the lower C/N ratio of the consortia (19) being closer to vetch C/N ratio (14.8) than to oat C/N ratio (40). In this study, the C/N ratio in the consortia (27) was closer to the oat C/N ratio (30) than that of vetch (14). In 2018/19, the release rate of the consortia was intermediate in relation to the use of Fabaceae and Poaceae species as a single crop. Lupine, however, although belonging to the Fabaceae family, presented a release rate similar to that of the consortia, up to 90 DACS, showing a rate similar to that of vetch in the last evaluation. Possibly, the higher volume of stems in relation to leaves (visual observation) as a function of the higher DM production in 2018/19 (Table 3), when compared to the previous crop (Table 2), influenced the N release rate in lupine tissues. In this study, the rate of N release, as well as the decomposition rate, varied considerably between the soil cover crop systems in both years. However, no differences were found in N release or decomposition rates as a function of N rate, which were applied to corn. In a study in the Midwest United States, researchers investigated the effects of different management practices (rotation, cover crops, and soil tillage system preparation) on the influence of N and C release from residues of rye and vetch cover (Lacey et al., 2020). The results of the study show that, despite the differences in soil conditions and N fertilization, the addition of N at a depth of 7 cm does not influence the rate of N and C release from the cover crop when compared to the system without N, because the fertilizer was placed at a depth that is difficult for soil microorganisms to access (Lacey et al., 2020).

In the northeastern United States, researchers have evaluated the methods of fertilizer application from pelletized poultry litter (PPL) (without PPL, surface, sub-surface with splits, and incorporated) on the rate of decomposition and N release in different proportions of rye and hairy vetch (Poffenbarger et al., 2015). The application of PPL occurred on the day of corn sowing (surface) and corn stages V5 and V8 (sub-surface). The results show that the addition of PPL (67 kg ha^{-1} of N readily available to the crop) on the surface increases the decomposition rate of residues with a high proportion of rye when compared to treatments without PPL and with PPL sub-surface depth (Poffenbarger et al., 2015).

Nevertheless, in the present study, the fertilizer was placed on the surface, and the rates of N release did not change. This lack of effect on the rate of N release may be related to two factors:1) the increase in lignin in the tissues owing to the application of N, and 2) the application of N in the corn phenological stage with high demand. For factor 1, Costa et al. (2016) evaluated the effects of decomposition rate, cellulose, lignin, and speed of nutrient release from *Urochloa brizantha* as a function of N fertilization (0 and 60 kg ha^{-1}) and found that N fertilization increased DM production, accumulated N, and reduced the C/N ratio; however, the decomposition and N release rates were not altered, which probably results from the 46 % increase in lignin content in *U. brizantha* with N fertilization. For factor 2, it was considered that most of the applied N were absorbed by the corn crop, being unavailable to soil microorganisms. This was observed in an assessment of soil mineral N in 2016 in the same experiment (unpublished data), in which, after N fertilization at 37 DACS, a rapid increase in the levels of N-NO_3^- (0.00-0.05 m soil layer) observed in the evaluation at 45 DACS for all cover crop systems. At 60 DACS, the cover crop systems with a high C/N ratio (>30) already had levels of N-NO_3^- equivalent to those without N fertilization. That is, the applied N was absorbed by the corn crop, resulting in higher values of soil plant analysis development (SPAD) index in relation to the systems without N. Thus, the changes in the decomposition and N release rates as a function of N fertilizer application may vary depending on the application method (cover or subsurface), application time (pre-planting or post-planting), the C/N ratio of the cover crops used, and the type of crop sown in succession, such as corn, which has a high demand for mineral N and reduces the influence of fertilizer application on these variables.

Based on these results, using consortia with at least one species of the Fabaceae family is a strategy farmers can implement to manage the C/N ratios of cover crop residues and release N in regions with a subtropical climate. Choosing a cover crop with these characteristics can minimize the effects of N immobilization, reducing the negative impact on commercial crops and reducing the need for mineral N fertilization. The application of mineral N carried out in cover in phase V4 of the corn crop (after 30 DACS) did not influence decomposition and N release, thus conserving the residues of cover crops on the surface for soil protection and contributing to the suppression of weeds and conservation of soil moisture.

