Chapter

Cover Crop Residue Management for Effective Use of Mineralized Nitrogen in Greenhouse Tomato Production

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Abstract

Adequate residue management may enhance the benefits of cover crops on greenhouse tomato (*Solanum lycopersicum* L.) productivity, soil N pool, N cycling, and environmental quality. Regardless of management, cover crops may maintain or increase soil N storage at 10 cm depth compared with bare fallow. Cover crops may also enhance microbial biomass N, as a result, soil N availability may increase with cover crops, except rye (*Secale cereale* L.), more so with hairy vetch (*Vicia villosa* R.; HV) incorporation than HV mulch and the biculture of HV and rye. Residual inorganic N at surface soil may increase with cover crops, more so with HV and rye monocultures than the biculture. Tomato yield may increase more with the biculture than either HV incorporation or HV mulch because of an efficient residue-N use by tomatoes. The biculture may change the N release pattern from both cover crops: rye of the biculture may release more N than the monoculture, while HV may release a similar or more N in the late than in the early period of tomato growth. With adequate seeding HV/rye ratio (2/1), biculture may maintain or increase soil N storage, increase N cycling and tomato yield, and improve environmental quality.

Keywords: soil and environmental quality, N dynamics, hairy vetch, rye, tomato yield

1. Introduction

Nitrogen (N) is the most important nutrient required by most crops, and if adequately used in cropping systems can contribute to increasing food production over the long-term, which may help sustain the growing world population. Nitrogen fertilizers have been used in amounts that often exceed the crop N requirements over the years worldwide. Nitrogen fertilizer rates in vegetable production systems worldwide can be as high as 200 to 900 kg N ha^{-1} [1, 2]. However, high N fertilization rates may result in increased soil residual inorganic N [3] that can be lost from the soil–plant system through volatilization to the atmosphere [4] or leaching to groundwater [5]. Cover cropping is an improved management practice that can help reduce N leaching to groundwater through soil N uptake and/or by reducing N fertilizer inputs into cropping systems. However, the efficiency of cover crops in reducing N leaching varies with plant species. Nonlegumes are about three times more efficient in reducing N leaching than legumes [5] because of greater above- and belowground biomass production [3, 6]. Also, nonlegumes can establish root systems and produce dry matter under cool conditions better than legumes. On the other hand, the ability of legume cover crops in reducing N leaching is limited by the fact that legumes meet some or all of their N requirements from symbiotic N_2 fixation [5].

The sustainability of the cropping systems depends on the maintenance or improvement of soil carbon (C) and N levels. Cover crops can maintain or improve soil organic C and N levels by adding large amounts of residues that provide C and N to the soil [7, 8]. An increase in soil C and N levels may result in a range of ancillary benefits to the growing plants such as improved microbial biomass and activity and soil structure [9, 10], crop growth and yield [10–12]. Cover cropping may also help mitigate greenhouse gas emissions by sequestering atmospheric C to the soil and through improving N use efficiency by crops [13, 14]. As with N leaching, the cover crops' ability to influence soil C and N levels, crop N uptake, N use efficiency, and crop yields vary with plant species. Because of greater biomass production, nonlegumes may be more effective in improving soil C pool than legumes, while legumes with higher N concentration may be more effective in improving soil N pool and crop yields [12]. Nitrogen use efficiency from plant residues by crops including tomatoes (*Solanum lycopersicum* L.) is often less than 50% [3, 15], and part of unrecovered N amount is prone to be lost from the soil–plant system; this low N recovery is, in part, related to the nature of plant residues added to the soil. Nonlegumes decompose and release N slowly to the growing crop because of high C/N ratio, whereas legume plant residues decompose rapidly after application in the soil, releasing high N amounts in the early growth stages when the crop requires low N amounts. Thus, there is a need to adopt plant residue management practices that help increased N use efficiency by crops thereby improving N cycling, environmental quality, and crop yields. This chapter discusses cover crop use in greenhouse tomato production systems and residue management practices that optimize N use efficiency and tomato yield, reduce or limit residual N accumulation while maintaining or improving soil N storage.

2. Greenhouse tomato production systems and cover crops

Tomato is one of the most widely grown and eaten vegetables worldwide, and the second most important after potato (*Tuberosum solanum* L.) [16]. In Japan, tomato is the most important vegetable crop, and the fresh-market tomato industry is larger than that of processing tomatoes. Fresh-market tomatoes are mainly grown in greenhouses, especially plastic high tunnels, throughout the year, mainly in warm regions. In these systems, farmers cultivate tomatoes continuously and often apply high amounts of synthetic N fertilizers (>200 kg N ha^{-1}) to maximize net returns, as a result, salt accumulation and fruit injury became serious problems [17]. The increased concerns about environmental problems and the consumer's preference for vegetables produced with fewer chemicals have become the driving forces for the development of alternative and sustainable fresh-market tomato production systems. The use of cover crops, especially legumes such as hairy vetch (*Vicia villosa* R.; HV), was seen as a promising practice that could help reduce N fertilizer inputs, while maintain or improving tomato yield and soil organic matter. Hairy vetch and rye (*Secale cereale* L.) cover crops were evaluated in the field and Wagner pots under plastic high tunnel conditions in northern Japan and the results are discussed below.

2.1 Hairy vetch and rye C and N accumulation and residue decomposition

Hairy vetch is a winter-hardy cover crop that can produce large biomass and accumulate about 92.1 to 187 kg N ha^{-1} in the open-field systems and 98.1 to 301 kg N ha^{-1} in greenhouse systems (**Table 1).** Because of a C/N ratio < 25 (**Table 1**) [23], HV residues breakdown rapidly after incorporation in the soil, releasing about 40% of its total N within the first 4 weeks after incorporation of residues in the soil [24]. This rapid N release increases the likelihood of N loss from the soil–plant system when used as an N source for crop production, especially in the open-field systems [3, 25].

