SUSTAINABLE PRODUCTION OF TOMATO

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1. Introduction

Tomato is the most popular home garden and the second most consumed vegetable after potato in the world. Originating in Central and South America, tomato was not recognized as a useful vegetable until 1800. As the taste and nutritious values of tomatoes were known, production and consumption of tomatoes increased rapidly. In 2001, consumption of tomato was three times greater in USA and two times greater in Europe than in the rest of world (Table 1) [24]. Out of the total area under tomato production in the world in 2001, the area was as much as 5% in USA and 19% in Europe. Similarly, USA had 11% and Europe 22% of world's total tomato production in 2001.

Today, tomatoes constitute an important part of salad containing leafy vegetables, green onions, cucumbers, peppers and other vegetables. Tomatoes are eaten as a part of sandwich, as stewed, fried, or as baked singly or in combination with other vegetables. They are eaten as soups, sauces, catsup or barbecue. In the fast-food service restaurants, tomatoes an essential ingredient in pizza, pasta, hamburger, hot dogs and other foods.

Tomatoes are rich in nutrients. They are low in calories and a good source of vitamin A, C and minerals (Table 2) [109]. A 230 g of tomato consumption can supply about 60% of the recommended daily allowance of vitamin C in adults and 85% in children. Similarly, consumption of 100 mL of tomato juice can supply 20% of the recommended daily allowance of vitamin A. In addition, tomatoes provide small amounts of vitamin B complex, such as thiamin, riboflavin and niacin. Tomatoes are also a good source of iron. Consumption of tomatoes can significantly reduce the risk of developing colon, rectal and stomach cancer. Recent studies suggest that tomatoes contain antioxidant, lycopene, the most common form of carotenoid, which markedly reduces the risk of prostate cancer [45]. Tomato is easily digestible and its bright color stimulates appetite.

Table 1. Production and consumption of tomato in the world in 2001 [24].

Place	Area (ha)	Production (mt)	Consumption (kg/person$^{.}$ yr^{-1})
USA	169,290	11,270,000	46.8
Europe	703,755	21,423,287	26.7
World	3,657,142	99,428,786	14.9

Table 2. Nutritional value of tomato [109].

	Fresh	Canned		Fresh	Canned
Water, %	93.5	93.7	Phosphorus, mg	27	19
Calories	2.2	21	Iron, mg	0.5	0.5
Protein, g	1.1	1.0	Sodium, mg	3	130
Fat, g	0.2	0.2	Potassium, mg	244	217
Carbohydrate:			Vitamin A, I.U.	900	900
Total, g	4.7	4.3	Vitamin C, mg	23	17
Fiber, g	0.5	0.4	Thiamine, mg	0.06	0.05
Ash, g	0.5	0.8	Riboflavin, mg	0.04	0.03
Calcium, mg	13	6	Niacin, mg	0.7	0.7

2. Methods of Tomato Production

2.1. Field methods

Tomatoes are not usually grown in places previously planted with other solanaceous crops, such as tomatoes or potatoes, for controlling soil-borne diseases. Tomatoes grow best on light, warm, sandy to sandy loam soils with good organic matter

Ramdane Dris PhD. (ed.), ''Crops: Quality, Growth and Biotechnology'', pp.190-216.

content that improves soil structure, holds water for long period, supplies adequate nutrients and promotes root development. The soil pH should be around 5.5 to 7.5. Liming is needed when pH falls below 5.5. For late-grown tomatoes, soils heavier than sands or sandy loams can sustain production by tolerating extreme heat and drought during warm weather due to greater water holding capacity. When soils are irrigated regularly, tomatoes can be grown in almost any kind of soil.

Tomatoes respond well to fertilization. Higher yields can be obtained with adequate amount of fertilizers. Nitrogen is the most limiting nutrient in tomato production. The rate and timing of N fertilization can significantly affect tomato yield. While N deficiency can result in the production of yellow foliage, excess N can enhance vegetative growth at the expense of fruit setting, thereby delaying its maturity. Because of its rapid solubility in water and leaching loss, N fertilizer should be applied two to three times during tomato growth. Although P is taken up by tomato in smaller amount than N and K, starter solution containing high concentration of soluble P should be applied at transplanting to promote root growth. Potassium is taken up by tomato in large amount. Depending on soil and environmental conditions, fertilizer is applied at N 90-235 kg ha^{-1}, P 90-224 kg ha^{-1} and K 62-471 kg ha^{-1} to tomato in USA [59]. The exact rate of fertilization at a location is, however, determined by soil and plant analysis.

Tomatoes can be planted either by direct seeding or by transplanting. While direct seeding can promote tap root development, lateral and basal roots often grow better by transplanting than by direct seeding [53,54,103]. Tomatoes are planted either in flat or raised seed beds at a distance of 40 to 60 cm between plants in rows that are 1.5 to 1.7 m apart, thereby maintaining a plant population of 25,000 to 40,000 ha^{-1} [42, 69]. The distance between single or double rows of plants is often maintained at ≥1 m for mechanical cultivation and harvesting. In order to maintain tomato size, quality and yield, tomatoes are staked, trellised or grown flat in the ground. For early markets, growers in California, USA set out transplants under paper cloches that act as miniature greenhouses [69]. As risk of frost diminishes, the cloches are gradually opened up plants roots. In Florida, USA, tomatoes are grown by direct seeding in flat bed covered by black plastic mulch, which conserves heat and moisture and controls weed growth [69]. Some growers use fluid-drilling, which consists of pregerminating the seed in a polyglycol solution until radicle emerges. As field conditions become stable, seeds are extruded out of gel solution and planted in the field.

Tomatoes should be irrigated frequently, depending on the amount of rain, to prevent soil moisture stress. Rather than sprinkling water, water should be applied directly in the soil through subsurface irrigation to soak the root zone. Production and quality of tomato depend not only in good supply of nutrients or the surrounding temperature but also on the amount of available soil moisture. Moisture stress or calcium-iron imbalance in the soil can lead to the development of blossom-end rot in tomatoes. However, excess water should not be applied to flood the surface. Where flooding is likely to occur, proper drainage is needed. To prevent flooding, well-drained sites containing permeable layers should be used to grow tomatoes. Weeds should be controlled by using cultivator, weeding manually or applying herbicides from time to time to reduce their competition for growth with tomato. Proper directions should be followed for handling and use of the herbicides. Similarly, insect and disease infestations should be controlled by applying pesticides, fungicides or bactericides as needed and local advisory information should be followed for using them.

Tomato harvest and storage are labor intensive jobs. Adequate care should be taken during handling of tomato fruits to prevent from crushing and to maintain their quality. Tomatoes are usually harvested when fruits are firm and color changes from green to pink. Since all fruits do not change their color at the same time, tomatoes need to be harvested at several times during plant growth. Complete harvest may take more than one month. Because of the greater need of manpower at harvest, machine has been increasingly used to harvest tomatoes. Tomatoes are also harvested at green stage to reduce damage from crushing. These are ripened during storage by treating with ethylene at room temperature and by adjusting the proportion of O_2 and CO_2 in the air. Machine harvest, however, reduces the shelf-life of tomatoes by increasing the potentials for bruising and breaking the skin. For fresh tomatoes, harvesting can be done either by manually or by using the machine. For processing tomatoes, direct seeding is done to obtain high stands and to harvest fruits by machine.

2.2. Greenhouse methods

Because of the taste and nutritional value, a year-round demand for tomato fruits exists. Also being a high-value cash crop, growers continuously produce tomato in the greenhouse throughout the year to meet the off-season demands. Although growing tomato is labor intensive, greenhouse production of tomato is getting increasingly popular. The greenhouse production differs from the field methods in several respects. Environmental conditions including temperature, relative humidity and concentration of CO_2 in the air are controlled in the greenhouse. Plants are grown in individual containers instead of seed beds as used in the field. Growing medium is replaced by rockwool, peat-vermiculite or baled straw for soil because these media are less bulky, porous and have high water holding capacity that stimulate root growth in the container compared with soil. Because of limited availability of nutrients, the growing medium is often fortified with adequate amount of essential nutrients needed for tomato growth.