Residue quality index

The RBQI theoretical model uses the RDMI and NRI of the cover crop systems in relation to an ideal system: the highest NAR and RDM values along 105 days among the systems (Table 6). The lupine system that presented 71 kg ha^{-1} N release and the O+V+R system that presented the highest remaining DM amount with 2.8 Mg ha^{-1} in the mean of both agricultural years corresponded to the ideal system.

The points in figure 3 indicate the intersection between the RDMI and NRI values for each cover crop system, in which some grouping is observed according to the characteristics of the species and consortia. Species with higher N release potential are seen in Q2 (Fabaceae species); species with high capability of residue permanence are seen in Q4 (oat and rye in Q3; however, there is a tendency to include oat in Q4); species with low N release and permanence of residues are found in Q1 (radish and ryegrass); and species that present high N release and at the same time permanence of residues are observed in Q3 (consortia). The resulting product of these two factors (NRI × RDMI) provides the RBQI of each cover crop system (Figure 4).

Thus, the RBQI appears to be an excellent indicator of the quality of the management system when considering the quantitative aspects of higher permanence of residues for soil protection and higher NAR from cover crops to succession crops at the end of 105 days. This is because higher RBQI values indicate a balance between N release and straw decomposition, achieving at the same time the objectives of releasing nutrients and providing the soil with protection against erosion.

Table 6. Nitrogen accumulated release (NAR), remaining dry mass (RDM), nitrogen release index (NRI), remaining dry mass index (RDMI), and residual biomass quality index (RBQI) of the cover crop system after 105 days evaluation, in both years 2017/18 and 2018/19

Cover crops	NAR	RDM	NRI	RDMI	RBQI
	kg ha^{-1}				
Oat	29	1943	0.42	0.70	0.28
O+V	50	2592	0.70	0.93	0.65
O+V+R	64	2788	0.91	1.00	0.91
Ryegrass	18	684	0.26	0.25	0.06
Rye	26	1353	0.36	0.49	0.18
Vetch	48	755	0.67	0.27	0.18
Radish	28	893	0.39	0.32	0.13
Lupine	71	1276	1.00	0.46	0.46
Ideal System	71	2788	1.00	1.00	1.00