Rye is the coldest tolerant and the easiest to establish, the most productive and the earliest to head among temperate region nonlegume cover crops [26]. It can produce as much as 6.75 Mg ha^{-1} of aboveground biomass in the open-field systems (**Table 1**). Because of the C/N > 25 (**Table 1**) [23], rye residues breakdown slowly after application in the soil resulting in a lack of synchrony between residue-N release and crop N demand, which leads to low residue-N recovery and crop yields. Our results from a litterbag experiment under the plastic high tunnel conditions showed that only 16.5% of buried dry weight rye residues decomposed during the first 4 weeks after the initiation of the experiment, whereas, during the same period, HV showed decomposition of 59.8% of buried dry weight residues (**Figure 1**). A more significant rye decomposition was observed after the first 4 weeks, whereas by the end of the experiment, 12 weeks after burying, the percentage of the initial dry weight of rye residues that remained in the soil was 24.5%, higher than 1.2% of HV (**Figure 1**). Despite greater biomass production, rye adds fewer N amounts to the soil compared with HV [6, 11] because of low N accumulation. In some cases, the application of rye residues (C/N ratio > 25) depletes soil N availability and decreases crop yields because of N immobilization by soil microbes [11, 25].

Alternatively, the biculture of HV and rye, with an intermediate C/N ratio between HV and rye (**Table 1**), may show a moderate decomposition speed that may result in an increased soil N availability and residue-N recovery by tomatoes. This assumption is supported by the results from a litterbag assay under the open-field conditions of Chinta et al. [27], who reported, with few exceptions, an intermediate decomposition level of residues of the biculture of HV and rye between pure HV (higher) and rye (lower) residues. Also, because of greater seeding rates, biculture of HV and rye may accumulate greater biomass and add more C to the soil than HV, and more N than rye monoculture [6, 11], thereby influencing soil C and N dynamics more significantly.

2.2 Effects of cover crop residue management on tomato yield, N uptake, and cover crop N recovery

Because of high N accumulation and low C/N ratio, HV adds more N to the soil and enhances N uptake and the yield of the subsequent crop better than nonlegumes or bare fallow [8, 11]. Cover crop treatments showed a 13.9 to 32.7% greater marketable yield than the bare treatment in 2017 (**Table 2**). The biculture of HV and rye (HV + RYE) showed the highest marketable yield. Similarly, the cover crop treatments showed 31.5 to 68.3% greater shoot biomass and N uptake compared with the bare treatment. Greater marketable yield with the biculture than with HV incorporation (HVI), although a similar total N uptake and residue-N recovered, may be explained by more efficient use of cover crop N by tomatoes throughout the growing period. Biculture with a moderate decomposition speed (C/N = 17.6 [22]) may have released more N during the period of high N demand, while HVI with fast

Cover crop	DW Biomass ($Mg\ ha^{-1}$)	C applied ($kg\ ha^{-1}$)	N applied ($kg\ ha^{-1}$)	C/N ratio	Examination period	Reference
Open-field systems						
Hairy vetch	4.97	2107	159	13.3	1989	Clark et al. [11]
	4.80	2112	187	11.4	1996–1997	Sainju et al. [12]
	4.23	1688	136	12.4	2000–2002	Sainju et al. [6]
	2.19	1049	92.1	11.4	1999	Horimoto et al. [18]
	—	1482	123	10	1992–1993	Kuo et al. [8]
Rye	6.75	3737	74.0	50.5	1989	Clark et al. [11]
	—	1630	47.5	35.0	1992–1993	Kuo et al. [8]
	6.37	2954	107	27.7	1996–1997	Sainju et al. [12]
	4.05	1795	41.6	43.1	2000–2002	Sainju et al. [6]
Hairy vetch/rye	6.63	2822	193	14.6	2000–2002	Sainju et al. [6]
	7.96	3956	168	23.6	1989	Clark et al. [11]
Greenhouse systems						
Hairy vetch	4.71	2050	203	10.1	2007–2012	Araki [19]
	6.52	2693	281	9.60	2017	Muchanga et al. [20]
	4.80	2037	193	10.6	2016–2017	Muchanga et al. [21]
	6.78	3018	301	10.0	2017	Muchanga et al. [22]
	2.46[z]	1003	98.1	10.2	2018	Muchanga et al. [22]
Rye	6.19	2639	43.1	61.3	2018	Muchanga et al. [22]
Hairy vetch/rye	8.02	3465	197	17.6	2017	Muchanga et al. [22]
	6.55	2777	117	23.7	2018	Muchanga et al. [22]

[z]*Low biomass resulted from a late planting of hairy vetch (planted on 25 April 2018) due to the low survival rate of the previous hairy vetch planting (planted on 21 September 2017) caused by a high snowpack (>1 m) and a long period of snow cover.*
—Aboveground biomass was not reported by the authors.

Table 1.
The dry weight (DW) biomass, carbon (C) and nitrogen (N) accumulation, and C/N ratio of cover crops grown in the open-field and greenhouse systems.

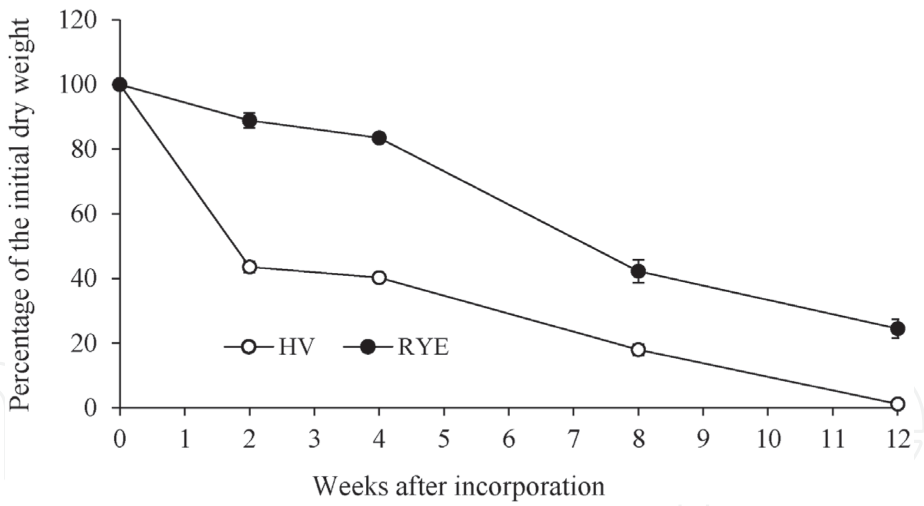

Figure 1.
Decomposition of 5 g dry weight of hairy vetch (HV) and RYE (RYE) residues buried at 10 cm soil depth in tomato plots during 12 weeks under the plastic high tunnel in 2018. Vertical bars represent standard errors (n = 3); only shown when larger than the symbols.

