COVER CROPS FOR SUSTAINING VEGETABLE PRODUCTION, IMPROVING SOIL AND WATER QUALITIES AND CONTROLLING WEEDS AND PESTS

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1. Introduction

Cover crops, grown to cover exposed soil for reducing soil erosion, play important roles in sustainable crop production. They influence on crop yields, soil and water qualities, and incidence of weeds, pests, and diseases [32, 33, 52, 67]. While no fertilizers, herbicides or pesticides are used to grow cover crops, they use residual nutrients, such as N, P, K, left in the soil after main crop harvest, thereby reducing the potentials of nutrient loss through erosion and leaching [43, 53]. When cover crop residues are incorporated into the soil, the increased biomass produced by cover crops compared with weeds in the bare soil not only recycle residual nutrients but also improve soil quality by increasing organic matter concentration, thereby improving the physical, chemical and biological properties of the soil [32, 33, 42, 64, 67]. While nonlegume cover crops are effective in removing soil residual N and reducing N leaching, legume cover crops are effective in supplying N to the summer crops, increasing their yields and reducing the rate of N fertilization [25, 31].

Abundant information is available about the effects of legume and nonlegume cover crops on the growth and yield of cereal crops [43, 63]. Relatively little is known about their effects on vegetable production. Vegetable production differs from cereal production in management intensity and amount of inputs required. While cereal crops are intensively managed mostly during planting and harvesting seasons, vegetables require greater degree of management throughout their growth. This is because vegetables grow and mature rapidly and compete intensively with weeds. Furthermore, pest and disease incidences are more likely to occur in vegetables than in cereals. As a result, cultural practices, such as weeding and applications of herbicides, pesticides or irrigation, need to be carried out more frequently throughout the vegetable growing season. Furthermore, fertilizers, such as N, needs to be applied more frequently than in cereals for obtaining optimum yields [54]. This is because nutrient uptake and recovery is lower in vegetables than in cereals, and most of nutrients in vegetables are used for the production of fruits, tubers or bulbs [40, 54]. Because of the rapid mineralization of cover crop residues in the soil [32, 33, 83, 93], cover crops have improved soil properties and increased vegetable yields, especially in tomatoes (*Lycopersicon esculentum* Mill.), eggplants (*Solanum melongena* L.) and bell peppers (*Capsicum annuum* L.), similar to those did by N fertilization [68, 69].

2. Cover Crop Biomass Yields and Carbon and Nitrogen Accumulations

In regions with mild winter, such as in the south or northwest USA, cover crops can be easily grown by planting in the fall after summer crop harvest [32, 33, 64, 76]. While a cooler winter (such as in northwest USA) requires that cover crops be planted in early autumn (September-October) [32, 33], warmer winter (such as in southern USA) allows cover crops to be planted in late fall (November-December) [64]. The establishment of cover crops in the regions with cold winter, however, is more trivial. The short growing season in these areas warrants that cover crops need to be planted early in the fall. As a result, cover crops are often established in late summer-early fall by overseeding under the standing canopy of the summer crop before it is harvested. In small areas, this can be achieved by spreading seeds with a hand-crank spanner [74]. In large areas, cover crops can be established under the standing canopy of the summer crop by broadcasting seeds with aerial crop dusters or tractor-mounted seeder [45]. The cost of seeding by this method, however, is a major shortcoming, which discourages the producers to grow cover crops. In areas with cold winter where cover crops are grown in the summer, cover crop seeds are broadcast in the frozen soil under the standing canopy of the winter cereal crops, such as wheat (*Triticum aestivum* L.) [74]. As freezing and thawing occur, cover crop seeds fall into crevices of the soil and start to germinate. At winter crop harvest in the late spring, cover crops establish well. In regions with hot weather, cover crops, such as cowpea (*Vigna unguiculata* L. Walp.), can be grown in the summer when high temperature prevents the growth of the cash crop [74].

Cover crops can be grown both in conventional and conservation tillage. Sainju et al. [65, 69] observed that biomass yield

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and C and N contents of hairy vetch (*Vicia villosa* Roth) were not different between no-till, chisel till and moldboard till. While nonlegume cover crops, such as rye (*Secale cereale* L.), establish rapidly in the early fall, legume cover crops, such as hairy vetch and crimson clover (*Trifolium incarnatum* L.), grow slowly in the fall and produce most of the biomass in the spring when temperature increases [64].

Cover crops can also be established by reseeding from the plant itself. Once a cover crop is planted in the fall, it is allowed to grow until full maturity in the spring when seeds dropped from plants are allowed to spread in the soil by wind. As cover crops die in the summer, summer crops are grown. In the fall, cover crop seeds germinate, thereby completing their life cycle. This method saves cost and time of planting cover crops for the grower. It may, however, delay planting of succeeding crops in the summer because the grower has to wait to plant the main crop until cover crop matures. In such cases, grower may have to choose a crop which matures early and which can be planted late in the growing season. For example, if barley (*Hordeum vulgare* L.) is grown as a cover crop in the winter, then soybean [(*Glycine max* L. (Merrill)] can be planted in the summer, because planting soybean in late summer generally does not affect its yield. Cover crops, such as crimson clover, have been successfully established by reseeding in the cotton (*Gossypium hirsutum* L.) production system [52].

Because of the varying soil and climatic conditions, a cover crop growing well in one region may not do so in another place. In such cases, various species of cover crops are grown in the region and the best species are chosen based on growth potential and biomass yield in that area. For example, a cold-tolerant species can grow well in the region with cold winter while a heat-tolerant species may be needed for the region with warm summer. Legume cover crops, such as hairy vetch and crimson clover, and nonlegume cover crops, such as rye, have been found to be well adapted to subtropical [64,76] and temperate regions [61, 74].

Biomass yields of cover crops and C and N accumulations have been known to vary from one region to another [63]. Small grain nonlegume cover crops, such as rye, have biomass yields that varied from 6.7 Mg ha^{-1} and N accumulation from 137 kg ha^{-1} in Georgia [68] (Table 1) to 5.0 Mg ha^{-1} and 74 kg ha^{-1}, respectively, in Maryland [16] and to 5.3 Mg ha^{-1} and 60 kg ha^{-1}, respectively, in Washington [33]. In contrast, biomass yields and N accumulation of legume cover crops, such as hairy vetch, varied from 4.8 Mg ha^{-1} and 188 kg ha^{-1} in Georgia [67, 69] to 3.0 Mg ha^{-1} and 100 kg ha^{-1}, respectively, in Maryland [16] and to 3.9 Mg ha^{-1} and 120 kg ha^{-1} in Washington [33]. While C concentrations in cover crops remain relatively constant and C accumulation is proportional to biomass yield [32], N accumulations vary because of difference in N concentrations between cover crops [64]. As a result, C accumulation has been known to be greater in nonlegume cover crops because of greater biomass yield but N accumulation has been known to be greater in legume cover crops because of increased N concentration [32, 33, 69]. The C:N ratio is usually lower in legume than in nonlegume cover crops because of difference in N concentrations between cover crops (Tables 1-4).