O+V: oat+vetch; O+V+R: oat+vetch+radish

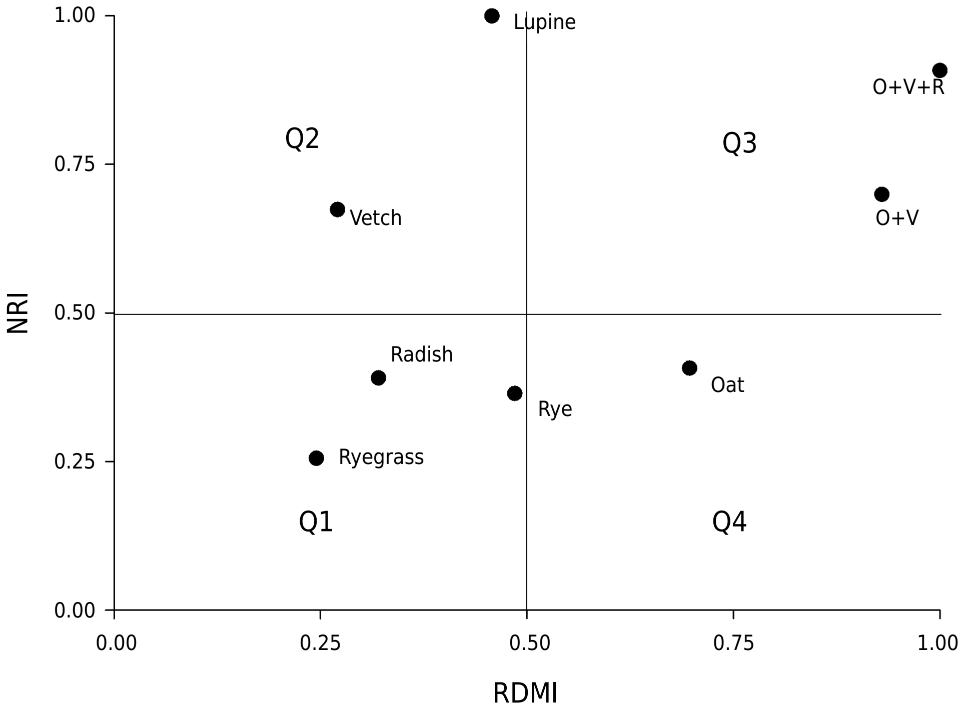

Figure 3. Points of intersection of the remaining dry mass index (RDMI) and nitrogen release index (NRI) in the cover crop systems.

Therefore, we verified that O+V+R showed the highest RBQI value (0.90) when compared to the other systems, followed by O+V with an RBQI value of 0.65. The highest RBQI for the consortia occurred as a function of the combination of higher DM production and N accumulation in the plant tissues in these systems, mainly radish and vetch, which together provided permanence and N release as a function of the intermediate C/N ratio (Tables 2 and 3).

There is a relationship between C stabilization and aggregation with the entrance of C from crop residues in no-tillage systems (Lal, 2015; Rigon et al., 2020). However, the quality of cover crop residues is fundamental to such changes because the entrance of residues with lower C/N ratios promotes the entrance of labile N and C and stabilization to provide soil resilience and physical protection compared to materials with high C/N ratios (Rigon et al., 2020). Therefore, using cover crop systems with higher RBQI tends to promote higher labile C and N entry into the system, promoting an increase in C stabilization and aggregation in the soil.

Lupine (Fabaceae species) presented an RBQI value of 0.46, higher than that of vetch (0.18), which belongs to the same botanical family. The highest RBQI value for lupine occurred because this species produced the highest DM amount, thus obtaining an ideal NRI (1.0) and a low C/N ratio (Tables 2 and 3). In addition, its higher RDMI might have resulted from the balanced volume of stems in relation to leaves (visual observation) associated with its high DM production in both years, resulting in longer permanence of these residues on the soil surface. The radish, ryegrass, rye, and vetch crops presented the lowest RBQI, ranging from 0.06 to 0.18, as a function of the low N release or low permanence of residues on the soil surface.

The permanence of straw in the soil, crop rotation intensity, and crop rotation diversity are indicators that compose the no-tillage system participatory quality index (PQI) used in Brazil to assess the level of adoption of conservation practices by farmers and to qualify the no-tillage system according to the regional reality (Nunes et al., 2020; Telles et al., 2020, 2022; Possamai et al., 2022). In this way, RBQI emerges as a potential tool for