Treatments[z]	Marketable yield		Dry weight shoot biomass		Total N uptake[y]		Recovered cover crop N[x] Total		Percentage of N input
	$Mg\ ha^{-1}$		$Mg\ ha^{-1}$		$kg\ N\ ha^{-1}$		$kg\ N\ ha^{-1}$		
2017									
BARE	101	c[w]	4.89	c	186	c	—		—
HVI	116	b	7.10	a	313	a	127	a	42.0
HVM	115	b	6.43	b	267	b	81	b	27.0
HV+RYE	134	a	7.47	a	312	a	126	a	63.9
2018									
BARE	60.1	b	4.37	ab	184	b	—		—
HVI	84.3	a	5.96	a	233	a	49.0	a	50.7
HVM	64.8	b	4.98	ab	195	b	11.0	b	11.4
RYE	49.8	c	3.64	b	153	c	-31	—	-71.8
HV+RYE	60.7	b	4.81	ab	188	b	4.0	c	3.42

[z]*BARE, no cover crop but fertilized with 150 kg N* ha^{-1}*; HVI, hairy vetch incorporation; HVM, hairy vetch mulch; RYE, rye monoculture; HV+RYE, biculture of hairy vetch and rye. All cover crop treatments received the controlled-release N fertilizer at a rate of 150 kg N* ha^{-1}*.*
[y]*Nitrogen uptake from the soil and cover crops = shoot N content × shoot dry weight biomass + fruit N content × fruit total dry weight.*
[x]*Calculated as the ratio of total N recovered from cover crops (N uptake in cover crop – N uptake in BARE) to the cover crop N input. Cover crop N input in HVI, HVM, and HV+RYE was 302, 300, and 197 kg N* ha^{-1} *in 2017, and 99.3, 96.8, and 117 kg N* ha^{-1} *in 2018, respectively. Rye residues (RYE) added to the soil 43.1 kg N* ha^{-1} *in 2018.*
[w]*Means followed by the same letters in each column and year are not significantly different at 5% by Tukey's honestly significant difference test.*

Table 2.
Effects of cover crop residue management on tomato marketable yield, shoot biomass, N uptake and recovery in 2017 and 2018 (Muchanga et al. [22]).

decomposition speed (C/N = 10.2), may have released more N in the early period of tomato growth [24], a period of low N demand. This assumption is supported by a lower growth index (GI = plant length × stem diameter × number of expanded leaves [28]) in the early period of tomato growth (5 and 7 weeks after transplanting; WAT) with the biculture than with HVI (**Table 3**). However, the rate of increase of GI from 7 to 9 WAT was higher with the biculture (82.9%) than with HVI (68.9%), which resulted in a similar GI of the biculture to HVI at 9 WAT. The results of Sugihara et al. [24] who found more HV-derived N concentration in the 1st and 2nd tomato fruit clusters than in upper fruit clusters, also supported the assumption that HV incorporation released more N in the early period of tomato growth, which favors more shoot biomass accumulation rather than fruit set and enlargement.

As opposed to 2017, the marketable yield, shoot biomass, and total N uptake increased with HVI only, compared with the bare treatment, in 2018. The biculture and HV mulch (HVM) showed similar marketable yield, shoot biomass, and total N uptake to the bare treatment, whereas rye treatment (RYE) showed adverse effects on tomato yield, shoot biomass, and total N uptake due to N immobilization (**Table 2**). The adverse effect of rye residues resulted from their C/N ratio > 25 [23]. Soil microbes require N for their growth and if residues cannot meet their N requirements, microbes immobilize soil inorganic N, resulting in soil inorganic N depletion. Sainju et al. [12] reported 27.2 and 28.9% lower tomato yield and plant biomass, respectively, in rye than in bare plots without N fertilization in 1997. Likewise, Clark et al. [11] reported a decrease in corn grain yield by 32.7% in rye plots compared with no cover crop plots. The increased effectiveness of the biculture on marketable yield observed in 2017 was not repeated in 2018. Biculture showed no effect on shoot biomass, tomato yield, and N uptake possibly because of low residue-N recovery in 2018. Tomatoes utilized only 3.42% of the biculture N amount applied (N applied by residues was 117 kg N ha^{-1} [22]) (**Table 2**). This ineffectiveness of the biculture may be explained by the higher C/N ratio of residues in 2018 (23.7) than in 2017 (17.6) [22]. This result highlights the importance of the C/N ratio in controlling the plant residue N release, so the decision on seeding rates HV/rye should be based on the expected C/N ratio of biculture residues. Greater tomato yield with HV than with bare fallow was reported by several researchers [10, 12]. Araki et al. [17] reported greater tomato yield and plant growth

Treatments^z	**Growth index**^{y}						
	WAT						
	3	**5**		**7**		**9**	
BARE	4031	12,474	b^x	29,185	c	46,074	c
HVI	4344	15,801	a	34,578	a	58,406	a
HVM	4112	12,634	b	32,577	b	55,906	b
HV + RYE	3967	13,316	b	32,173	b	58,846	a
Significance	NS						

^{z}*BARE, no cover crop but fertilized with 150 kg N ha^{-1}; HVI, hairy vetch incorporation; HVM, hairy vetch mulch; HV+RYE, biculture of hairy vetch and rye. All cover crop treatments received the controlled-release N fertilizer at a rate of 150 kg N ha^{-1}.*
^{y}*GI = Plant length (cm) × stem diameter (mm) × number of expanded leaves. WAT, weeks after transplanting.*
^{x}*Means followed by the same letters in each column are not significantly different at 5% by Tukey's honestly significant difference test.*
NS, not significant.

Table 3.
Tomato growth index (GI) as influenced by cover crop residue management in 2017.

with HV mulch than with bare fallow. Likewise, Muchanga et al. [21] reported greater marketable and total yields and shoot biomass with HV incorporation than with the bare fallow.