Biomass yields, C and N concentrations and C and N accumulations in cover crops also vary from one year to another due to difference in climatic conditions, particularly temperature and rainfall (Tables 1-4). Sainju et al. [68, 69, 71] found that biomass yields and N accumulations in rye varied from 2.3 Mg ha^{-1} and 25 kg ha^{-1} in 2002 to 6.7 Mg ha^{-1} and 137 kg ha^{1} in 1997. In contrast, biomass yields in hairy vetch and crimson clover varied from 2.4 Mg ha^{-1} in 2001 to 6.3 Mg ha^{-1} in 1997, while N accumulations varied from 73 kg ha^{-1} in 1999 to 299 kg ha^{-1} in 1997. The biculture of hairy vetch and rye has further advantages of increased biomass yields and C and N accumulations compared with monocultures of either species alone (Table 4). Sainju et al. [71] described these advantages in biculture cover crops as due to N transfer from legumes to nonlegumes during cover crop growth, thereby increasing biomass yield and N concentration of nonlegumes and to reduced interspecies competition in growth of legumes and nonlegumes in the mixture.

Besides the aboveground biomass growth, Sainju et al. [71] also observed greater belowground (roots) biomass growth and C and N accumulations in hairy vetch and rye biculture than in monocultures (Table 5). Biomass yield and N content from belowground portion of cover crops, such as roots, has been estimated to be as much as 10% of aboveground portion for hairy vetch and 25% for rye [77]. Root biomass yield and C and N contents in hairy vetch and rye at 0- to 20-cm depth can account for 8 to 32% of aboveground biomass yield and C and N contents [32, 33, 71]. Sainju et al. [72] found that increased root growth of hairy vetch and rye biculture also increased root growths of succeeding cotton and sorghum (*Sorghum bicolor* L.) compared with monocultures. Cover crops have shown to increase root growth and yield of the succeeding crops by increasing the number of biopores made by their roots, especially in compacted soil [59, 81, 92]. Roots may play a dominant role in soil C cycle [23, 57, 90] and may have relatively greater influence on soil organic C level than the aboveground plant biomass [9, 44, 50]. Root-derived C is retained longer and forms a major proportion of soil organic C that is responsible for soil structural improvement than shoot-derived C in no-tilled soil [22, 57].

Table 1. Biomass yield, C and N concentrations, and C and N accumulations in cover crops and winter weeds in the N fertilization treatments in 1996 and 1997 [68].

Cover crop	Biomass yield (Mg ha^{-1})	Concentration (g kg^{-1}) C	N	Accumulation kg/ha^{-1} C	N	C:N ratio
			1996			
Rye	6.03a [a]	479a	12.8c	2888a	76.4b	37.4a
Hairy vetch	4.87a	475a	34.6a	2313a	167.3a	13.7b
Crimson clover	6.13a	467a	24.3b	2863a	147.0a	19.2b
N 0 kg ha^{-1} [b]	2.05b	408b	22.3b	836b	45.2b	18.3b
N 90 kg ha^{-1} [b]	1.82b	412b	23.4b	750b	42.6b	17.6b
N 180 kg ha^{-1} [b]	2.10b	405b	22.8b	850b	47.9b	17.8b
			1997		*1997*	
Rye	6.71a	450a	20.4c	3020a	136.9b	22.1a
Hairy vetch	4.73a	404a	43.9a	1911ab	207.9a	9.2b
Crimson clover	6.31a	422a	35.7b	2663a	225.3a	11.8b
N 0 kg ha^{-1} [b]	1.43b	416a	34.1b	595b	48.5c	12.2b
N 90 kg ha^{-1} [b]	1.56b	420a	33.5b	655b	52.3c	12.5b
N 180 kg ha^{-1} [b]	1.62b	423a	33.1b	685b	53.6c	12.8b
Significance						
Treatment (T)	***	NS[c]	***	*	***	**
Year (Y)	NS	NS	*	NS	**	**
T x Y	**	*	**	*	***	**

[a] Within a column and set, numbers followed by different letter are significantly different ($P<0.05$, least square means test).
[b] These treatments consisted of weeds which were dominated by henbit (*Lamium amplexicaule* L.) and cut-leaf evening primrose (*Oenothera laciniata* L.).
[c] Not significant. * Significant at $P<0.05$. ** Significant at $P<0.01$. *** Significant at $P<0.001$.

Table 2. Carbon and N concentrations in cover crops and winter weeds from 1996 to 2000 [69].

Treatment	1996	1997	1999	2000
C concentration (kg ha^{-1})				
Rye	2888a [a]	3020a	3704a	3000a
Hairy vetch	2313a	1911b	704c	1723bc
Crimson clover	2863a	2663a	1231b	2285ab
Control [b]	836b	595c	305c	835c
HN [b]	750 b	655c	299c	1340c
FN [b]	850b	685c	324c	944c
N concentration (kg ha^{-1})				
Rye	77b	137b	78a	86b
Hairy vetch	167a	207a	73a	173a
Crimson clover	147a	299a	87a	166a
Control	45b	49c	18b	39c
HN	43b	52c	23b	56bc
FN	48b	54c	25b	50c
C:N ratio				
Rye	38.3a	25.3a	49.2a	35.2a
Hairy vetch	13.8b	9.2b	9.8b	9.8d
Crimson clover	19.6b	12.3b	14.3b	13.8d
Control	18.8b	12.3b	17.9b	23.1b
HN	17.4b	12.6b	12.6b	24.4b
FN	17.7b	12.7b	14.1b	19.4c

[a] Within a column and a set, numbers followed by different letter are significantly different ($P<0.05$, least significant difference test). [b] Contains winter weeds dominated by henbit (*Lamium amplexicaule* L.) and cut-leaf evening primrose (*Oenothera laciniata* L.). HN is the half N rate for tomato (N 90 kg ha^{-1}) or eggplant (N 80 kg ha^{-1}) and FN is the full N rate for tomato (N 180 kg ha^{-1}) or eggplant (N 160 kg ha^{-1}).

Table 3. Carbon and N concentrations in cover crop and winter weeds from 1996 to 1999 [69].