Plant population in the greenhouse is maintained from 19,000 to 27,000 ha^{-1} [69]. Plants are usually staked in each container. Unlike in the field, greenhouse tomatoes are pollinated by vibrating the plants manually or using a vibrator for setting the fruit. In the winter, the air in the greenhouse is enriched with CO_2 during bright sunny days to aid photosynthesis. Weeds, pests and diseases are controlled by applying herbicides and pesticides, as in the field. The tobacco mosaic virus is often a serious problem in tomato in the greenhouse. Therefore, the greenhouse and the surrounding areas should be kept free from smoking. The person who smokes should thoroughly wash his/her hand and mouth before entering greenhouse. As fruits mature, they are harvested manually once the color turns from green to pink. Although greenhouse can control the growing environment of tomato, problems, such as pests and diseases build-up, salt deposition or improper water balance in the growing medium, can occur. These problems can be reduced by sterilizing the growing media with steam, flushing salt deposition with salt-free water, or applying irrigation to reduce moisture stress. As a result, constant attention is needed for growing tomatoes in the greenhouse.

3. Management Practices

3.1. Tillage

3.1.1. *Tomato production*

3.1.1.1. *Fruits*

Tomatoes are usually grown by plowing the land which loosens the soil for deep root and water penetration. As a result, plowing enhances tomato growth and production. When a hard pan or an impervious layer occurs in the soil, plowing can break the layer so that roots can grow deeper into the soil. Continuous plowing, on the other hand, can develop a hard pan, called “plow sole”. A deep tillage, called “subsoiling”, can be used to break this layer.

Plowing is usually done to a depth of 20 cm. Plowing is done not only in the spring before tomato planting but also in the autumn after harvest to promote decay of roots and organic matter and to keep the soil in a friable condition after alternate freezing and drying in the winter [9,74]. Fall plowing also makes the land easier for spring plowing. Plowing should be done when soil is friable but not during wet condition, because tilling in wet soil can damage its physical condition [74]. While plowing can increase tomato production compared with no plowing, it can reduce soil quality and productivity by increasing soil erosion and mineralizing organic matter. It can also increase nutrient loss due to increased surface run-off and leaching in the surface and groundwater. Nitrate-nitrogen loss through leaching from agricultural land is a major problem [33,58]. Therefore, tillage practices which can sustain tomato yields, reduce soil and nutrient losses and improve soil and water quality, are needed.

Sainju et al. [85] conducted an experiment on the effects of tillage (no-till, chisel plowing and moldboard plowing) on tomato yield and N uptake (Table 3). No-till treatment included undisturbed plots except during planting of cover crops in

Table 3. Effects of tillage and N fertilization on tomato fruit number, fresh and dry yield, and N concentration and uptake in 1996 and 1997 [85].

	Yield ($Mg\ ha^{-1}$)									
	Fruit no./plant		Fresh		Dry		N conc. ($g\ kg^{-1}$)		N uptake ($kg\ ha^{-1}$)	
Treatment	1996	1997	1996	1997	1996	1997	1996	1997	1996	1997
Tillage[z]										
NT	18.7 a	40.3 a	35.0 a	32,1 a	1.32 a	1.68 a	38.5 a	40.9 a	50.6 a	69.1 a
CH	25.7 a	34.9 a	66.4 b	33.5 a	2.48 b	1.69 a	37.8 a	37.9 a	93.8 b	64.3 a
MB	25.9 a	39.8 a	62.9 b	30.5 a	2.44 b	1.66 a	35.8 a	38.8 a	86.9 b	63.1 a
N fertilization ($kg\ ha^{-1}$)										
0	22.8 a	36.7 a	49.5 a	26.6 a	1.83 a	1.32 a	38.0 a	39.1 a	69.1 a	51.8 a
90	22.6 a	40.2 a	58.1 b	36.0 b	2.20 b	1.86 b	37.1 a	39.9	82.4 b	73.1 b
180	25.0 a	38.1 a	56.6 b	33.6 b	2.22 b	1.87 b	37.0 a	38.7 a	80.0 b	71.7 b
Significance[x]										
Tillage	NS	NS	**	NS	**	NS	NS	NS	**	NS
N fertilization	NS	NS	*	**	*	***	NS	NS	*	***

[z] NT denotes no-till; CH, chisel plowing; and MB, moldboard plowing.
[y] Mean separation within columns of a treatment by the least square means test, P 0 05.
[x] Sources of variation that were not significant are excluded.
NS, *, **, and *** Not significant or significant at P 0.05, 0.01, and 0.001, respectively.

treatment and consisted of disc harrowing, followed by moldboard plowing to a depth of 15-20-cm in the fall and spring.

the autumn and tomatoes in the spring when lines were drawn by a seed driller for planting in rows. Chisel plowing was the reduced till treatment and consisted of disc harrowing to a depth of 10-15-cm, followed by chisel plowing to a depth of 15-20-cm in the autumn and spring. Similarly, moldboard plowing was the conventional till treatment and consisted of disc harrowing, followed by moldboard plowing to a depth of 15-20-cm in the fall and spring. After plowing, both chisel and moldboard till treatments were leveled with a S-tine harrow to a depth of 10-15-cm before planting cover crops and tomatoes. They observed similar tomato fruit number per plant but lower fresh and dry yields and N uptake in no-till than in chisel or moldboard plowing in 1996 (Table 3). In 1997, however, fruit number, fresh and dry yields and N uptake were similar between tillage treatments. They presumed that the lower fruit yield and N uptake in no-till than in chisel or moldboard plowing in 1996 may have resulted from increased soil compaction and/or development of root restricting layers due to incomplete amelioration of compacted soil over the winter. In 1997, continuous cropping may have reduced soil compaction, thereby resulting in similar tomato production between the tillage treatments. They concluded that reduced till, such as chisel plowing, can produce sustainable tomato yield, with reduced potentials for soil erosion and nutrient loss compared with the conventional till. Similar or improved tomato yield in no-till compared with conventional till were also reported by Abdul-Baki and Teasdale [1] and Abdul-Baki et al. [2].

3.1.1.2. *Stems and leaves*

Stems and leaves constitute the aboveground biomass of tomato, except fruits. Stems support the aboveground plant parts such as leaves and fruits and aid to transfer water and nutrients from roots to leaves and fruits.Similarly, leaves help to manufacture food, such as glucose, by photosynthesis and transfer them back to roots through stems. Although increased stem and leaf growth may or may not increase fruit production, depending on tomato cultivars and type and amount of available soil nutrients, vigorous growth of stems and leaves are needed for increased fruit production. If stems and leaves are damaged as a result of pests and diseases, fruit production suffers. When determining parameters, such as aboveground biomass production and nutrient uptake, dry weight of stems, leaves and fruits are needed.

As with fruits, tillage can influence the growth of tomato stems and leaves. While deep tillage can promote vigorous growth of stems and leaves, shallow or no tillage can reduce their growth because of the compaction or presence of hard pan in the soil. Sainju et al. [85] observed that tomato stem growth and N uptake remained constant after 70 d of transplanting (Fig. 1) but leaf growth and N uptake declined after this date, regardless of tillage treatments (Fig. 2). While stem dry weight and N uptake were lower in no-till than in chisel and moldboard plowing from 38 to 120 d after transplanting, leaf dry weight and N uptake were lower in no-till than in chisel and moldboard plowing from 38 to 80 d after transplanting. They speculated that similar leaf dry weight between tillage treatments after 80 d of transplanting was probably resulted from leaf fall at tomato maturity. They concluded that chisel plowing was as good as moldboard plowing for maintaining tomato stem and leaf growth and N uptake. Chisel plowing can promote tomato root and shoot growth by subsoiling and breaking the hard pan below the plow layer [110].

3.1.1.3. *Roots*

Aboveground growth of tomato depends on root growth. Optimum root growth is needed not only for proper shoot anchorage but also for water and nutrient uptake and crop yield. The stress observed in the root can also be reflected in the shoot, thereby influencing dry matter partitioning between root and shoot and crop yields [14,54]. Root growth needs to be quantified for characterizing partitioning of photosynthates [13], for examining the movement and uptake of water and nutrients in the plant [11,44], and for modeling root, plant and soil characteristics [66,80].

Tillage can influence root growth by affecting soil properties. Tillage loosens the soil particles and breaks the hard pans for increased root growth. While deep tillage can promote root growth, continuous tillage year after year can also develop hard layers that may restrict root growth [31]. No-till can increase root growth compared with conventional till by conserving moisture and providing cooler temperature [43,65], but it can also develop root restricting layers because of increased soil compaction [7,40,113]. Similarly, use of heavy machines, such as the tractor used for cultivation, can compact soil and lead to development of root restricting layers because of traffic [7,40,113].