2.3 Effects of cover crop residue management on soil N pool

2.3.1 Soil microbial biomass N and N availability

The quantity, quality, and management of cover crop residues may influence N dynamics and storage in the soil, which affects crop yield and environmental quality. Regardless of residue management (residue placement or the mixing of legumes and nonlegumes residues), the addition of cover crops residues to the soil increased significantly soil microbial biomass N (MBN) levels at 0–10 cm bulk soil by 25.4 to 121% at 4 and 8 WAT in 2017, and by 26.8 to 187% at 2 and 8 WAT in 2018, compared with the bare treatment (no cover crop but fertilized with 150 kg N ha^{-1}) (**Figure 2**). In both years, HV incorporation showed the highest increment of MBN, whereas, despite a similar N input [22], HV mulch showed the least increment of MBN. This fact points out that the placement of residues in the soil may determine the cover crop N mineralization and contribution to the growing crop. The increase in MBN with cover crops than with no cover crop resulted from greater C and N inputs, especially N because it is the most limiting nutrient for microbial growth [29, 30]. However, with high levels of soil inorganic N, even residues with low N content, such as rye residues, may increase MBN levels in the early period after residue application because if plant residues do not satisfy microbes N requirements, microbes obtain N from the soil [29].

Soil N availability (soil inorganic N during the crop growing period) varied significantly ($P < 0.05$) with treatments at 0–10 cm depth at 2, 8, and 16 WAT in 2017 and 2018 (**Figure 3**). Averaged across sampling dates, soil N availability followed these orders: HVI > HV + RYE > BARE > HVM in 2017, and HVI = HVM > HV + RYE > BARE > RYE in 2018. The decrease in soil N availability in HVM in 2017 may be the result of slow N mineralization of mulch residues compared with incorporated residues [31], and higher N uptake compared with the bare treatment (**Table 2**). On the other hand, the decrease in soil N availability in RYE in 2018 resulted from N immobilization due to the C/N ratio > 25 [23]. Therefore, even in greenhouse production systems where water is applied regularly and the soil temperature is relatively higher compared to that of the open-field systems, cover crops such as rye, with a high C/N ratio, may have little or no N contribution to the growing crop, so biculture of HV and rye may be a better management option. It's noteworthy that the effectiveness of biculture in increasing MBN and soil N availability diminished from 2017 to 2018 as a result of the increase in the C/N ratio of residues. Therefore, the use of adequate seeding HV/rye rates is crucial to maximizing residue-N utilization by the growing crop.

2.3.2 Soil total N

Increasing or maintaining soil N levels is vital for sustaining soil quality, crop growth and yield [8]. Soil N storage may vary with cover crop species due to differences in biomass production and N accumulation [32], and residue management. In 2017, HV incorporation increased significantly soil total N (STN) by 11.3% at 0–10 cm depth and 8.14% at 10–30 cm depth, compared with the bare treatment (**Table 4**). The biculture showed a 1.76% increase in STN compared with bare treatment at 10–30 cm depth only. In contrast, HVM showed no or negative effect on STN in 2017. In 2018, all cover crop treatments increased STN by 10.1% to 12.6%