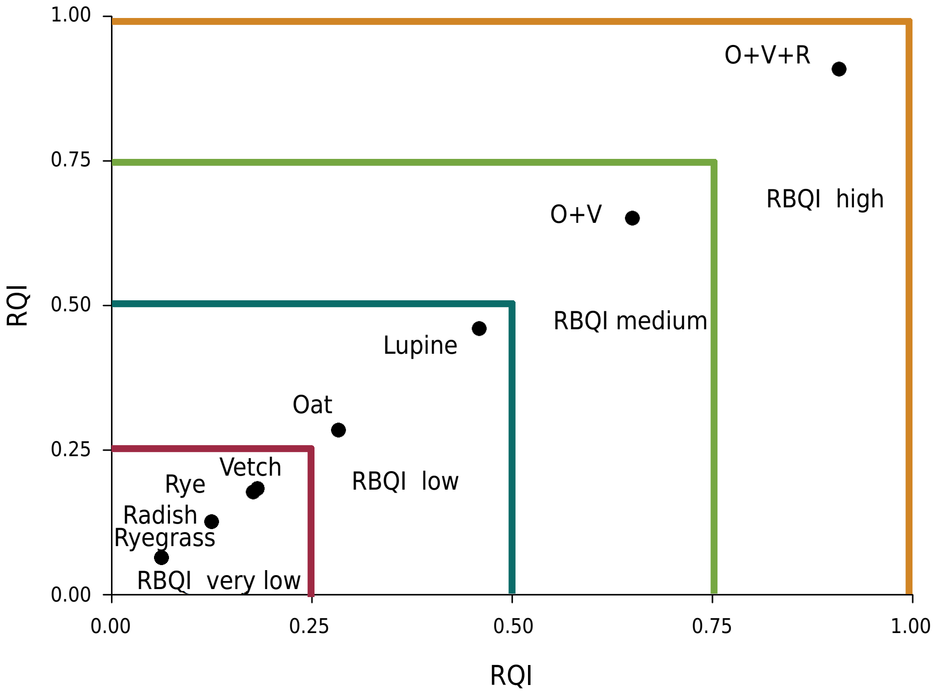

Figure 4. Residual biomass quality index (RBQI) of cover crops systems (mean data for the years 2017/18 and 2018/19).

choosing cover crop systems to assist rural properties in increasing their PQI regarding straw persistence and crop rotation, improving the quality of the no-tillage system.

CONCLUSIONS

The consortia O+V+R and O+V resulted in a decomposition rate and N release rate closer to the rates observed for oats and rye. The NAR was similar to that observed for Fabaceae species, and the RDM was similar or superior to that found for black oat. With these characteristics, the systems in the O+V+R and O+V consortia presented the highest values of RBQI, ranging from 0.61 to 0.90, indicating (or suggesting) that RBQI is a potential indicator for choosing cover crop systems that promote greater sustainability of the no-till production system. The use of N fertilizer in corn did not change decomposition rates and N release from the residues of cover crops.

ACKNOWLEDGEMENTS

The authors are thankful to the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES) for the scholarship granted to the first author (Financial code 001), to the Fundação Agrisus (Agricultura Sustentável) for the financial support (Project No. 3079/21), and to the Fundação Araucária (TC 73/2017).

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REFERENCES

Acosta JAA, Amado TJC, Silva LS, Santi A, Weber MA. Decomposição da fitomassa de plantas de cobertura e liberação de nitrogênio em função da quantidade de resíduos aportada ao solo sob sistema plantio direto. Cienc Rural. 2014;44:801-9. https://doi.org/10.1590/S0103-84782014005000002

Aita C, Giacomini SJ. Decomposição e liberação de nitrogênio de resíduos culturais de plantas de cobertura de solo solteiras e consorciadas. Rev Bras Cienc Solo. 2003;27:601-12. https://doi.org/10.1590/S0100-06832003000400004

Aita C, Giacomini SJ, Ceretta CA. Decomposição e liberação de nutrientes dos resíduos culturais de adubos verdes. In: Lima Filho OF, Ambrosanno EJ, Rossi F, Carlos JAD, editors. Adubação verde e plantas de cobertura no Brasil: Fundamentos e prática. Brasília, DF: Embrapa; 2014. p. 225-64.

Aita C, Giacomini SJ, Hübner AP, Chiapinotto IC, Fries MR. Consorciação de plantas de cobertura antecedendo o milho em plantio direto. I - Dinâmica do nitrogênio no solo. Rev Bras Cienc Solo. 2004;28:739-49. https://doi.org/10.1590/S0100-06832004000400014

Baraibar B, Hunter CM, Schipanski ME, Hamilton A, Mortensen DA. Weed suppression in cover crop monocultures and mixtures. Weed Sci. 2017;66:121-33. https://doi.org/10.1017/wsc.2017.59