Sainju et al. [86] examined the effects of tillage practices (no-till, chisel plowing and moldboard plowing), cover crops (hairy vetch and winter weeds) and N fertilization rates (N 0 and 180 kg ha^{-1}) on tomato root growth by counting the number of roots at various soil depth using minirhizotron (Figs. 3 and 4). They found that, with or without N fertilization, no-till increased root growth from 6.5- to 13.0-cm soil depth but moldboard plowing with N 180 kg ha^{-1} increased root growth

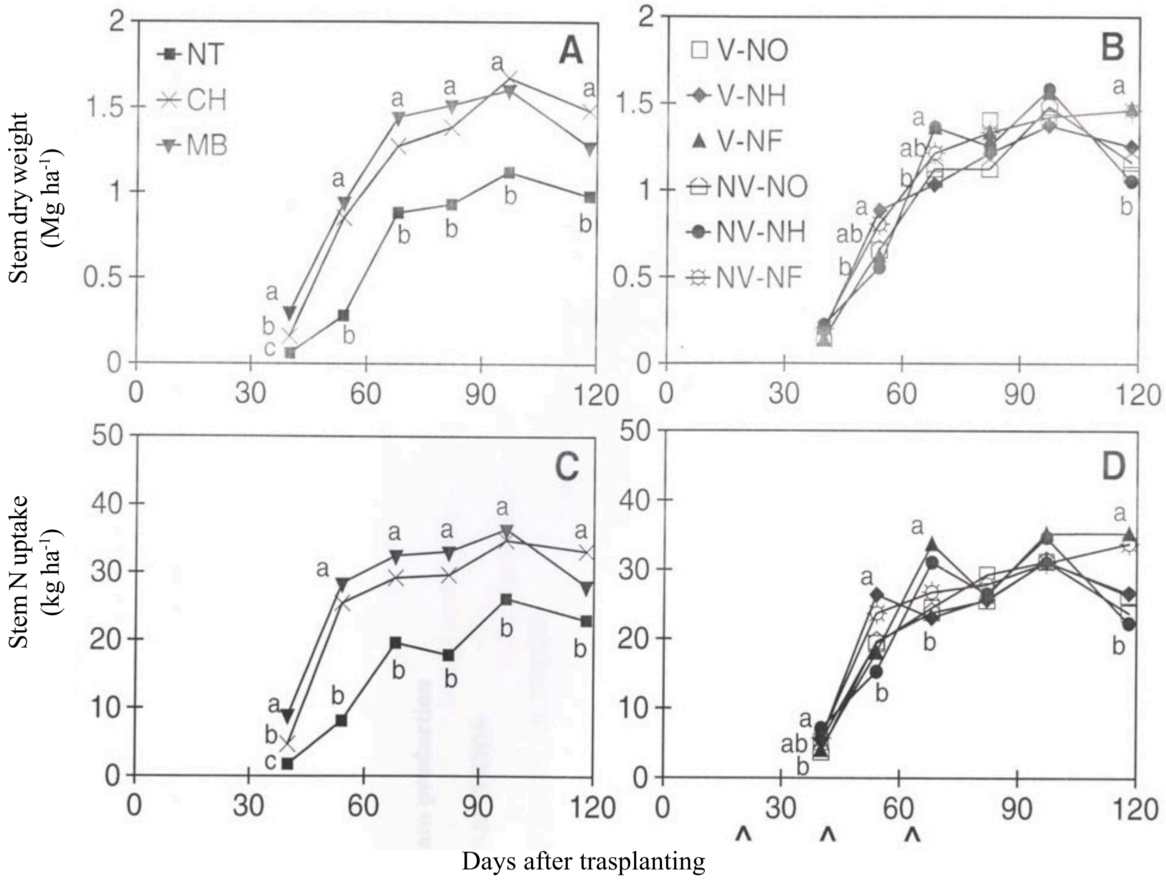

Figure 1. Tomato stem dry weight and N uptake as influenced by tillage, cover cropping, and N fertilization in 1996. NT denotes no-till; CH, chisel plowing; MB, moldboard plowing; V, hairy vetch; NV, no hairy verch; NO, N 0 kg ha^{-1}; NH, N 90 kg ha^{-1}, and NF, N 180 kg ha^{-1}. Mean separation by the least square means test, $P \leq 0.05$. ^ denotes the time of N fertilization [85].

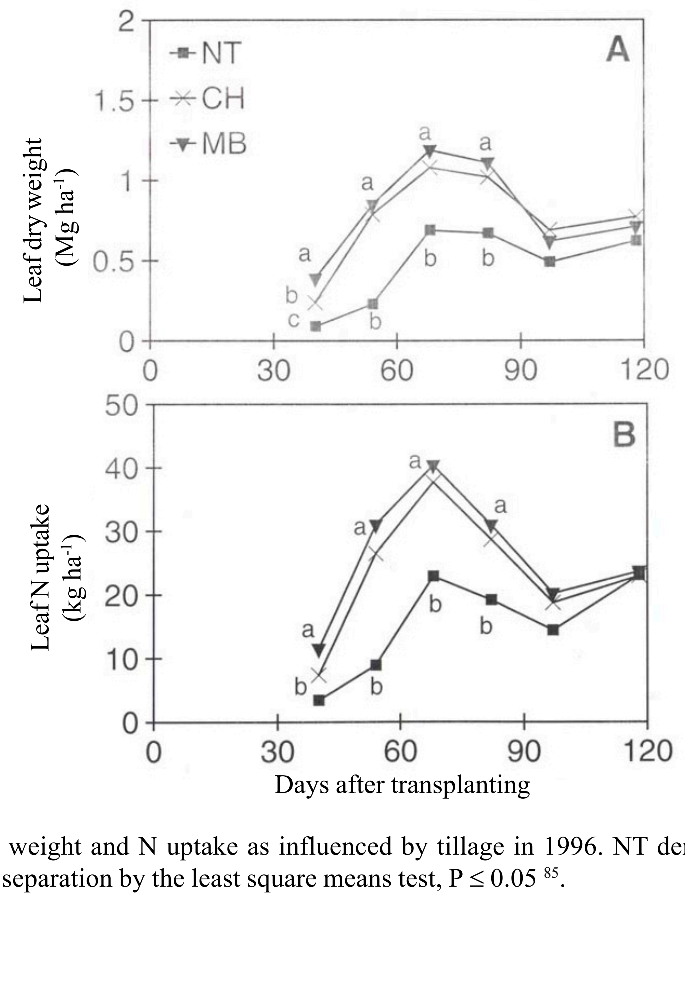

Figure 2. Tomato leaf dry weight and N uptake as influenced by tillage in 1996. NT denotes no-till; CH, chisel plowing; MB, moldboard plowing. Mean separation by the least square means test, $P \leq 0.05$ [85].

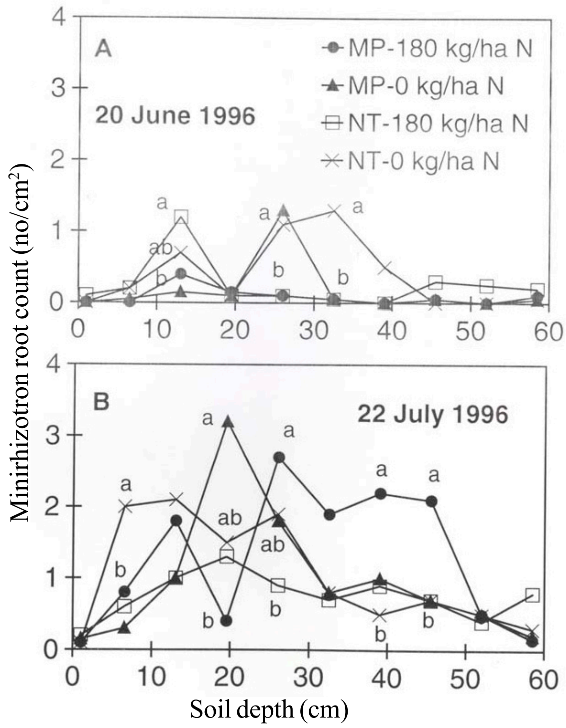

Figure 3. Tomato minirhizotron root counts as influenced by tillage and N fertilization by soil depth. MP denotes moldboard plowing and NT, no-till. Mean separation within soil depths by the least square means test, $P \leq 0.05$ [86].