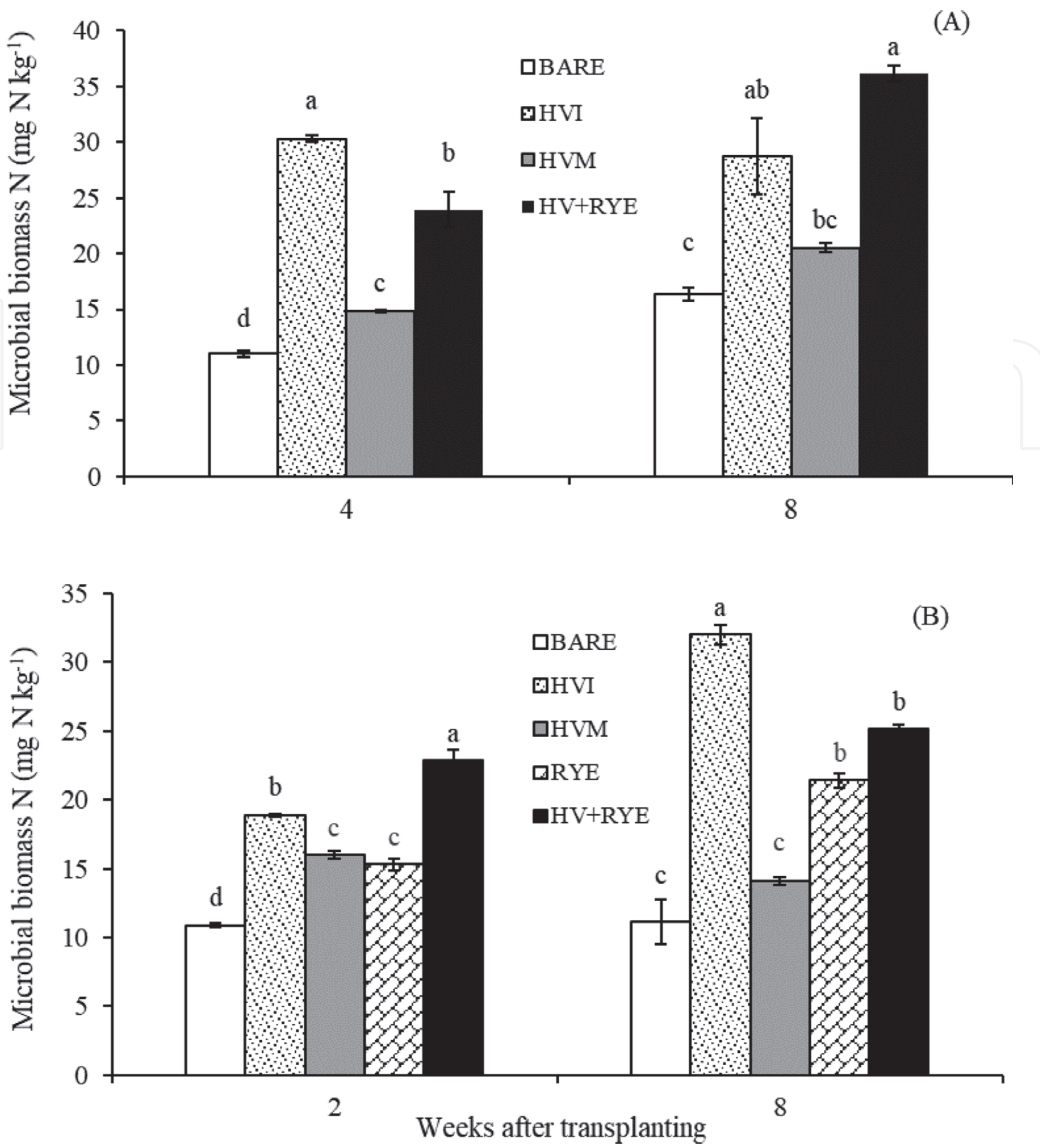

Figure 2.
Effects of cover crop residue management on microbial biomass nitrogen at surface 10 cm bulk soil depth during the period of tomato cultivation in (A) 2017 and (B) 2018. Vertical bars represent standard errors (n = 3). Means followed by the same letters on each sampling date and year are not significantly different at 5% by Tukey's honestly significant difference test (Muchanga et al. [22]).

at 0–10 cm depth only, compared with no cover crop treatment. Greater STN with cover crops than without cover crops observed mostly in 2018 agreed with the results of Kuo et al. [8] and Sainju et al. [12] and may be the result of greater C and N inputs by cover crop residues. In both years, HVI was the most effective treatment in increasing STN. The positive effects of HVI on STN shown in **Table 4** agreed with the results of our previous study [21] where the effects of HV (incorporation) were compared to those of livestock compost. In that study, HV incorporation showed 7.29% greater STN stock than the bare treatment (no HV and compost) and a 17.3% increase of STN stock compared with the baseline stock (initial STN stock measured before any treatment application). However, HV was not as effective as the livestock compost in building up STN stock.

The cover crops and bare treatments shown in the **Table 4** were fertilized with the controlled-release N fertilizer at a rate of 150 kg N ha^{-1} to sustain crop growth when the cover crop N supply ceases or reduces. This N fertilizer follows a sigmoidal pattern (S-type), releasing 80% of its total N slowly for 70-day after a lag period

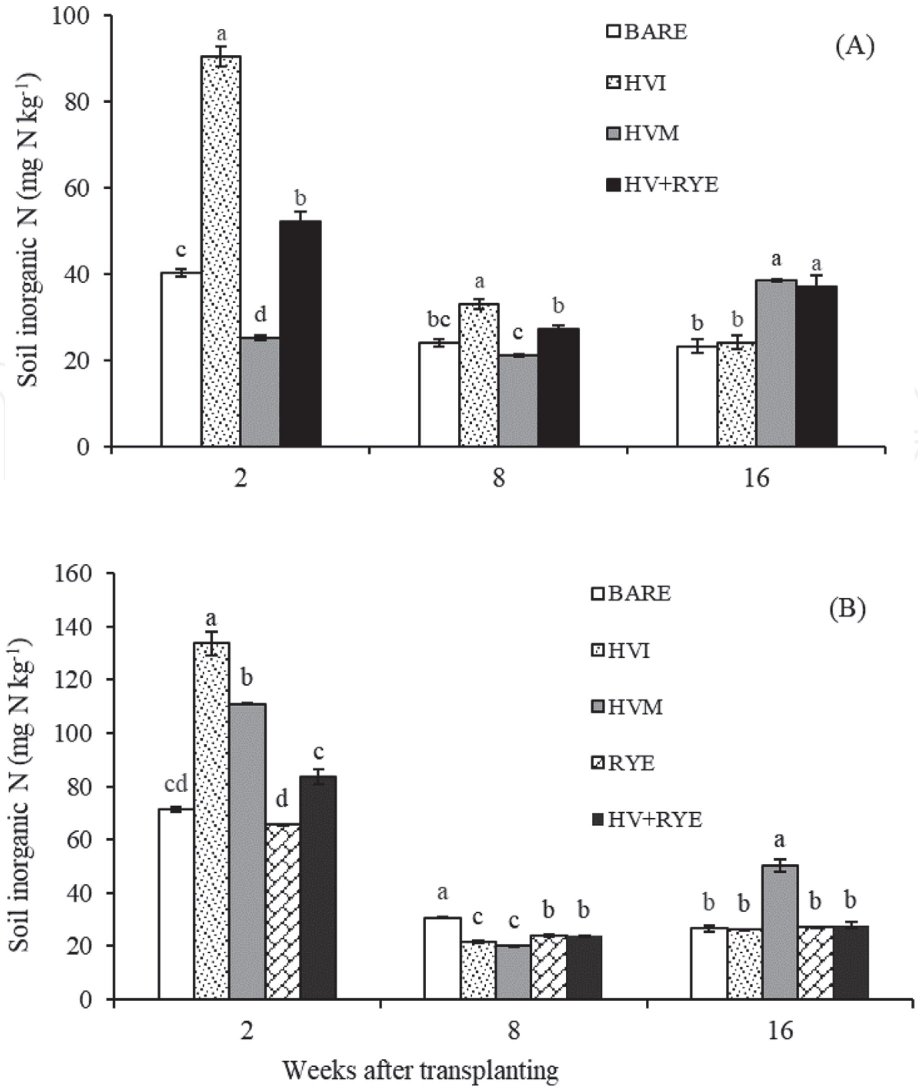

Figure 3.
Effects of cover crop residue management on soil inorganic nitrogen (NO_3^-—N + NH_4^+ − N) at surface 10 cm soil depth during the period of tomato cultivation in (A) 2017 and (B) 2018. Vertical bars represent standard errors (n = 3). Means followed by the same letters on each sampling date and year are not significantly different at 5% by Tukey's honestly significant difference test (Muchanga et al. [22]).

of 30-day in the soil at 25° C (LPS100, 41%N; JCAM AGRI, Tokyo, Japan). Because of its N release pattern, it was included in our experiments for developing low N input systems. The N fertilizer effects on soil C and N were examined in 2016 under plastic high tunnel conditions (**Table 5**). The controlled-release N fertilizer showed no effect on soil organic C (SOC) and STN at 0–10 cm depth, but HV × fertilizer interaction was significant for SOC. The N fertilizer enhanced the positive effects of HV mulch on SOC, whereas it diminished the effectiveness of HV incorporation in increasing SOC (**Table 5**). As opposed to fast-release N fertilizers that were reported to decrease SOC and STN [33, 34], this controlled-release N fertilizer may be used safely in greenhouse tomato production systems, preferably applying N amounts ≤ 150 kg N ha^{-1}.