Cover crop	1996	1997	1998	1999
C concentration (kg ha^{-1})				
Hairy vetch	2390a [a]	1802a	2668a	2952a
No hairy vetch [b]	656b	817b	772b	732b
N concentration (kg ha^{-1})				
Hairy vetch	205a	77a	242a	196a
No hairy vetch	37b	27b	30b	40b
C:N ratio				
Hairy vetch	11.7b	23.6b	11.1b	15.0b
No hairy vetch	18.0a	32.3a	28.3a	19.9a

[a] Within a column and a set, numbers followed by different letter are significantly different (P<0.05, least significant difference test).
[b] Contains winter weeds dominated by henbit (*Lamium amplexicaule* L.) and cut-leaf evening primrose (*Oenothera laciniata* L.).

Table 4. Effects of cover crop species on aboveground biomass yield and C and N contents in cover crops averaged across tillage and N fertilization rates from 2000 to 2002 [71].

Cover crop†	Biomass yield Mg ha^{-1}	Concentration g kg^{-1} C	Concentration g kg^{-1} N	Content kg ha^{-1} C	Content kg ha^{-1} N	C:N ratio
			2000			
Weeds	1.65d‡	370b	15b	587d	25d	24b
Rye	6.07b	430a	15b	2670b	68c	29a
Vetch	5.10c	394ab	33a	2006c	165b	12c
Vetch/rye	8.18a	366b	38a	3512a	310a	10c
			2001			
Weeds	0.75d	391b	20b	277d	15b	20c
Rye	3.81b	448a	8d	1729b	32b	57a
Vetch	2.44c	398b	32a	964c	76a	12c
Vetch/rye	5.98a	434a	14c	2693a	84a	32b
			2002			
Weeds	1.25c	375b	18b	476c	23b	21b
Rye	2.28b	434a	11b	986b	25b	40a
Vetch	5.16a	361b	36a	2094a	167a	10c
Vetch/rye	5.72a	381b	33a	2260a	186a	11c

† Cover crops are rye, cereal rye; vetch, hairy vetch; vetch/rye, hairy vetch and rye biculture; and weeds, winter weeds.
‡ Numbers followed by the different letter within a column of a year are significantly different at $P \leq 0.05$ by the least square means test.

3.Vegetable Production

3.1.Fruits

Fresh-market yields of several summer vegetables have been known to increase substantially with winter legume cover crops compared with nonlegume or no cover crops. Yields were greater in tomato [2, 65, 76], brassica (*Brassica* sp. L.) [75], lettuce (*Lactuca sativa* L.) [81], eggplant and bell pepper [69, 70]. Tomato yields were greater with hairy vetch mulch than with polyethylene mulch or bare soil even during the late season with adverse climatic conditions, thereby increasing monetary return [28]. Similarly, Sainju et al. [70] observed that increases in tomato, eggplant and bell pepper yields with hairy vetch and crimson clover were similar to those increased by half (N 80 to 90 kg ha^{-1}) to full (N 160 to 180 kg ha^{-1}) rates of N fertilization (Table 6). Similarly, Sainju et al. [68a] found that tomato number, fresh and dry yields and N uptake were greater with than without hairy vetch residue and that yields and N uptake were similar with vetch residue and N fertilization (Tables 7 and 8). As a result, legume cover crops can replace or reduce the rate of N fertilization to summer vegetables. In contrast, yields of snap bean (*Phaseolus vulgaris* L.) and pea (*Pisum sativum* L.) were found to be not significantly different between legume cover crops and bare soil [47, 48, 85].

The increased vegetable yields with legumes compared with nonlegumes or no cover crop result from their increased N supply [2, 67]. Because of their higher N concentration and lower C/N ratio, legumes decompose rapidly in the soil and release N earlier than nonlegumes do [32, 33, 67, 88]. Half of N supplied by legume cover crops is available for uptake by succeeding crops within 2 to 4 wk of their incorporation into the soil [33, 83, 93]. As a result, N supplied by legume cover crops synchronizes with N needs of tomato during its growth [95]. Nitrogen supplied by legume cover crops usually increase yields of succeeding nonlegume vegetables, such as tomato, eggplant and lettuce. Yields of legume vegetables, such as snap beans and peas, however, may not increase with increased N supplied by legume cover crops because these vegetables, being legumes, fix N from the atmosphere and usually do not respond with N applied from green manures of N fertilizers. Sainju et al. [65] reported that N recovery by tomato fruits at 82 days after transplanting were lower with hairy vetch than with N 90 and 180 kg ha^{-1}, probably due to slow release of N by hairy vetch residue compared with N fertilization (Table 9).

Table 5. Effects of cover crop species on belowground (0- to 120-cm depth) biomass yield and C and N contents in cover crops averaged across tillage and N fertilization rates from 2000 to 2002 [71].

Cover crop†	Biomass yield kg ha^{-1}	Content kg ha^{-1} C	N	C:N ratio	Root to shoot ratio
			2000		
Weeds	208b‡	73b	3.0b	24b	0.13a
Rye	174b	60b	1.3c	45a	0.03b
Vetch	147b	59b	4.0b	14c	0.03b
Vetch/rye	421a	154a	8.1a	19bc	0.05b
			2001		
Weeds	423c	130c	5.0b	25b	0.56a
Rye	772ab	250ab	6.9b	33a	0.20b
Vetch	656b	208b	10.6a	20c	0.27b
Vetch/rye	880a	269a	10.6a	25b	0.15b
			2002		
Weeds	175b	57c	1.7b	33a	0.14ab
Rye	395a	137a	3.6a	38a	0.17a
Vetch	236b	78bc	4.2a	19b	0.05c
Vetch/rye	372a	130ab	4.0a	32a	0.10bc

† Cover crops are rye, cereal rye; vetch, hairy vetch; vetch/rye, hairy vetch and rye biculture; and weeds, winter weeds.
‡ Numbers followed by the different letter within a column of a year are significantly different at $P \leq 0.05$ by the least square means test.

Table 6. Effects of cover crops and N fertilization rates on yields (Mg ha^{-1}) of fresh-market tomato, eggplant, and bell pepper [70].

Treatment	Tomato 1996	Tomato 1997	Tomato 1999	Eggplant 2000	Bell 2001
Rye	19.0b [a]	13.6c	37.0c	21.0c	6.3b
Hairy vetch	40.2a	31.5a	75.2a	52.1a	34.2a
Crimson clover	40.9a	30.0a	65.4ab	45.5a	29.1a
Control [b]	20.0b	17.3bc	56.1b	23.7c	7.6b
HN[2]	39.1a	27.9ab	66.2ab	44.3ab	28.8a
FN[2]	43.1a	27.0ab	67.4ab	37.1b	30.1a

[a] Within a column, numbers followed by different letter are significantly different ($P<0.05$, least significant difference test).
[b] Control contains no cover crop or N fertilization; HN denotes is the half N rate for tomato, eggplant and bell pepper (N 80-90 kg ha^{-1}); and FN is the full N rate for tomato, eggplant and bell pepper (N 160-180 kg ha^{-1}).