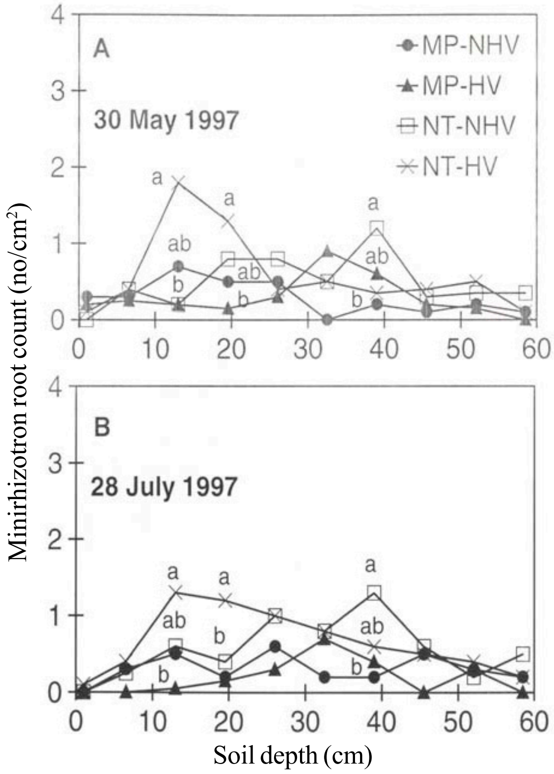

Figure 4. Tomato minirhizotron root counts as influenced by tillage and N fertilization by soil depth. MP denotes moldboard plowing; NT, no-till; HV, hairy vetch; and NHV, no hairy vetch. Mean separation within soil depths by the least square means test, $P \leq 0.05$ [86].

Table 4. Effects of tillage, cover crop, and N fertilization rate on soil organic C and N contents in August 1997. For the interaction of tillage and cover crop, values were averaged across N fertilization rate. For the main treatment, means were obtained by averaging the values of a treatment (i.e. tillage) across the other two treatments (i.e. cover crop and N fertilization rate) [91].

Tillage†	Cover crop‡	Organic C D1§	D2§	D3§	Organic N D1	D2	D3	C:N ratio D1	D2	D3
		----------(Mg· ha^{-1})----------			----------(kg· ha^{-1})----------					
NT	HV	11.9a¶	16.8a	28.7a	1135a	1508a	2643a	10.6b	11.2b	10.9b
	WW	11.6a	14.7b	26.3ab	994b	1150bc	2144b	11.8a	12.8a	12.3a
CP	HV	11.1a	12.9b	24.0ab	955b	1012c	1967b	11.6a	11.8ab	12.2a
	WW	11.3a	13.7b	25.0ab	950b	1118bc	2068b	11.9a	12.4a	12.1ab
MP	HV	9.4b	14.1b	23.5b	774c	1233bc	2007b	12.2a	11.6ab	11.7ab
	WW	8.6b	14.2b	22.8b	689c	1286b	1975b	12.6a	11.1b	11.5ab
Means										
NT		11.7a	15.8a	27.5a	1065a	1329a	2394a	11.2b	12.0a	11.5a
CP		11.2a	13.3b	24.5b	953a	1105b	2058b	11.8ab	12.1a	11.9a
MP		9.0b	14.2ab	23.2b	731b	1260ab	1991b	12.4a	11.3a	11.7a
HV		10.8a	14.6a	25.4a	955a	1278a	2233a	11.5b	11.5b	11.4b
WW		10.5a	14.2a	24.7a	878b	1185b	2063b	12.1a	12.1a	12.0a
N fertilization rate (N kg ha^{-1})										
0		10.5a	14.0a	24.5a	903ab	1177b	2080b	11.9a	12.1a	11.8a
90		10.3a	14.0a	24.3a	871b	1182b	2053b	11.9a	11.9a	11.8a
180		11.1a	15.2a	26.3a	975a	1334a	2309a	11.5a	11.5a	11.4a

† Tillage treatments are NT, no-till; CP, chisel plowing; and MP, moldboard plowing. ‡ Cover crops are HV, hairy vetch; and WW, winter weeds [dominated by henbit (*Lamium amplexicaule* L.) and cut-leaf evening primrose (*Oenothera laciniata* L.)]. § D1, 0-7.5 cm depth; D2, 7.5-20.0 cm depth; and D3, 0-20.0 cm depth. ¶ Within a column and a set, numbers followed by different letters are significantly different at $P \leq 0.05$ by the least square means test.

from 26- to 45-cm depth compared with moldboard plowing with no N fertilization (Fig. 3). Similarly, with hairy vetch cover crop, no-till increased root growth compared with moldboard plowing from 6.5- to 13.0-cm depth (Fig. 4). They concluded that no-till with N fertilization or hairy vetch cover crop may have promoted root growth at the surface soil because of superior moisture conservation and/or cooler temperature, followed by increased N availability from N fertilization or legume (hairy vetch) cover crop residue. Plant residue accumulated at the soil surface in no-till act as mulch, thereby promoting root development [65]. Increased tomato root growth in no-till with hairy vetch compared with bare soil were also observed by Abdul-Baki and Teasdale [1] and Abdul-Baki et al. [2]. In contrast, Sainju et al. [86] reported that increased root growth at deeper depth in moldboard plowing with N 180 kg ha^{-1} (Fig. 3B) may have resulted from less soil impedance and increased N availability due to N fertilization and/or soil N mineralization. Singh and Sainju [82] reported that number of tomato roots per cm^2 of soil profile area from 19.5 to 58.8 cm depth was 65% greater with moldboard plowing than with no-till. Increased root growth in depth restricting layers following conventional till compared with following no-till were also observed by several researchers [6,10].

3.1.2. *Soil properties*

3.1.2.1. *Organic carbon and nitrogen*

Soil organic C and N are key components of soil organic matter that has favorable effects on physical, chemical and biological properties. They are also good indicators of soil quality and productivity [8,21]. They play critical roles in nutrient cycling, water retention, root growth [80,81], plant productivity and environmental quality. Increasing organic C and N concentrations in the soil also help to reduce global warming by sequestering atmospheric C and N [49,73].

Tillage promotes mineralization of soil organic C and N by disrupting soil aggregates, exposing new soil surfaces, and increasing aeration [5,16]. Tillage also incorporates plant residue into the soil and enhances its decomposition [26,27,92]. Practices that reduce residue incorporation and aggregate degradation, such as no-till or minimum till, can conserve and/or maintain organic C and N concentrations in the soil [20,26,36].

In an experiment on the effects of tillage, cover cropping and N fertilization on soil organic C and N contents under tomato, Sainju et al. [91] found that organic C and N were greater in no-till and chisel plowing than in moldboard plowing at 0-7.5-cm depth but were greater in no-till with hairy vetch than in chisel and moldboard plowing with hairy vetch or winter weeds at 7.5-20.0-cm depth after 3 yr (Table 4). At 0-20-cm depth, organic C and N were greater in no-till with hairy vetch than in moldboard plowing with hairy vetch or weeds. As a result, organic C and N decreased by 2-4% in no-till, 14-16% in chisel plowing and 18-19% in moldboard plowing after 3 yr. They speculated that the increase in organic C and N contents in no-till compared with moldboard plowing probably resulted from the surface placement of plant residues that are in less contact with microorganisms for decomposition. They concluded that no-till with legume cover crop can conserve organic C and N concentrations in the soil better than chisel and moldboard plowing with or without cover crop, probably by reducing their loss through mineralization and erosion. Increased organic C and N concentrations in the surface soil in no-till compared with conventional till were also observed by several researchers [26,36,92].

3.1.2.2. *Potential carbon mineralization*

Potential C mineralization (PCM) measures short-term changes in organic C and reflects microbial activities in the soil [26,92]. The PCM measures the amount of CO_2 respired by microorganisms and mineralization of organic C in the soil. Because microorganisms mineralize organic forms of nutrients into inorganic forms that become available to the plants, PCM can influence nutrient dynamics in the soil [26,92]. The PCM is also considered as an active fraction of organic C and vary seasonally due to changes in the amount of plant residues brought by management practices [26,92], rhizodeposition of organic materials in the soil from roots during crop growth [15] or seasonal changes in soil moisture and temperature [38]. As a result, PCM has been identified as an early indicator of changes in soil organic C. The PCM also provides a good estimate of the availability of C substrate and its decomposition potential in the soil [98].