2.3.3 Soil residual N

Soil residual inorganic N may represent 50 to 80% of total fertilizer N applied to crops, more so in vegetable than field crop systems because of higher N inputs and lower N recovery of vegetable crops including tomatoes [35]. Thus, the N loss potential from the soil–plant system through volatilization and/or leaching is higher in vegetable systems. Because temperate region soils are negatively charged

Treatments[z]	STN				Change[y]	
	0–10 cm		10–30 cm		0–10 cm	10–30 cm
	Mg N ha^{-1}				%	
2017						
BARE	3.10	b[x]	7.37	bc	—	—
HVI	3.45	a	7.97	a	11.3	8.14
HVM	3.20	b	7.25	c	—	−1.63
HV + RYE	3.22	b	7.50	b	—	1.76
2018						
BARE	2.47	b	5.94		—	—
HVI	2.78	a	5.99		12.6	—
HVM	2.73	a	5.92		10.5	—
RYE	2.75	a	5.92		11.3	—
HV + RYE	2.72	a	5.80		10.1	—
Significance			NS			

[z]BARE, no cover crop but fertilized with 150 kg N ha^{-1}; HVI, hairy vetch incorporation; HVM, hairy vetch mulch; RYE, rye monoculture; HV+RYE, biculture of hairy vetch and rye. All cover crop treatments received the controlled-release N fertilizer at a rate of 150 kg N ha^{-1}.
[y]Change (%) = (STN in cover crop − STN in BARE)/STN in BARE × 100
[x]Means followed by the same letters in each column and year are not significantly different at 5% by Tukey's honestly significant difference test. NS, not significant.

Table 4.
Soil total nitrogen (STN) at surface 0–30 cm depth as influenced by cover crop residue management in 2017 and 2018 (Muchanga et al. [22]).

Treatments[z]	Soil N				Soil organic C	
	Inorganic		Total			
	mg N kg^{-1}		g kg^{-1}			
BARE-NF	15.8	b[y]	2.39	b	29.2	b
BARE-F	19.9	b	2.18	b	29.5	b
HVI-NF	15.5	b	2.67	a	32.3	a
HVI-F	43.6	a	2.59	a	30.4	ab
HVM-NF	21.6	b	2.52	a	30.8	ab
HVM-F	50.1	a	2.68	a	31.8	a
Hairy vetch (HV)	***		*		***	
Fertilizer (F)	***		NS		NS	
HV × F	**		NS		***	

[z]BARE-NF, no cover crop and no N fertilization; BARE-F, no cover crop with N fertilization; HVI-NF, hairy vetch incorporation without N fertilization; HVI-F, hairy vetch incorporation with N fertilization; HVM-NF, hairy vetch mulch without N fertilization; HVM-F, hairy vetch mulch with N fertilization. Controlled-release N fertilizer applied at a rate of 150 kg N ha^{-1}.
*[y]Means followed by the same letters in each column are not significantly different at 5% by Tukey's honestly significant difference test. NS, *, **, ***Not significant or significant at $P < 0.05$, 0.01, and 0.001, respectively.*

Table 5.
Effects of hairy vetch residue management and nitrogen fertilization on soil carbon (C) and nitrogen (N) at 0–10 cm depth in 2016.

retaining most of NH_4^+ –N [32], NO_3^- –N leaching is more important, especially after winter when a large amount of snow melts. The use of cover crops may reduce N fertilization rates and thereby reducing N leaching potential. Moreover, the management of cover crop residues may affect the decomposition speed of the residues thereby influencing crop N uptake and residual inorganic N. Generally, the decomposition speed of residues that are incorporated in the soil is faster than that of residues that are placed on the soil surface [29, 31], therefore the net N release of surface-placed residues is delayed [36].

The effects of cover crop residue management on soil residual N (soil inorganic N levels after tomato harvest) in tomato production in a Gleysol were assessed in 2017 and 2018 in northern Japan. Because of greater N input and slow or fast decomposition speed, HVM and HVI showed 25.2 to 386% greater NO_3^- –N and soil inorganic N (SIN) at 0–10 cm depth in 2017 (**Table 6**). On the other hand, despite a higher N input (biculture residues added 117 kg N ha^{-1} to the soil [22]), the biculture showed NO_3^- –N and SIN levels similar to those of the bare treatment. Least NO_3^- –N and SIN levels with the biculture may be the result of higher residue-N recovery by tomatoes (**Table 2**) possibly due to a moderate decomposition speed of residues.

As opposed to 2017, NO_3^- –N, NH_4^+ – N, and SIN levels increased by 54.2 to 218% with all cover crop treatments compared with the bare treatment in 2018. In both years, HVM showed the highest NO_3^- –N and SIN levels suggesting its use in greenhouse tomato production systems may represent a high risk of N leaching to groundwater after winter. As opposed to 2017, the fact the biculture increased NO_3^- –N and SIN levels in 2018 may be explained by the increase of its C/N ratio to 23.7, which resulted in low N recovery due to slow residue decomposition [37].