Table 7. The effects of hairy vetch residue and N fertilization on number, fresh and dry yields, N concentration, and N uptake of tomato fruits. Plants were grown in a mixture of 3 perlite: 1 vermiculite in the greenhouse and lathhouse [68a].

Treatment	No. fruits per plant	Yield ($g\ plant^{-1}$) Fresh	Dry	N conc. ($g\ kg^{-1}$)	N uptake ($mg\ plant^{-1}$)
		Greenhouse			
Residue					
+	9.8 a[z]	869 a	63.2 a	13.0 a	817a
-	8.3 a	815 a	58.8 a	12.2 a	706 a
N fertilization ($g\ plant^{-1}$)					
0	6.3 b	501 c	38.6 c	11.8 a	479 c
4.1	8.5 b	854 b	59.9 b	12.5 a	813 b
8.2	12.3 a	1172 a	84.4 a	13.6 a	992 a
Interaction	NS [y]	NS	NS	NS	NS
		Lathhouse			
Residue					
+	9.3 a	1018 a	64.3 a	37.4 a	2389 a
-	3.7 b	496 b	31.6 b	38.1 a	1196 b
N fertilization ($g\ plant^{-1}$)					
0	4.3 b	423 b	28.1 b	38.8 a	1072 b
4.1	6.3 ab	865 a	55.9 a	36.3 a	2053 a
8.2	8.8 a	983 a	59.8 a	38.1 a	2252 a
Interaction	NS	NS	NS	NS	NS

[z] Mean separation within columns and sets by the least square means test, $P \le 0.05$. [y] Not significant.

3.2. Stems and leaves

Stems and leaves provide the physical support and transport and manufacturing of nutrients and food for tomato plants. They constitute bulk of biomass production. Increased tomato fruit production requires proportionally large increase in biomass production. Therefore, management practices, such as cover cropping, used for sustainable production of tomato fruits, can also increase production of stems and leaves. A large increase in stems and leaves production can increase N uptake from the soil and reduce potential for N leaching. Sainju et al. [66] found that hairy vetch and crimson clover increased tomato biomass production and N uptake similar to that did by N 90 and 180 kg ha^{-1} (Table 8). The percentage of N recovered by tomato stems and leaves at 54 and 82 days after transplanting was similar or lower with hairy vetch than with N fertilization (Table 9), suggesting that hairy vetch residue is equally effective in supplying N to and recovering it in tomato plants as N fertilizer. Stems and leaves dry weight and N uptake were greater with than without hairy vetch residue and similar with hairy vetch residue and N fertilization (Table 10).

Table 8. The effects of cover crops and N fertilization on marketable tomato fresh fruit yield, biomass (leaves + stems + fruits dry wt.) and N uptake in 1996 and 1997 [65].

Treatment	Fruit yield ($Mg\ ha^{-1}$) 1996	1997	Biomass ($Mg\ ha^{-1}$) 1996	1997	N uptake ($kg\ ha^{-1}$) 1996	1997
Rye	19.0b[a]	13.6c	1.51b	1.28c	30.9b	32.8c
Hairy vetch	40.2a	31.5a	3.14a	2.92a	75.8a	78.2a
Crimson clover	40.9a	30.0a	3.22a	2.80a	78.8a	74.6a
N 0 kg ha^{-1}	20.0b	17.3bc	1.60b	1.65bc	35.3b	44.4bc
N 90 kg ha^{-1}	39.1a	27.9ab	3.03a	2.82a	72.9a	76.0a
N 180 kg ha^{-1}	43.1a	27.0ab	3.39a	2.33ab	83.0a	63.5ab
Significance						
Treatment (T)		**		**		**
Year (Y)		*		*		NS [b]
T x Y		**		**		*

[a] Within a column, numbers followed by different letter are significantly different ($P<0.05$, least square means test).
[b] Not significant. * Significant at $P<0.05$. ** Significant at $P<0.01$.

Table 9. Percentage of recovered N supplied by hairy vetch residue or N fertilization by tomato stems, leaves and fruits at 54 and 82 days after transplanting (DAT) in 1996 and 1997 [65].

	Stems		Leaves		Fruits		Total	
Treatment	1996	1997	1996	1997	1996	1997	1996	1997
				54 DAT				
Hairy vetch	0.9	2.4	0.5	0.8	-	-	1.4	3.2
N 90 $kg{\cdot}ha^{-1}$	1.7	0.4	4.0	0.8	-	-	5.7	1.2
N 180 $kg{\cdot}ha^{-1}$	0.8	2.9	2.3	0.8	-	-	3.1	3.7
				82 DAT				
Hairy vetch	0.2	16.2	1.4	5.8	2.4	2.0	4.0	24.0
N 90 kg ha^{-1}	5.2	3.8	4.9	11.7	14.9	11.0	25.0	26.5
N 180 kg ha^{-1}	3.2	2.7	3.6	3.1	6.1	23.7	12.9	29.5

Table 10. The effects of hairy vetch residue and N fertilization on dry weight, N concentration, and N uptake of tomato stems and leaves, and total (fruits + stems + leaves + roots) dry weight and N uptake. Plants were grown in a mixture of 3 perlite : 1 vermiculite in the greenhouse and lathhouse [88].

	Stems			Leaves			Total	
Treatment	Dry wt. (g plant)	N conc. (g kg^{-1})	N uptake (mg/plant)	Dry wt. (g/plant)	N conc. (g kg^{-1})	N uptake (mg/plant)	Dry wt. (g/plant)	N uptake (mg/plant)
				Greenhouse				
Residue								
+	37.1 a[z]	6.7 a	247 a	32.8 a	11.5 a	393 a	135.7 a	1490 a
-	30.4 a	6.5 a	195 b	24.8 b	11.8 a	284 b	116.2 b	1213 b
N fertilization (g $plant^{-1}$)								
0	21.6 c	6.6 a	143 c	17.5 c	11.6 a	200 c	79.5 c	849 c
4.1	34.3 b	6.8 a	228 b	28.3 b	11.2 a	313 b	125.0 b	1385 b
8.2	45.4 a	6.4 a	291 a	40.6 a	12.2 a	502 a	173.4 a	1823 a
Interaction	NS	NS	NS	NS	NS	NS	NS	NS
				Lathhouse				
Residue								
+	26.5 a	9.1 a	236 a	20.5 a	13.3 a	285 a	117.1 a	3002 a
-	13.2 b	9.8 a	126 b	12.0 b	13.6 a	168 b	60.9 b	1556 b
N fertilization (g $plant^{-1}$)								
0	13.0 b	10.1 a	120 b	9.3 c	12.2 a	115 b	54.3 b	1368 b
4.1	19.0 ab	8.3 a	160 b	16.4 b	13.6 a	227 ab	96.3 a	2513 a
8.2	27.6 a	10.1 a	262 a	22.9 a	14.5 a	337 a	116.5 a	2954 a
Interaction	NS	NS	NS	NS	NS	NS	NS	NS

[z] Mean separation within columns and sets by the least square means test, $P \leq 0.05$. NS Not significant.