Tillage can influence PCM by increasing aeration and incorporating plant residue into the soil. Sainju et al. [91] observed that PCM was greater in April, May and September than in other sampling dates, regardless of tillage, because of cover crop residue addition in the spring and tomato residue (leaves and roots) addition in the autumn (Fig. 5). They also observed greater PCM in no-till and chisel plowing than in moldboard plowing at 0-7.5-cm depth but greater in moldboard plowing than in no-till and chisel plowing at 7.5-20.0-cm depth during these periods. Averaged across sampling dates, they

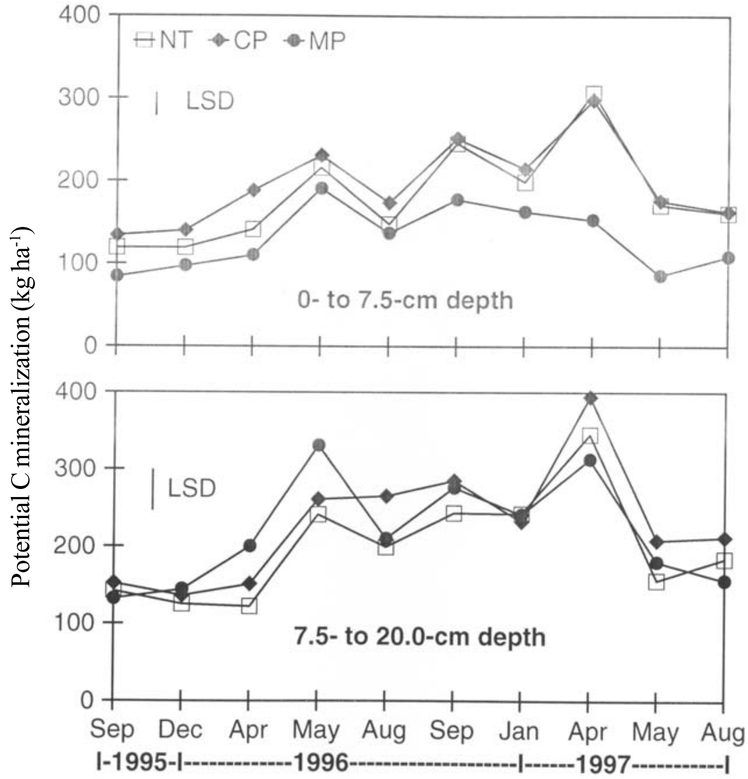

Figure 5. Soil potential C mineralization, averaged across cover crops and N fertilization rates, as affected by tillage and date of sampling at 0-7.5 and 7.5-20.0 cm depths from September 1995 to August 1997. NT denotes no-till; CP, chisel plowing; MP, moldboard plowing. The vertical bar is the least significant difference (LSD, P=0.05) for measuring significant difference between treatments [91].

Table 5. Effects of tillage, cover crop, and N fertilization rate on soil potential C mineralization (PCM), potential N mineralization (PNM), and inorganic N contents. Values of a treatment (i.e. tillage) were averaged across the other three treatments (i.e. cover crop, N fertilization rate, and date of sampling) [91].

	PCM			PNM			Inorganic N		
Treatment	D1†	D2†	D3†	D1	D2	D3	D1	D2	D3
	($kg\ ha^{-1}$)								
Tillage‡									
NT	182a§	200a	382ab	40a	56ab	96a	26a	41a	67a
CP	197a	230a	427a	40a	52b	92a	27a	40a	67a
MP	131b	218a	349b	30b	61a	91a	23a	46a	69a
Cover crop¶									
HV	176a	227a	403a	41a	62a	103a	28a	47a	75a
WW	164b	204b	368b	33b	50b	83b	22b	38b	60b
N fertilization rate (N ($kg\ ha^{-1}$)									
0	173a	218a	391a	36a	50b	86b	22b	36b	58b
90	166a	207a	373a	35a	53b	88b	24ab	40b	64b
180	173a	223a	396a	40a	66a	106a	30a	52a	82a

† D1, 0-7.5 cm depth; D2, 7.5-20.0 cm depth; and D3, 0-20.0 cm depth. ‡ Tillage treatments are NT, no-till; CP, chisel plowing; and MP, moldboard plowing.§ Within a column and a set, numbers followed by different letters are significantly different at $P \leq 0.05$ by the least square means test.
¶ Cover crops are HV, hairy vetch; and WW, winter weeds [dominated by henbit (*Lamium amplexicaule* L.) and cut-leaf evening primrose. (*Oenothera laciniata* L.)].

observed greater PCM in no-till and chisel plowing than in moldboard plowing at 0-7.5-cm depth (Table 5). Like organic C, they speculated that increased PCM in no-till and chisel plowing than in moldboard plowing at 0-7.5-cm depth probably resulted from reduced decomposition of plant residue due to surface placement or reduced degree of incorporation into the soil. In contrast, greater PCM in moldboard plowing than in no-till and chisel plowing at 7.5-20.0-cm depth may have resulted from increased incorporation of plant residue at greater depth. They concluded that no-till or conservation till, such as chisel plowing, can improve microbial activities, especially at the surface soil, compared with conventional till, such as moldboard plowing. Increased PCM at the surface soil in no-till compared with conventional till were also reported by several researchers [26,27,92].

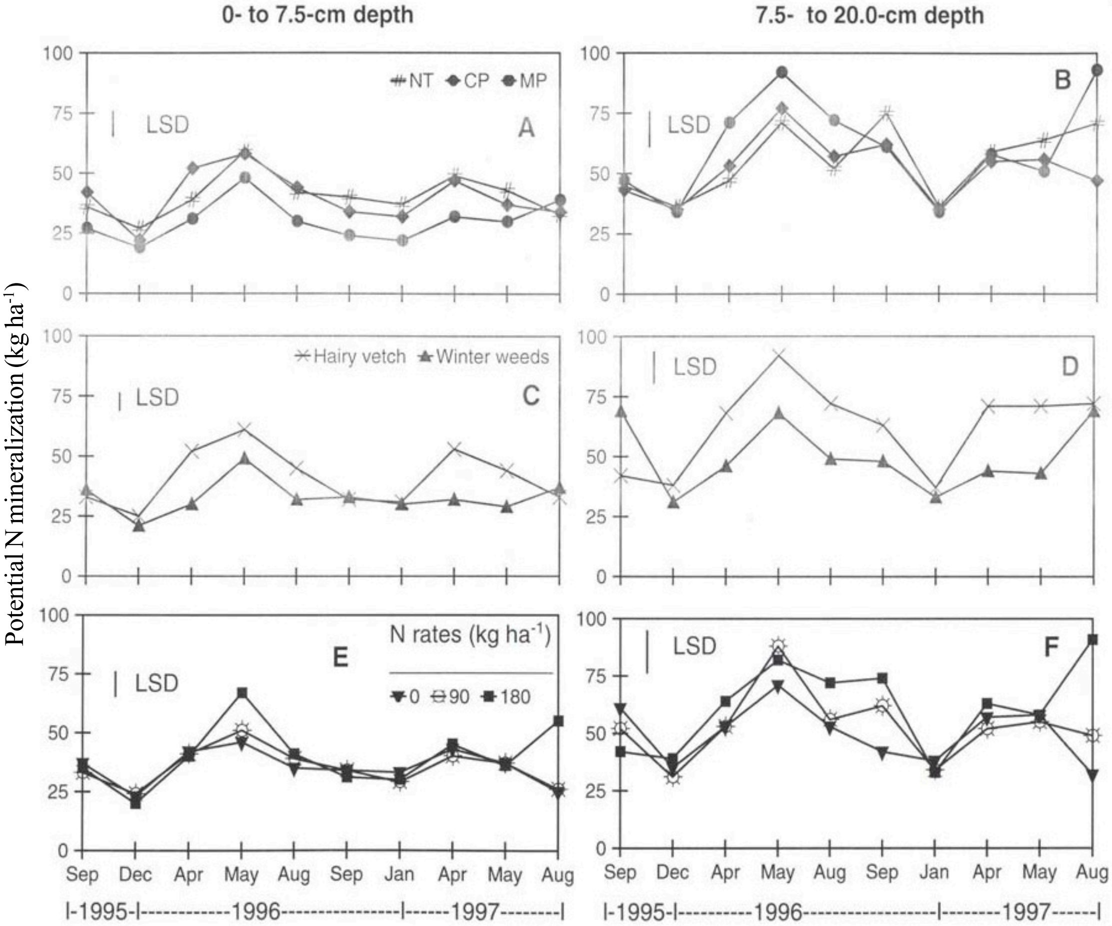

Figure 6. Soil potential N mineralization as affected by tillage, cover crop, N fertilization rate, and date of sampling at 0- to 7.5- and 7.5- to 20.0-cm depths from September 1995 to August 1997. NT denotes no-till; CP, chisel plowing; MP, moldboard plowing. Values of a treatment (i.e. tillage) were averaged across two other treatments (i.e. cover crop and N fertilization rate). The vertical bar is the least significant difference (LSD, P=0.05) for measuring significant difference between treatments [91].