Treatments[z]	NO_3^-–N		NH_4^+ – N		SIN		Percentage of SIN-derived from cover crop N input[y]
	kg N ha^{-1}						%
2017							
BARE	4.59	c[x]	23.0	b	27.6	c	—
HVI	9.14	b	25.4	b	34.5	b	2.30
HVM	22.3	a	32.0	a	54.3	a	8.92
HV + RYE	4.11	c	22.8	b	26.9	c	−0.91
2018							
BARE	20.8	d	5.7	c	26.4	d	—
HVI	35.7	c	11.4	a	47.1	c	20.8
HVM	73.9	a	10.2	ab	84.1	a	59.5
RYE	47.5	b	12.7	a	60.2	b	78.3
HV + RYE	32.0	c	10.0	ab	42.0	c	13.3

[z]*BARE, no cover crop but fertilized with 150 kg N ha^{-1}; HVI, hairy vetch incorporation; HVM, hairy vetch mulch; RYE, rye monoculture; HV+RYE, biculture of hairy vetch and rye. All cover crop treatments received the controlled-release N fertilizer at a rate of 150 kg N ha^{-1}.*
[y]*%SINdfCCNinput = (SIN in cover crop – SIN in BARE)/Cover crop N input ×100. Cover crop N input in HVI, HVM, and HV+RYE was 302, 300, and 197 kg N ha^{-1} in 2017, and 99.3, 96.8, and 117 kg N ha^{-1} in 2018, respectively. Rye N input was 43.1 kg N ha^{-1}.*
[x]*Means followed by the same letters in each column and year are not significantly different at 5% by Tukey's honestly significant difference test.*

Table 6.
Soil inorganic nitrogen (SIN; NO_3^-–N + NH_4^+ – N) after tomato harvest at surface 10 cm depth as influenced by cover crop residue management in 2017 and 2018 (Muchanga et al. [22]).

In 2017, the proportion of the seeding rates of HV/rye was 2/1 (20 kg ha^{-1} HV/10 kg ha^{-1} rye), while in 2018 was 1/1 (50 kg ha^{-1} HV/50 kg ha^{-1} rye). The reasons for using different seeding rates among the years were explained by Muchanga et al. [22]. Thus, seeding rates of HV/rye in a proportion of 2/1 (in kg ha^{-1}) that may lead to a C/N ratio of about 17.6 are recommended. The percentage of SIN-derived from cover crop N input (%$SINdfCCN_{input}$) was lower in 2017 than in 2018 (**Table 6**), suggesting that more residue-N applied in 2017 was utilized by plants than in 2018. Hairy vetch mulch and rye showed higher %$SINdfCCN_{input}$ than other treatments in 2018, suggesting that more residue-N was released in the late period, more so from rye than HV mulch.

The data from **Table 5** suggests that the increase in residual SIN in HVM and HVI plots is more related to the addition of the controlled-release N fertilizer, so the rate of 150 kg N ha^{-1} added to HVI and HVM plots may be excessive. A further study determining a better N fertilization rate for HVI and HVM that leads to a high yield, increased soil N storage, and least residual SIN is needed.

2.4 Rye-derived nitrogen dynamics in the soil-tomato system in a greenhouse using ^{15}N tracer technique

Since neither HV nor rye can simultaneously provide N and enhance tomato yield, increase soil N storage, and reduce N leaching through residual N uptake, the use of the biculture of HV and rye in tomato production is seen as a promising practice that can provide most of the benefits [32]. The positive effects of the biculture on tomato yield and residue-N recovery observed in 2017 discussed in the previous section suggest that residue management may improve the N contribution of cover crops to tomato production, and more importantly, the N release pattern of HV and rye may change when applied together in the soil. While dynamics of N derived from HV in the soil—tomato system have been studied [24], studies on dynamics of N derived from rye in the soil—crop system are limited, possibly due to detrimental effects of rye on crop yields. A ^{15}N tracer examination was conducted in Wagner pots in a plastic high tunnel in northern Japan to understand the reasons for the high effectiveness of the biculture in increasing residue-N recovery and tomato yield by examining the uptake and recovery, and retention in the soil of N derived from rye residues applied as a monoculture and biculture with HV. The major findings are discussed below.

2.4.1 Rye-derived nitrogen accumulation in tomato, uptake and recovery

Because of higher rye-derived N input, tomatoes (shoot + fruit) in the rye treatment (N input was 1943 mg N/plant [38]) accumulated more rye-derived N than those in the biculture treatment (N input was 972 mg N/plant) on all sampling dates (**Figure 4A**). Rye-derived N accumulation in both treatments increased from 2 to 8 WAT and then decreased afterward. This decline of rye-derived N accumulation indicates the cessation of N uptake (determined as the positive difference between rye-derived N accumulation of a given week and the preceding week). The cessation of N uptake by tomato shoot and fruit or the decline in N accumulation after 8 WAT may be the result of N partitioning to roots, a process that occurs when soil inorganic N is least [39, 40]. Rye-derived N uptake by tomatoes was 70.2% and 75.5% greater with rye than with the biculture at 0–2 and 4–8 WAT, respectively (**Table 7**). Rye is often regarded as a delayed-N release, so the fact that rye treatment released a high amount of N at 0–2 WAT may be explained by a C/N ratio < 25 (C/N ratio = 17.4) [23], which is lower than a normal range (25.3 to 66.9) reported by several researchers [6, 8, 10, 11]. This lower C/N ratio resulted from N

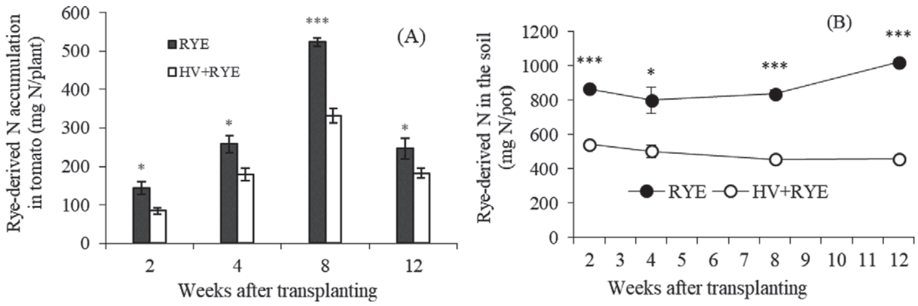

Figure 4.
*Influence of residue management on rye-derived nitrogen accumulation in tomato shoot and fruit (a) and retained in the soil (B). Vertical bars represent standard errors (n = 3); only shown when larger than the symbols. *, ***significant at P < 0.05, and 0.001, respectively (Muchanga et al. [38]).*