3.3. Roots

As with stems and leaves, roots provide physical support and absorb water and nutrients for tomato growth. Stress in the root zone can be expressed in the shoots, thereby influencing dry-matter partitioning between root and shoot and crop yields [12, 36]. Quantification of root growth is essential for characterizing partitioning of photosynthetic materials [10], for examining water and nutrient movement and uptake [7, 29] and for modeling root, plant and soil characteristics [46, 62]. Cover cropping can promote root growth by increasing the amount of plant residue returned to the soil, thereby increasing soil organic matter concentration, decreasing bulk density, decreasing or increasing temperature and increasing the density of biopores in the soil profile, where roots of succeeding crops grow even in the root restricting layers [7, 27]. Sainju et al. [67] reported that hairy vetch residue increased tomato root growth at 6.5 to 19.5 cm depth in no-till system by increasing moisture conservation and N availability compared with no residue in conventional till system. Similarly, Sainju et al. [68] found that tomato total minirhizotron root counts from 1 to 32.5 cm depths were similar or greater with rye, hairy vetch and crimson clover than with N 90 and 180 kg ha^{-1} (Table 11). Tomato root length, dry weight and N uptake were greater with and without hairy vetch residue and similar with hairy vetch residue and N fertilization (Table 12).

Table 11. The effects of cover crops and N fertilization on number of tomato roots per square centimeter of soil profile area (NR) and total NR from 1 to 32.5 cm soil depth (TNR) at 89 days after transplanting (DAT) in 1996 and at 96 DAT in 1997 [68].

Treatment	NR at soil depths (cm) 1	6.5	13.0	19.5	26.0	32.5	TNR
			89 DAT in 1996				
Rye	0.00a[a]	0.55ab	2.31a	1.87ab	1.10ab	1.43a	7.26a
Hairy vetch	0.00a	0.33b	2.53a	1.98ab	1.87a	0.66a	7.37a
Crimson clover	0.00a	0.33b	2.53a	2.31a	1.10ab	0.66a	6.93a
N 0 kg ha^{-1}	0.00a	0.00b	0.99b	0.64b	0.30b	0.65a	2.58b
N 90 kg ha^{-1}	0.00a	1.54a	1.65ab	1.21ab	0.99ab	1.10a	6.49a
N 180 kg ha^{-1}	0.00a	0.22b	1.43ab	0.22b	0.66ab	0.66a	3.19b
			96 DAT in 1997				
Rye	0.00a	0.33a	0.55ab	1.87ab	0.55b	0.88a	4.18ab
Hairy vetch	0.33a	0.44a	1.32ab	1.21ab	2.09a	0.99a	6.38a
Crimson clover	0.00a	0.22a	1.65a	1.43ab	1.87a	1.10a	6.27a
N 0 kg ha^{-1}	0.22a	0.22a	0.33b	0.88b	0.22b	0.55a	2.42b
N 90 kg ha^{-1}	0.00a	0.44a	1.43ab	2.53a	1.43ab	0.66a	6.49a
N 180 kg ha^{-1}	0.11a	0.44a	1.65ab	1.65ab	2.20a	0.88a	6.93a
Significance							
Treatment (T)		*					*
Year (Y)		*					*
T x Y		**					*
Soil depth (D)		***					---
T x D		*					---
Y x D		NS [b]					---
T x Y x D		*					---

[a] Within a column and set, numbers followed by different letter are significantly different ($P<0.05$, least square means test).
[b] Not significant. * Significant at $P<0.05$. ** Significant at $P<0.01$. *** Significant at $P<0.001$.

Table 12. The effects of hairy vetch residue and N fertilization on length, dry weight, N concentration, and N uptake of tomato roots and root to shoot ratio [root dry weight/(fruits + stems + leaves) dry weight]. Plants were grown in a mixture of 3 perlite: 1 vermiculite in the greenhouse and lathhouse [68a].

Treatment	Roots Length (m $plant^{-1}$)	Dry wt. (g $plant^{-1}$)	N conc. (g kg^{1})	N uptake (mg $plant^{-1}$)	Root to shoot ratio
			Greenhouse		
Residue					
+	350 a[z]	2.7 a	12.7 a	34 a	0.07 a
-	317 a	2.3 a	12.8 a	28 a	0.08 a
N fertilization (g $plant^{-1}$)					
0	248 b	1.9 b	14.0 a	26 a	0.09 a
4.1	365 a	2.6 a	11.8 a	30 a	0.07 a
8.2	389 a	3.0 a	12.5 a	37 a	0.07a
Interaction	NS [y]	NS	NS	NS	NS
			Lathhouse		
Residue					
+	157 a	5.8 a	15.9 a	92 a	0.23 b
-	135 b	4.1 b	16.2 a	67 b	0.38 a
N fertilization (g $plant^{-1}$)					
0	124 b	3.9 b	16.2 a	61 b	0.38 a
4.1	156 a	4.9 ab	15.3 a	74 ab	0.29 ab
8.2	158 a	6.2 a	16.7 a	104 a	0.24 b
Interaction	NS	NS	NS	NS	NS

[z] Mean separation within columns and sets by the least square means test, $P \leq 0.05$. [y] Not significant.

4. Soil Properties

Cover crops can improve soil quality by conserving and/or increasing organic matter concentration due to increased above and below ground plant biomass yield and C and N accumulations compared with weeds in the fallow [32, 43, 67]. Organic matter is the key component of soil quality that helps to sustain its fertility and productivity by influencing on its physical, chemical and biological properties [6, 18]. While tillage increases mineralization of organic matter by incorporating plant residues, disrupting soil aggregates and altering its temperature, moisture and aeration [14, 17, 94], cover crops maintain or improve soil organic matter by replacing organic matter lost by tillage through plant residue addition and by reducing soil erosion [25, 32, 43]. Sainju et al. [69] observed that cover crops increased soil organic C and N by 9 to 19% compared with the bare soil after 7 yr when residues were incorporated into the soil (Table 13). They also observed that soil organic C was increased by 17 to 23% after 6 yr when cover crop residues were placed at the soil surface in no-till system as opposed to the residue incorporation into the soil in moldboard till (Table 14). The no-till practice reduces mineralization of the

Table 13**.** Effects of cover crops and N fertilization on concentrations of soil organic C and N at 0- to 20-cm depth from 1994 to 2000[69].