3.1.2.3. *Potential nitrogen mineralization and inorganic nitrogen*

Potential N mineralization (PNM) represents the amount of N mineralized from soil within a growing season of plants. Like PCM, PNM is an active fraction of soil organic N and vary seasonally due to changes in the amount of plant residues brought by management practices and to seasonal changes in temperature and moisture [26,27,92]. As a result, PNM is considered as an early indicator of change in soil organic N because organic N also changes slowly over time, similar to organic C [26,92]. Inorganic N is the sum of NH_4-N and NO_3-N concentrations that are available to plants. Like PNM, it also varies seasonally.

Tillage can influence PNM and inorganic N contents by mineralizing soil organic N. Sainju et al.[91] observed that PNM and inorganic N were greater in May 1996 and April 1997 than in other sampling dates, regardless of tillage practices, due to N inputs from cover crop residue (Figs 6A, 6B, 7A and 7B). They found that PNM and inorganic N were greater in moldboard plowing than in no-till and chisel plowing at 7.5-20.0-cm depth in April and May 1996 but were greater in no-till and chisel plowing than in moldboard plowing at 0-7.5-cm depth in April 1997. Averaged across sampling date, they observed that PNM was greater in no-till and chisel plowing than in moldboard plowing at 0-7.5-cm depth but was greater in moldboard than in chisel plowing at 7.5-20.0-cm depth (Table 5). As with PCM, they described that greater PNM and inorganic N in no-till and chisel plowing than in moldboard plowing at 0-7.5-cm depth was probably due to reduced degree of cover crop residue incorporation into the soil. In contrast, greater PNM and inorganic N in moldboard plowing than in no-till and chisel plowing at 7.5-20.0-cm depth was probably due to incorporation of cover crop residue at greater depth. They concluded that no-till or conservation till, such as chisel plowing, can increase mineralizable and available N at the surface soil compared with conventional till, such as moldboard plowing. Increased PNM and inorganic N in no-till compared with conventional till at the surface soil were also reported by several researchers [26,27,92].

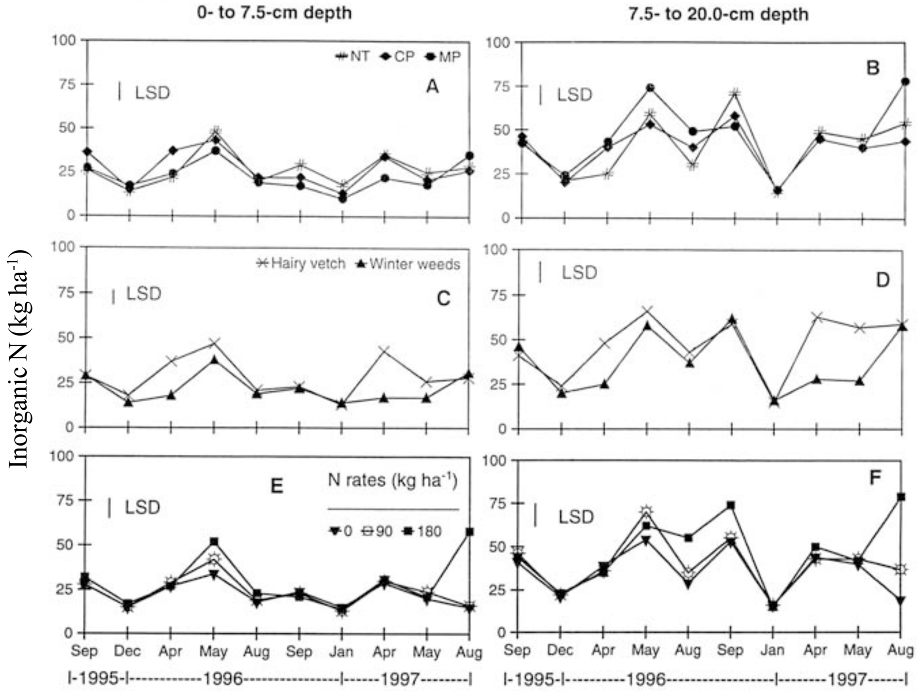

Figure 7. Soil inorganic N concentration as affected by tillage, cover crop, N fertilization rate, and date of sampling at 0- to 7.5- and 7.5- to 20.0-cm depths from September 1995 to August 1997. NT denotes no-till; CP, chisel plowing; MP, moldboard plowing. Values of a treatment (i.e. tillage) were averaged across two other treatments (i.e. cover crop and N fertilization rate). The vertical bar is the least significant difference (LSD, *P*=0.05) for measuring significant difference between treatments [91].

3.1.2.4. *Nitrate-nitrogen movement and leaching*

Nitrate-N is the form of N taken up by plants. It is supplied by soil and soil amendments, such as manures and fertilizers. Nitrate-N is soluble in water. As a result, soil residual NO_3-N unused by crops after harvest can leach from the soil profile into groundwater during the period of heavy rainfall. Nitrate-N movement in soil profile and leaching in the surface and groundwater occur mostly during autumn, winter and spring seasons when evapotranspiration is low and precipitation exceeds water holding capacity of soil [63]. Liang et al. [57] and Liang and McKenzie [56] found that changes in soil NO_3-N level between autumn and spring were a function of autumn NO_3-N level and over-winter precipitation. About 15 to 55% of N applied to crops is lost by leaching every year, depending on soil and environmental conditions [33, 117]. As a result, agricultural practices remain a major source of NO_3-N contamination in groundwater, although contamination also results from several sources, such as industrial wastes, municipal landfills, mining or septic systems [23,34,100]. Nitrate-N level at concentration >10 mg L^{-1} in the drinking water is considered as health hazard in USA [67]

Nitrate leaching from agricultural soils occurs because of the inefficiency of crops in N uptake. Nitrogen recovery in plants seldom exceeds 70% of the applied N and averages 50% for most crops [4,33,112]. For vegetable crops, it may be even lower. For example, Errebhi et al. [22] reported that N recovery in potato ranged from 25 to 40%. Similarly, Sainju et al. [85] observed that N recovery in tomato that was applied from hairy vetch residue or N fertilizer ranged from 1 to 30% (Table6). Vegetable cropping systems require a greater degree of management and involve a larger amount of N input than cereal cropping systems [76]. As a result, potentials to accumulate residual N in the soil from applied N and its leaching in the groundwater are even greater under vegetable than under cereal cropping systems.

Tillage can influence NO_3-N movement and leaching from soil by enhancing mineralization of N from plant residue and soil organic matter. In an experiment on the effects of tillage and cover crop on soil NO_3-N movement under tomato, Sainju et al. [84] found that NO_3-N level increased with increasing soil depth, regardless of tillage and cover crops, and that the level was greater with that without hairy vetch (Fig. 8). This indicated that NO_3-N moved from surface to subsurface soil where it accumulated, probably due to slow water movement in the clay layer. The NO_3-N level at 60- 120-cm depth was greater in September 1997 than in March 1998 and greater in chisel and moldboard plowing than in no-till in March 1998 (Table 7). Total NO_3-N loss from 0-120-cm depth from autumn to spring was 58% in no-till compared with 26% in chisel plowing and 22% in moldboard plowing. They concluded that large loss of NO_3-N in no-till compared with chisel and moldboard plowing was probably due to presence of large macropores in no-till where water moved rapidly. Increased NO_3-N leaching in no-till compared with conventional till were also observed by several researchers [106- 108].