Bocock KL, Gilbert OJW. The disappearance of litter under different woodland conditions. Plant Soil. 1957;9:179-85. https://doi.org/10.1007/BF01398924

Brust J, Weber J, Gerhards R. Do cover crop mixtures have the same ability to suppress weeds as competitive monoculture cover crops? Julius-Kühn-Archiv. 2014;443:422-30. https://doi.org/10.5073/jka.2014.443.053

Carvalho AMD, Coser TR, Rein TA, Dantas RDA, Silva RR, Souza KW. Manejo de plantas de cobertura na floração e maturação fisiológica e seu efeito na produtividade do milho. Pesq Agropec Bras. 2015;50:551-61. https://doi.org/10.1590/S0100-204X2015000700005

Costa CHM, Crusciol CAC, Soratto RP, Ferrari Neto J, Moro E. Nitrogen fertilization on palisadegrass: phytomass decomposition and nutrients release. Pesq Agropec Trop. 2016;46:159-68. https://doi.org/10.1590/1983-40632016v4639297

Cruz CD. Genes Software - extended and integrated with the R, Matlab and Selegen. Acta Sci. 2016;38:547-52. https://doi.org/10.4025/actasciagron.v38i4.32629

Doneda A, Aita C, Giacomini SJ, Miola ECC, Giacomini DA, Schirmann J, Gonzatto R. Fitomassa e decomposição de resíduos de plantas de cobertura puras e consorciadas. Rev Bras Cienc Solo. 2012;36:1714-23. https://doi.org/10.1590/S0100-06832012000600005

Drost SM, Rutgers M, Wouterse M, Boer W, Bodelier PLE. Decomposition of mixtures of cover crop residues increases microbial functional diversity. Geoderma. 2020;361:114060. https://doi.org/10.1016/j.geoderma.2019.114060

IUSS Working Group WRB. World reference base for soil resources 2014, update 2015: International soil classification system for naming soils and creating legends for soil maps. Rome: Food and Agriculture Organization of the United Nations; 2015. (World Soil Resources Reports, 106).

Kumar K, Goh KM. Nitrogen release from crop residues and organic amendments as affected by biochemical composition. Commun Soil Sci Plant Anal. 2003;34:2441-60. https://doi.org/10.1081/CSS-120024778

Lacey C, Nevins J, Camberato E, Kladivko A, Sadeghpour A, Armstrong S. Carbon and nitrogen release from cover crop residues and implications for cropping systems management. J Soil Water Conserv. 2020;75:505-14. https://doi.org/10.2489/jswc.2020.00102

Lal R. Soil carbon sequestration and aggregation by cover cropping. J Soil Water Conserv. 2015;70:329-39. https://doi.org/10.2489/jswc.70.6.329

Lawson A, Fortuna AM, Cogger C, Bary A, Stubbs T. Nitrogen contribution of rye–hairy vetch cover crop mixtures to organically grown sweet corn. Renew Agr Food Syst. 2013;28:59-69. https://www.jstor.org/stable/26324746

Nunes ALP, Bartz ML, Mello I, Bortoluzzi J, Roloff G, Llanillo RF, Canalli L, Wandscheer CAR, Ralisch R. No-till system participatory quality index in land management quality assessment in Brazil. Eur J Soil Sci. 2020;71:974-87. https://doi.org/10.1111/ejss.12943

Poffenbarger HJ, Mirsky SB, Weil RR, Kramer M, Spargo JT, Cavigelli MA. Legume proportion, poultry litter, and tillage effects on cover crop decomposition. Agron J. 2015;107:2083-96. https://doi.org/10.2134/agronj15.0065

Possamai EJ, Conceição PC, Amadori C, Bartz MLC, Ralisch R, Vicensi M, Marx EF. Adoption of the no-tillage system in Paraná State: A (re)view. Rev Bras Cienc Solo. 2022;46:e0210104. https://doi.org/10.36783/18069657rbcs20210104