Treatment	1994	1995	1996	1997	1998	1999	2000	LSD[a]	Mean
Organic C (Mg ha^{-1})									
Rye	18.1	18.9	18.3	18.5	18.3	18.5	18.7	1.3	18.4
Hairy vetch	18.1	18.7	18.2	17.6	17.3	17.7	18.0	1.3	17.9
Crimson clover	18.1	17.8	18.1	17.0	17.7	17.7	17.9	1.4	17.8
Control[b]	18.1	17.8	16.6	16.3	16.1	15.6	14.9	1.5	16.5
HN[b]	18.1	18.0	17.4	17.2	17.4	17.5	17.1	0.8	17.5
FN[b]	18.1	17.9	17.2	17.2	17.4	17.4	17.1	0.7	17.5
LSD[a]	----	1.1	1.3	2.0	1.4	2.1	2.2	----	0.3
Mean	18.1	18.2	17.6	17.3	17.4	17.4	17.3	0.7	----
Organic N (Mg ha^{-1})									
Rye	1.39	1.43	1.45	1.43	1.44	1.45	1.45	0.14	1.43
Hairy vetch	1.39	1.41	1.46	1.38	1.38	1.41	1.41	0.13	1.40
Crimson clover	1.39	1.36	1.33	1.36	1.36	1.44	1.42	0.10	1.38
Control	1.39	1.31	1.29	1.28	1.28	1.32	1.31	0.12	1.31
HN	1.39	1.31	1.32	1.34	1.31	1.33	1.33	0.11	1.33
FN	1.39	1.32	1.32	1.35	1.34	1.39	1.40	0.10	1.36
LSD	----	0.12	0.12	0.12	0.13	0.13	0.12	----	0.05
Mean	1.39	1.36	1.36	1.36	1.35	1.39	1.39	0.04	----
C:N ratio									
Rye	13.1	13.2	12.6	12.9	12.7	13.1	12.9	1.3	12.9
Hairy vetch	13.1	13.4	12.5	12.7	12.6	12.6	12.8	1.0	12.8
Crimson clover	13.1	13.1	13.6	12.5	13.0	12.3	12.6	1.0	12.9
Control	13.1	13.5	12.9	12.7	12.5	11.8	11.4	1.1	12.6
HN	13.1	13.7	13.2	12.9	13.2	13.1	12.9	1.2	13.2
FN	13.1	13.6	13.0	12.7	13.0	12.5	12.2	1.0	12.8
LSD	----	1.0	1.1	0.9	0.8	1.3	1.2	----	0.6
Mean	13.1	13.4	13.0	12.7	12.8	12.6	12.6	0.8	----

[a] Least significant difference between treatments within a row or a column ($P<0.05$).
[b] Control contains no cover crop or N fertilization, HN is the half N rate for tomato (90 kg N ha^{-1}) or eggplant (80 kg N ha^{-1}), and FN is the full N rate for tomato (180 kg N ha^{-1}) or eggplant (160 kg N ha^{-1}).

residue due to its decreased contact with soil microorganisms [20, 73].

The amount and type of cover crop residue added to the soil and its rate of decomposition determines the levels of soil organic C and N [32, 33, 66]. Larson et al. [35] and Rasmussen et al. [58] observed that changes in soil organic C were linearly related with the amount of plant residue applied to the soil and were independent of the type of residue. Similarly, Kuo et al. [32, 33] and Sainju et al. [67, 69] observed greater levels of soil organic C and N with nonlegume cover crops, such as rye, than with legume cover crops, such as hairy vetch and crimson clover. They stated this due to greater biomass yields and C:N ratio of nonlegume cover crops (Table 1) that may have slowed their rate of decomposition. In contrast, several researchers have reported greater soil organic C and N with legume than with nonlegume cover crops (Table 15). The differences in soil and climatic conditions among regions probably reflect cover crop growth, their rate of decomposition, and soil organic C and N. The growth stage of cover crops at the time of incorporation also influences their rate of decomposition in the soil because of variation in their C:N ratio [19].

Sainju et al. [67, 70] reported that legume cover crops, such as hairy vetch and crimson clover, increased soil inorganic N, potential N mineralization and microbial biomass N while nonlegume cover crops, such as rye, increased soil aggregation, potential C mineralization and microbial biomass C compared with no cover crops. They stated these due to higher N concentration in legume cover crops and higher biomass yields in nonlegume cover crops. Based on the soil N enriching ability of legumes and organic C increasing ability of nonlegumes, a mixture of legume and nonlegume cover crops may be needed to increase organic matter concentration and N levels in the soil. Such a mixture will also help in sequestering both atmospheric C and N in the soil, thereby reducing the deleterious effects of greenhouse gases.

Cover crops also improve soil physical properties, such as water content, temperature, aggregation, bulk density, infiltration capacity and hydraulic conductivity. The water content and temperature of the soil is altered by the mulch effect of the cover crop residue [30, 79]. While cover crop residue can increase soil water content, especially in no-till practice, thereby improving tomato yields [1, 2], it can reduce soil temperature during hot weather, thereby promoting root development in vegetables and fruits [3, 28, 49]. It can also improve soil aggregation, hydraulic conductivity [42, 60] and water infiltration capacit[42, 91]. Cover crops reduced soil erosion from 18 to 2 Mg ha^{-1} yr^{-1} [21] and by 62% in Ultisols and 72% in Alfisols [34].

Table 14. Effects of tillage, cover crop, and N fertilization on concentration of soil organic C at 0- to 20-cm depth from 1994 to 1999 [69].