Table 6. 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 [85].

	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 7. Nitrate-N content at 0-60, 60-120 and 0-120 cm depth in the fall (September 1997) and the spring (March 1998) as influenced by 3 yr of tillage, cover cropping, and N fertilization [84].

	0-60 cm depth			60-120 cm depth			0-120 cm depth		
Treatment	Fall	Spring	Loss	Fall	Spring	Loss	Fall	Spring	Loss
Tillage									
No-till	95a†	25b	70 (74)‡	127a	68b	59 (46)‡	222a	93b	129 (58)‡
Chisel	68b	26b	42 (62)	147a	134a	12 (9)	215a	160a	55 (26)
Moldboard	107a	58a	49 (46)	144a	136a	7 (5)	250a	194a	56 (22)
Cover crop									
Hairy vetch	104a	43a	61 (58)	170a	128a	42 (25)	274a	171a	103 (38)
No hairy vetch	76b	30b	47 (61)	107b	98b	10 (9.0)	184b	127b	56 (34)
N fertilization, kg ha^{-1}									
0	51b	26b	26 (50)	76b	65b	11 (15)	127c	91b	37 (29)
90	83b	29b	54 (65)	160a	113ab	48 (30)	243b	142b	104 (42)
180	136a	55a	82 (60)	180a	161a	19 (11)	316a	216a	101 (32)
Significance									
Tillage (Till)	*	*		NS	*		NS	*	
Cover crop Ccrop	*	*		*	*		*	*	
Till x Ccrop	NS	NS		NS	NS		NS	NS	
N fertilization (Fert)		***	*		***	***		***	***
Till x Fert		NS	NS		NS	NS		NS	NS
Ccrop x Fert	NS	NS		NS	NS		NS	NS	
Till x Ccrop x Fert	NS	NS		NS	NS		NS	NS	

* and *** Significant at $P \leq 0.05$ and 0.001, respectively; NS, not significant.

† Numbers followed by the same letter within a column of a particular treatment are not significantly different at *P*#0.05 by the least square means test.

‡ Number in parenthesis denote % decrease in soil NO_3 content from fall to spring.

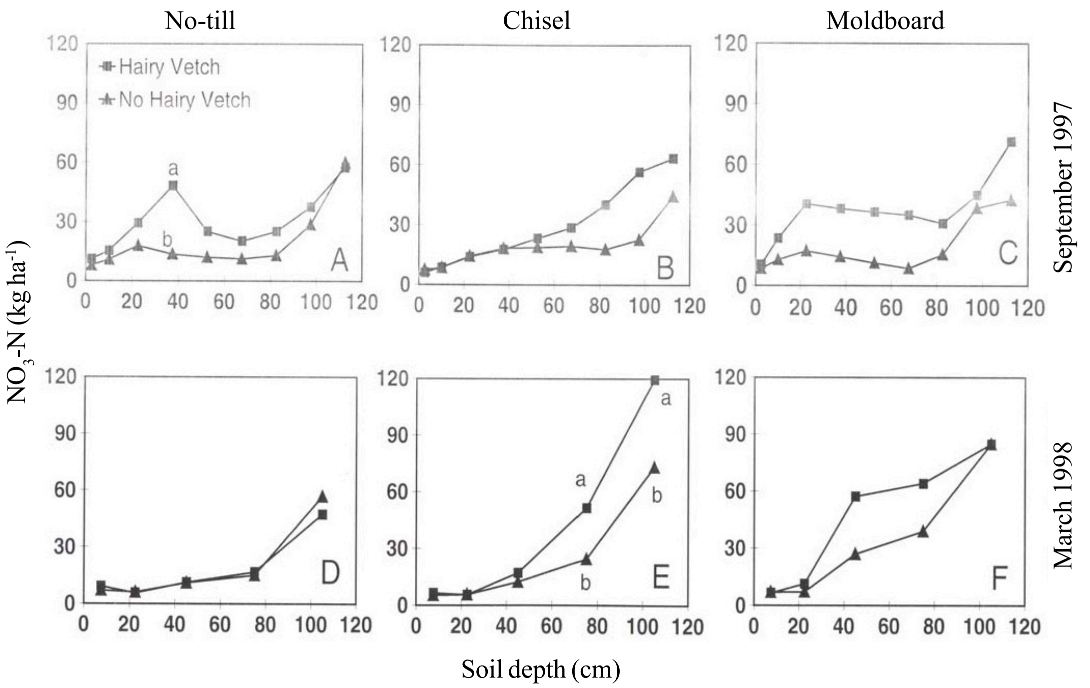

Figure 8. Soil NO_3-N with depth in the autumn (September 1997) and spring (March 1998) as influenced by tillage and cover cropping. Nitrate content at a particular depth is plotted at the mid-point of the depth range. Symbols followed by different letter at a particular depth are significantly different at P ≤0.05 by the least square means test [84].

3.2. Cover crop

Cover crops are crops grown usually in the winter after harvest of annual crops to cover the bare soil. In the spring, cover crop biomass is either placed at the soil surface in no-till or incorporated into the soil in conventional till before summer crop is planted. As a result, cover crops not only reduce soil erosion but also provide many benefits, such as (1) removing soil residual N in the autumn, thereby reducing its loss from leaching, (2) improving soil properties, such as soil organic matter, water holding capacity, infiltration capacity and aggregation, thereby improving soil quality and productivity, (3) legume cover crops fixing N from the atmosphere, thereby supplying N to the summer crops, reducing the amount of N fertilizer and increasing crop production, (4) helping to reduce the concentration of greenhouse gases by sequestering atmospheric C and N in the soil and (5) controlling weeds, pests and diseases.

3.2.1. *Cover crop biomass yield and carbon and nitrogen accumulation*

Cover crops vary in the amount of biomass production and C and N accumulations due to differences in species, length of growing seasons, climate and soil conditions between locations [94]. While nonlegume cover crops usually produce higher biomass yield and C content, legume cover crops have higher N content due to increased N concentration from atmospheric N fixation. Sainju and Singh [82] reviewed literatures on biomass yield and N accumulation of legume and nonlegume cover crops and reported that biomass yield of nonlegume cover crops varied from 1.5 to 7.1 Mg ha^{-1} and N accumulation varied from 14 to 90 kg ha^{-1} (Table 8). In contrast, biomass yield of legume cover crops varied from 0.7 to 7.2 Mg ha^{-1} and N accumulation varied from 38 to 220 kg ha^{-1}. The C accumulation in cover crops is proportional to biomass yield because C concentration remains constant, regardless of species [47]. In Georgia, USA, Sainju et al. [87] found that biomass yield of nonlegume cover crop (rye) ranged from 6.0 to 6.7 Mg ha^{-1}, C accumulation ranged from 2888 to 3020 kg ha^{-1}, and N accumulation ranged from 76 to 137 kg ha^{-1} (Table 9). In contrast, biomass yield of legume cover crops (hairy vetch and crimson clover) ranged from 4.7 to 6.3 Mg ha^{-1}, C accumulation ranged from 1911 to 2863 kg ha^{-1}, and N accumulation ranged from 147 to 225 kg ha^{-1}. Because of high N concentration, C:N ratio was lower in legume than in nonlegume cover crops.

3.2.2. *Tomato production*

3.2.2.1. *Fruits*

Legume cover crops can increase tomato yields better than nonlegume or no cover crops do [94,102]. In an experiment on the effect of hairy vetch residue on tomato yield, Sainju et al. [88] observed that 100 g of residue per pot increased number of tomato fruits, yield and N uptake compared with no residue in the lathhouse but not in the greenhouse (Table 10). Although tomatoes were grown in individual containers on both greenhouse and lathhouse, environmental conditions for tomato growth were controlled in the greenhouse but not in the lathhouse. Hairy vetch cover crop mulch in a no-till system can increase tomato yield compared with black polyethylene mulch or bare soil [1,2]. Kelly et al. [41] observed that hairy vetch mulch increased tomato yield late in the growing season and increased monetary returns, even during adverse climatic conditions, compared with polyethylene mulch or bare soil. Similarly, Sainju et al. [89] found that hairy vetch and crimson clover increased tomato yields compared with rye or N 0 kg ha^{-1} and these yields were similar to those produced by N 90 and 180 kg ha^{-1} (Table 11). They described that because of higher N concentration, hairy vetch and crimson clover supplied greater amount of N in the soil and increased tomato yields. They concluded that hairy vetch and crimson clover can produce sustainable tomato yields and may reduce potential for N leaching compared with N fertilization.