Reiss ER, Drinkwater LE. Ecosystem service delivery by cover crop mixtures and monocultures is context dependent. Agron J. 2020;112:4249-63. https://doi.org/10.1002/agj2.20287

Rigon JPG, Franzluebbers AJ, Calonego JC. Soil aggregation and potential carbon and nitrogen mineralization with cover crops under tropical no-till. J Soil Water Conserv. 2020;75:601-9. https://doi.org/10.2489/jswc.2020.00188

Santos HG, Jacomine PKT, Anjos LHC, Oliveira VA, Lumbreras JF, Coelho MR, Almeida JA, Araújo Filho JC, Oliveira JB, Cunha TJF. Sistema brasileiro de classificação de solos. 5. ed. rev. ampl. Brasília, DF: Embrapa; 2018.

Silva FC. Manual de análises químicas de solos, plantas e fertilizantes. 2. ed rev ampl. Brasília, DF: Embrapa Informação Tecnológica; 2009.

Soil Survey Staff. Soil taxonomy: a basic system of soil classification for making and interpreting soil surveys. 2nd ed. Washington DC: United States Department of Agriculture, Natural Resources Conservation Service; 1999. (Agricultural Handbook, 436).

Telles TS, Melo TR, Righetto AJ, Didoné EJ, Barbosa GMC. Soil management practices adopted by farmers and how they perceive conservation agriculture. Rev Bras Cienc Solo. 2022;46:e0210151. https://doi.org/10.36783/18069657rbcs20210151

Telles TS, Righetto AJ, Lourenço MA, Barbosa GMC. No-tillage system participatory quality index. Rev Bras Eng Agric Ambient. 2020;24:128-33. https://doi.org/10.1590/1807-1929/agriambi.v24n2p128-133

Thapa R, Tully KL, Reberg-Horton C, Cabrera M, Davis BW, Fleisher D, Gaskin J, Hitchcock R, Poncet A, Schomberg HH, Seehaver SA, Timlin D, Mirsky SB. Cover crop residue decomposition in no-till cropping systems: Insights from multi-state on-farm litter bag studies. Agr Ecosyst Environ. 2022;326:107823. https://doi.org/10.1016/j.agee.2021.107823

Tian G, Brussaard L, Kang BT. An index for assessing the quality of plant residues and evaluating their effects on soil and crop in the (sub-) humid tropics. Appl Soil Ecol. 1995;2:25-32. https://doi.org/10.1016/0929-1393(94)00033-4

Vieira FMC, Machado JMC, Vismara ES, Possenti JC. Distribuições de probabilidade da análise de frequência de chuvas na região sudoeste do estado do Paraná, Brasil. Rev Cienc Agrovet. 2018;17:260-6. https://doi.org/10.5965/223811711722018260

Weiler DA, Bastos LM, Schirmann J, Aita C, Giacomini SJ. Changes in chemical composition of cover crops residue during decomposition. Cienc Rural. 2022;52:e20210357. https://doi.org/10.1590/0103-8478cr20210357

Wendling M, Büchi L, Amossé C, Jeangros B, Walter A, Charles R. Specific interactions leading to transgressive overyielding in cover crop mixtures. Agr Ecosyst Environ. 2017;241:88-99. https://doi.org/10.1016/j.agee.2017.03.003

Wieder RK, Lang GE. A critique of the analytical methods used in examining decomposition data obtained from litter bags. Ecology. 1982;63:1636-42. https://doi.org/10.2307/1940104

Yeomans JC, Bremner JM. Um método rápido e preciso para a determinação de rotina de carbono orgânico no solo. Commun Soil Sci Plant Anal. 1988;19:1467-76. https://doi.org/10.1080/00103628809368027

Ziech ARD, Conceição PC, Luchese AV, Balin NM, Candiotto G, Garmus TG. Proteção do solo por plantas de cobertura de ciclo hibernal na região sul do Brasil. Pesq Agropec Bras. 2015;50:374-82. https://doi.org/10.1590/S0100-204X2015000500004