Tillage age[a]	Cover crop[b]	N fertilization (N kg ha^{-1})	Organic C concentration (Mg ha^{-1})								
			1994	1995	1996	1997	1998	1999	LSD[c]	Mean	Mean[d]
NT	HV	0	23.9	24.2	28.4	24.5	23.9	24.4	3.6	24.9	23.5
		90	23.9	21.3	26.9	23.9	23.9	24.3	2.8	24.0	23.2
		180	23.9	21.3	24.8	22.9	23.6	24.2	3.3	23.5	23.5
	NHV	0	23.9	20.5	26.0	21.8	21.4	19.9	3.4	22.2	----
		90	23.9	21.6	24.5	22.8	21.2	19.8	3.2	22.3	----
		180	23.9	22.5	28.8	24.9	21.0	19.8	3.8	23.5	----
CP	HV	0	23.9	21.3	23.3	23.1	20.7	20.1	3.6	22.1	22.1
		90	23.9	22.1	20.1	23.7	20.7	20.3	3.2	21.8	21.7
		180	23.9	24.7	27.1	26.0	20.7	19.9	2.5	23.7	23.6
	NHV	0	23.9	23.2	22.7	21.4	21.6	20.1	3.6	22.2	----
		90	23.9	21.5	20.2	22.0	22.6	20.0	3.7	21.7	----
		180	23.9	24.7	23.2	24.8	23.7	20.3	4.0	23.4	----
MP	HV	0	23.9	19.4	23.2	19.4	21.9	20.8	3.0	21.4	21.1
		90	23.9	18.0	17.9	18.2	22.1	21.0	3.6	20.2	20.0
		180	23.9	19.0	21.3	20.4	22.1	20.0	1.8	21.1	20.5
	NHV	0	23.9	20.4	21.1	19.5	20.1	20.1	2.2	20.8	----
		90	23.9	17.0	19.7	18.1	20.1	20.3	1.7	19.9	----
		180	23.9	18.2	18.0	19.1	20.1	20.3	4.1	19.9	----
LSD[c]			----	3.1	5.3	5.5	2.9	2.8	----	1.5	1.0
Mean			23.9	21.2	23.2	22.0	21.8	20.9	1.3	----	----
Mean across cover crop and N fertilization											
NT			23.9a[e]	21.9a	26.6a	23.5a	22.5a	22.1a	1.4	23.4a	----
CP			23.9a	22.9a	22.8ab	23.5a	21.7a	20.1b	1.7	22.5ab	----
MP			23.9a	18.6b	20.2b	19.1b	21.1a	20.4b	1.0	20.6b	----
Mean across tillage and cover crop											
0 kg N ha^{-1}			23.9a	21.5a	24.1a	21.6a	21.6a	20.9a	1.5	22.3a	----
90 kg N ha^{-1}			23.9a	20.2b	21.5b	21.4a	21.8a	21.0a	1.3	21.6b	----
180 kg N ha^{-1}			23.9a	21.7a	23.9a	23.0a	21.9a	20.8a	1.7	22.5a	----

[a] Tillage are NT, no-till; CP, chisel plowing; and MP, moldboard plowing. [b] Cover crops are HV, hairy vetch; and NHV, no hairy vetch (winter weeds).
[c] Least significant difference between treatments within a row or column ($P<0.05$). [d] Mean across year and cover crop.
[e] Within a column and a set, numbers followed by different letter are significantly different ($P<0.05$, least significant difference test).

5. Water Quality

Cover crops can improve water quality by absorbing nutrients, such as NO_3-N, from the soil and reduce its potential for leaching in the groundwater [43, 63]. After the autumn crop harvest, some portion of N fertilizer applied to summer crop is left as residual N in the soil, because plants do not absorb 100% of applied N [24]. Because vegetable production systems require greater input of N and N uptake by vegetables is often lower than that by cereals, the potential for NO_3-N leaching under vegetables is often greater [40, 54]. Although N leaching increases with increased rate of N fertilization [37, 38], mineralization of N from soil and plant residue further increase potentials for leaching. In humid regions, N leaching occurs mostly during autumn, winter and spring seasons when evapotranspiration is low and precipitation exceeds water holding capacity of the soil [15, 43]. Winter cover crops use residual N and moisture after crop harvest in the autumn, thereby reducing the amount of NO_3-N and water available for leaching [43, 53].

Table 15. Cover crop effects on soil organic C and N concentrations [63].

Reference	Cover crop	Soil depth (cm)	Organic component C ($g\ kg^{-1}$)	Organic component N ($g\ kg^{-1}$)
Frye et al. [21]	Fallow	0-7.5	10.6	1.2
	Hairy vetch		13.5	1.5
	Big flower vetch		12.7	1.4
	Rye		11.5	1.2
Hargrove[25]	Initial	0-7.5	11.3	0.77
	Fallow		7.9	0.58
	Rye		8.7	0.65
	Crimson clover		8.4	0.65
	Subterranean clover		10.0	0.81
	Hairy vetch		9.7	0.80
	Common vetch		10.2	0.63
	Initial	7.5-15	6.1	0.49
	Fallow		4.8	0.37
	Rye		5.4	0.42
	Crimson clover		4.9	0.41
	Subterranean clover		5.5	0.48
	Hairy vetch		5.5	0.51
	Common vetch		5.1	0.45
Kuo et al. [30]	Fallow	0-15	15.7	1.22
	Austrian winter pea		16.0	1.26
	Hairy vetch		15.8	1.28
	Canola		15.4	1.23
	Cereal rye		16.6	1.34
	Annual ryegrass		16.6	1.28
McVay et al. [42]	Fallow	0-5	8.5-10.1	1.0-1.3
	Wheat		8.9-11.8	1.1-1.4
	Crimson clover		10.6-12.8	1.3-1.5
	Hairy vetch		10.2-11.8	1.3-1.5
	Fallow	5-10	7.2-8.7	0.9-1.0
	Wheat		7.3-9.5	1.0-1.2
	Crimson clover		7.7-10.3	1.0-1.2
	Hairy vetch		7.4-9.3	1.0-1.2
Touchton et al. [84a]	Fallow	0-11	7.0	0.32
	Crimson clover		8.7	0.43
	Hairy vetch		10.8	0.42
Wilson et al. [93a]	Initial	0-15	17.0	1.6
	Fallow		12.0	1.2
	Grasses		15.0	1.8
	Legumes		16.0	2.0

Cover crop species vary in their ability to absorb residual N from the soil and reduce N leaching. Nonlegume cover crops are more effective in reducing N leaching than legumes do [30, 43, 63]. This is because nonlegume cover crops, such as rye, grow and establish rapidly in the autumn[64], thereby absorbing residual N and reducing its amount available for leaching[43]. In contrast, legume cover crops, such as hairy vetch and crimson clover, grow mostly during spring when temperature increases [43, 64]. As a result, soil residual N in the autumn is not being effectively removed by legume cover crops [64]. The N fixing characteristics of legumes also interfere with their ability to reduce N leaching [64]. In a review of literature, Sainju and Singh[63] observed that nonlegume cover crops reduced NO_3-N leaching from 29 to 94% compared with -6 to 48% by legumes (Table 16). Similarly, McCracken et al.[41] reported that rye reduced NO_3 leaching by 94% compared with 48% by hairy vetch. Besides grasses, several brassica species, such as mustard (*Brasssica* sp. L.), canola *(Brassica napus* L.*)*, radish (*Raphanus sativus* L.) and turnip (*Brassica rapa* L.), can also effectively remove residual N from the soil and reduce N leaching[26, 43, 82]. Based on the ability of nonlegumes to reduce N leaching and N fixing characteristics of legumes to supply N for the succeeding crop, a mixture of legume and nonlegume cover crops may be needed to improve both water and soil qualities and sustain crop yields.