		Rye-derived N							
Treatments[z]	**Input in the soil (mg N/pot)**	**Uptake**[y] **(mg N/plant)**				**Recovery**[x] **(%)**			
		WAT			**Total**	**WAT**			**Total**
		0–2	2–4	4–8		0–2	2–4	4–8	
RYE	1943	144	114	265	523	7.39	5.87	13.7	26.9
HV + RYE	972	84.3	94.9	151	331	8.67	9.77	15.6	34.0
t-test	***	**	NS	***	***	**	NS	***	***

[z]RYE, 15N-labeled rye residues; HV+RYE, biculture of hairy vetch and 15N-labeled rye residues.
[y]Determined as the positive difference of rye-derived N accumulation (Figure 4A) between a given week and the preceding week.
[x]Rye-derived N recovery (%) = rye-derived N uptake/ rye-derived N input × 100.
*NS, **, *** Not significant or significant at P < 0.01, and 0.001, respectively.*

Table 7.
Rye-derived nitrogen input in the pot, and its uptake and recovery by tomatoes (shoot + fruit) as influenced by residue management in 2018 (Muchanga et al. [38]).

fertilization with $^{15}NH_4Cl$ and soil N uptake (rye grew in soil with the initial NO_3^-−N concentration of 65.2 mg N kg^{-1} [38]).

As opposed to rye-derived N uptake, the biculture showed a total rye-derived N recovery of 34%, higher than 26.9% of rye treatment (**Table 7**). This result suggests that biculture of HV and rye may be an effective management practice to increase the N contribution from rye to tomato growth and fruit production. Consequently, if more N from residues is used by tomatoes, less supplemental N fertilizer may be needed, and the environmental problems associated with high N fertilization rates may be avoided. The biculture may provide many benefits such as enhancing tomato yield and residue-N recovery better than HV and rye monocultures and reduce residual N better than HV [41]. Several researchers [3, 25] have reported increased residual nitrate levels and leaching to groundwater with HV than with no cover crop, more so when high N fertilization amounts were added.

Although the N contribution from rye to tomato growth and fruit production increased when applied with HV to the soil, HV in the biculture may play a major role by contributing more N than rye in the early (0–4 WAT) and late periods (4–8 WAT) of tomato cultivation (**Table 8**). Hairy vetch and rye N contributions from 0 to 8 WAT represented 25.3% and 17.3% of the total N uptake (1914 mg N/plant [38]), respectively. Sugihara et al. [24] reported N recovery by tomatoes (shoot + fruit) of 40.3% by 4 WAT and an additional 15% at 4–10 WAT (HV-derived N uptake ceased at 10 WAT). In this study, HV contributed 9.65% more N to shoot growth and fruit production at 4–8 WAT than at 0–4 WAT, suggesting that the biculture may change the N release pattern from both cover crops: rye may release

Component of the biculture	N uptake from cover crops (mg N/plant)			Percentage of total N uptake[z]
	WAT		Total	
	0–4	4–8		
Hairy vetch	231	253	484	25.3
Rye	179	151	331	17.3
t − test	*	**	***	—

[z]*Calculated as the ratio of the total N uptake from hairy vetch or rye to the total N uptake of the biculture (1914 mg N/plant [38]).*
*, **, ****Significant at P < 0.05, 0.01, and 0.001, respectively.*

Table 8.
Nitrogen uptake by tomatoes (shoot + fruit) from each cover crop of the biculture (Muchanga et al. [35]).

more N when mixed with HV, in turn, HV may release a similar or more N amount after 4 weeks following the transplanting than before that period.

2.4.2 Retention in the soil of nitrogen derived from rye

Residue management and the quantity of residues applied to the soil [7, 8] may influence the amount of N retained by the soil. Rye-derived N retained in the soil was markedly higher with rye monoculture than with the biculture on all sampling dates (**Figure 4B**). The rye treatment showed an increasing trend of rye-derived N levels in the soil from 2 to 12 WAT, more so at 8 to 12 WAT. In contrast, the biculture showed a decreasing trend of rye-derived N levels in the soil from 2 to 12 WAT. Greater rye-derived N retention with rye than with the biculture treatment may be the result of higher rye-derived N input in rye treatment [(1943 mg N/plant) (**Table 7**)] than in biculture (972 mg N/plant), and also lower N mineralization rate of rye residues in RYE treatment than in HV + RYE treatment. The decreasing trend of rye-derived N in the soil with biculture suggests that slow decomposition of residues may be advantageous over fast decomposition in building up STN.

By 12 WAT, the amount of rye-derived N retained in the soil represented 52.5% and 47.0% of the total rye-derived N input in rye monoculture and biculture, respectively. The ability of the soil to retain plant-derived N is stronger than the ability of different loss mechanisms to remove it [15]. Thus, the lower rye-derived N recovery observed in both treatments resulted from increased soil N retention. Rye-derived N retained in the roots and/or lost (difference of rye-derived N input and rye-derived N uptake and retained in the soil) was estimated at 20.6% and 19.0% in rye monoculture and biculture treatments, respectively.

3. Conclusion

Adequate cover crop residue management may help increase N contribution from residues to tomato production, thereby enhancing tomato yield, reduce N fertilization rates, and maintain or improve soil and environmental quality. Regardless of residue management cover crops may maintain or increase soil N storage at surface 10 cm soil depth. Residual soil inorganic N at surface 10 cm soil depth, subject to leaching losses after tomato harvest, may increase with cover crops, more so with hairy vetch (incorporation and mulch) and rye monocultures than the biculture of hairy vetch and rye because of rapid or delayed N release.

With adequate seeding hairy vetch/rye ratio (2/1), the biculture may be a better management practice to increase tomato yield and residue-N recovery, and maintain or increase soil N storage at surface 30 cm depth with no or least residual N. Biculture may promote efficient use of residue-N by tomatoes by releasing high amount of N in both the early and late periods of tomato growth. Biculture may change the N release pattern of both hairy vetch and rye residues: hairy vetch may release a similar or more N in the late (reproductive growth stage) than in the early period (vegetative growth stage) of tomato growth, while rye may release more N when applied with than without hairy vetch.

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