Table 16. Reduction in NO_3^- leaching from soil due to cover crops[63].

Reference	Cover crop	Reduction due to cover crop (%)
Bertilsson[6a]	Rape	62
Chapman et al.[14a]	Sweet clover	1
	Purple vetch	10
	Mustard	80
Karrakar et al.[27a]	Rye	72
McCracken et al.[41]	Rye	94
	Hairy vetch	48
Meisinger et al.[43]	Rye	29
	Hairy vetch	-6
Morgan et al.[44a]	Oat	48
	Rye	62
	Timothy	33
Volk and Bell[87a]	Turnip	84

6. Control of Weeds, Pests and Diseases

Cover crops can also effectively control weed population. A well grown cover crop competes vigorously with weeds for nutrient, water and light, thereby reducing their growth. Some cover crops, such as rye, produce phytotoxins which has allelopathic effects in weeds, thereby inhibiting their growth[56]. When cover crop residues are placed either at the soil surface in the no-till system, the mulch effect of the residue can control weed population. Cover crops have been known to effectively control weeds in vegetables[11, 89] and small fruits, such as strawberry (*Fragaria* x *ananassa* Duch)[49, 55, 78].

Cover crop species vary in their ability to suppress weeds. Nonlegume cover crops, such as rye and oat (*Avena sativa* L.), establish early and rapidly in the autumn[43, 64], thereby competing vigorously with weeds[61, 87]. In contrast, legume cover crops, due to their slow establishment in the autumn[64], are not quite effective compared with nonlegumes in suppressing weeds, although they control some species of weeds[61]. For example, hairy vetch, subterranean clover (*Trifolium subterraneum* L.) and crimson clover reduced emergence of morning glory (*Ipomoea lacunosa* L.) and redroot pigweed (*Amaranthus retroflexus* L.). Brassica species are also effective in controlling weeds[11]. The ability of a cover crop species to suppress weed growth is proportional to the amount of cover crop canopy produced[39]. Rye, being tall and producing larger biomass, has larger canopy than hairy vetch and crimson clover[64] and can effectively control weed growth[61].

Little attention has been paid on the effects of cover crops in controlling pests and diseases. Cover crops have been successfully used to control pest population in lettuce[86] and in orchards and vineyards[4, 13, 96]. Cover crops have also reduced the population of nematodes due to increase in soil organic matter[52]. Several cover crops, such as rye, sorghum, and brassicas can produce nematicidal effects[5, 51]. In contrast, populations of fungivorous and bacterivorous nematodes have been found to be significantly increased following hairy vetch/rye cover crop mixture[8]. Cover crops can also improve the habitat for harboring beneficial insects and reduce the population of unwanted pests[52]. For example, hairy vetch, crimson clover and brassicas can increase the population of beneficial insects, such as insidius flower bugs (*Orius insidiosus*), big-eyed bugs (*Geocoris* sp.) and lady beetles (*Coleoptera coccinellidae*)[13, 51]. Cover crops can also control some diseases. For example, the incidence of *Verticillium* on potato was reduced by 24 to 29% following a sorghum-sudangrass [(*Sorghum bicolor* L. (Moench)] cover crop[80].

7. Economic Evaluation of Cover Crops

Although cover crops have many benefits in increasing crop production, improving soil and water qualities and controlling pests and diseases, their economic benefits have not been fully evaluated. For a farmer or producer to grow cover crops, their economic benefit should outweigh the cost of growing them. Because cover crops improve soil and water qualities by increasing organic matter concentration and reducing soil erosion and nutrient loss, the returns in terms of these benefits are often ignored during economic evaluation of the cover crops, since returns are generally calculated in terms of crop yields. One of the reasons is that it takes longer time and often harder to measure these benefits. In such cases, the benefits from cover crops averaged across years should be used to calculate the annual return. The total return from crop production system using cover crops should include returns from grain and straw production of main crops, improvement in soil and water qualities, control of weeds, pests and diseases and C and N credits due to reduction in greenhouse gases. The decreases in the costs of purchasing herbicides and pesticides due to the control of weeds, pests and diseases and in the amount of N fertilizer from growing cover crops should also be considered to calculate the benefits while costs are calculated to purchase seeds and other items required for cultivation.

Frye et al. [21] observed substantial economic returns in corn production using hairy vetch cover crop compared with rye, crimson clover and big flower vetch *(Vicia grandiflora* Koch) or no cover crop in Kentucky. A net return of \$199 ha^{-1} over no cover crop was observed for hairy vetch compared with -\$35 ha^{-1} for rye, \$4 ha^{-1} for crimson clover and -\$64 ha^{-1} for big flower vetch. When 100 kg ha^{-1} of fertilizer N was added with cover crop residue, the net return of corn production over no cover crop was \$157 ha^{-1} for hairy vetch, \$18 ha^{-1} for rye, -\$6 ha^{-1} for crimson clover and -\$138 ha^{-1} for big flower vetch. Similarly, Kelly et al. [28] observed a greater economic return using hairy vetch cover crop than using polyethylene mulch or bare soil in tomato production. Because of the benefits of soil N enrichment by legumes and soil and water qualities by nonlegumes, a mixture of legume and nonlegume cover crops may provide greater economic return compared with individual cover crops. However, due to limited data on the use of biculture cover crops on crop production, soil and water qualities and pest and diseases control, more research is needed on the use of such management practice before a thorough economic analysis is made.

Conclusion

Cover crops are usually grown after the harvest of main crops to cover soil and reduce erosion. Besides sustaining crop yields, cover crops have many benefits in improving soil and environmental qualities. They use residual soil N and reduce N leaching in the groundwater. They increase soil organic matter and improve soil physical, chemical and biological properties. Legume cover crops fix N from the atmosphere, supply N to the succeeding crops and reduce the rate and cost of N fertilization. As a result, they increase crop yields compared with nonlegume or no cover crops. They control many weeds, pests and diseases. Cover crops also sequester atmospheric C and N in the plant biomass and soil and help to reduce global warming. However, some of disadvantages associated with cover crops include cost of seeding and their growth restriction on places with cold winter. Cover crops need to be economically evaluated for their benefits on vegetable production and soil and water qualities versus their cost of seeding that are socially acceptable to the producers.

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