3.2.2.2. *Stems and leaves*

Cover crops can influence growth of tomato stems and leaves, similar to fruits. Sainju et al. [88] observed that 100 g of hairy vetch residue per pot increased dry weight and N uptake of tomato stems and leaves compared with no residue in the greenhouse and lathhouse (Table 12). Similarly, Sainju et al. [85] found that, with or without N fertilization, hairy vetch increased tomato stem weight and N uptake compared with no cover crop at 50, 70, and 120 d after transplanting (Figs 1B and 1D). While leaf N concentration decreased as tomato grew from 35 to 104 d after transplanting, concentration was greater with than without hairy vetch at 82 and 104 d after transplanting (Fig. 9A). Sainju et al. [89] also found that hairy vetch and crimson clover increased tomato biomass (leaves + stems + fruits dry weight) yields and N uptake compared with rye or N 0 kg ha^{-1} but these were similar to that produced by N 90 and 180 kg ha^{-1} (Table 11). They concluded that legume cover crops can produce tomato biomass yields and N uptake similar to that produced by half to full rate of N fertilization in Georgia, USA.

Table 8. Cover crop yields and their N contributions, and yield and N uptake of succeeding crop [82].

Reference and location	Cover crop	Succeeding crop/rotation	Cover crop Yield (Mg ha^{-1})	Cover crop N contribution (kg ha^{-1})	Succeeding crop Yield (Mg ha^{-1})	Succeeding crop N contribution (kg ha^{-1})
Clark et al. [119]	Hairy vetch	Field corn	0.7-5.2	38-161	5.5-10.7	-------
Maryland	Rye		2.9-7.1	58-90	3.1-6.1	-------
	Hairy vetch + rye		3.4-8.1	104-185	5.2-8.4	-------
	Control		--------	---------	3.6-6.9	-------
Decker et al. [124]	Hairy vetch	Field corn	2.9-5.1	109-206	7.2-8.9	140-204
Maryland	Austrian winter pea		1.9-4.7	73-180	7.5-8.9	144-201
	Crimson clover		2.1-6.5	59-170	7.2-8.9	138-190
	Wheat		2.1-4.0	35-42	6.2-7.2	128-165
	Control		-------	-------	6.3-7.7	121-175
Ebelhar et al. [120]	Hairy vetch	Field corn	5.1	209	6.4	-------
Kentucky	Big flower vetch		1.9	60	4.2	-------
	Crimson clover		2.4	56	4.4	-------
	Rye		3.4	36	-------	-------
	Fallow		-------	-------	4.4	-------
Hargrove [35]	Rye	Sorghum	4.0	38	2.6	-------
Georgia	Crimson clover		7.2	170	3.9	-------
	Subterranean clover		4.0	114	3.8	-------
	Hairy vetch		4.3	153	4.0	-------
	Common vetch		4.3	134	3.7	-------
Huntington et al. [121]	Rye	Field corn	1.5	14	0.9	17
Kentucky	Hairy vetch		3.3	125	4.1	110
	Control		-------	-------	0.4	14
Kamprath et al. [125] North Carolina	Austrian winter pea	Field corn	2.0	51	3.0	-------
	Oat + hairy vetch		2.9	87	3.3	-------
	Hairy vetch		3.0	120	3.9	-------
	Austrian winter pea	Cotton	2.1	79	95.9	-------
	Oat + hairy vetch		3.3	106	87.7	-------
	Hairy vetch		3.2	131	87.2	-------
Kelly et al. [41]	Hairy vetch mulch	Tomato	-------	-------	104	-------
Maryland	Polyethylene mulch		-------	-------	80	-------
	Bare soil		-------	-------	55	-------
Kuo et al. [46]	Rye	Silage corn	5.3	60	7.4	112
Washington	Annual ryegrass		7.1	56	7.2	62
	Hairy vetch		3.2	120	12.3	179
	Austrian winter pea		3.9	100	9.6	118
	Canola		3.3	44	7.8	78
	Control		2.1	30	7.6	73
McVay et al. [62]	Hairy vetch	Field corn	3.4	128	8.5	90
Georgia	Crimson clover		3.5	108	-------	-------
	Wheat		1.8	32	3.5	30
Shennan [94]	Purple vetch	Field corn/tomato^{z}	5.3	178	12.3 (103)^{z}	-------
California	Lana woollypod vetch		6.3	220	-------	-------
	Oat + vetch		6.3	130	10.6 (90)^{z}	-------
	Faba beans + vetch		5.1	174	-------	-------
	Winter annual grass		2.9	51	-------	-------
	Austrian winter pea		3.2	110	11.1 (77)^{z}	-------
	Oat		5.4	52	6.8 (62)^{z}	-------
	Bell bean		-------	-------	10.2 (84)^{z}	-------
Touchton et al. [123]	Fallow	Cotton	2.7	31	0.6	-------
Alabama	Crimson clover		4.5	95	0.9	-------
	Common vetch		4.9	118	0.8	-------

^{z} Value outside parenthesis is field corn, value inside parenthesis is tomato yield. Summer crops were 2 years of field corn and 2 years of tomato in 4 years rotation.

Table 9. 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 [89].

Cover crop	Biomass yield (Mg ha^{-1})	Concentration C	Concentration N	Accumulation C	Accumulation N	C:N ratio
		----(g kg^{-1})----		-------(kg ha^{-1})--------		
			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			
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 10. 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 [88].

Treatment	No. fruits per plant	Yield Fresh	Yield Dry	N conc. (g kg^{-1})	N uptake (mg plant^{-1})
		-------(g 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)					
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, $P \leq 0.05$.
[y] Not significant.

Table 11. 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 [86].

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 12. 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, $P \leq 0.05$.

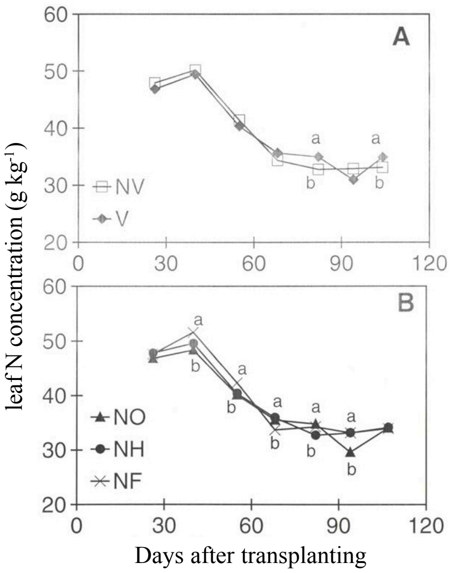

Figure 9. Tomato leaf N concentration as influenced by cover cropping and N fertilization in 1997. V, denotes hairy vetch; NV, no hairy verch; NO, N 0 kg ha^{-1}; NH, N 90 kg N ha^{-1}, and NF, N 180 kg ha^{-1}. Mean separation by the least square means test, P ≤ 0.05. ^ denotes the time of N fertilization [85].

3.2.2.3. *Roots*

Cover crops can promote root growth by increasing the amount of plant residue returned to the soil, thereby increasing soil organic matter content and increasing the density of biopores in the soil profile, where roots of succeeding crops can grow even in root-restricting layers [13,39]. Increased organic matter content in the soil decreases its bulk density, increases moisture content, and conserves heat during hot and cold weather that help to stimulate root growth [80]. Sainju et al. [86] reported that hairy vetch increased tomato root growth compared with no hairy vetch at 13.0-19.5-cm soil depth, probably due to greater amount of N supply (Fig. 4). In an experiment on the effect of hairy vetch residue on tomato root growth, Sainju et al. [88] observed that the residue increased length, dry weight and N uptake of tomato roots compared with no residue in the lathhouse but not in the greenhouse (Table 13). Similarly, Sainju et al. [89] observed that hairy vetch and crimson clover increased tomato root growth compared with N 0 kg ha^{-1} but root growth was similar to those with rye,

Table 13. 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 [88].

	Roots				
Treatment	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.

Table 14. 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 [89].

	NR at soil depths (cm)						TNR
Treatment	1	6.5	13.0	19.5	26.0	32.5	
			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 $P<0.001$.

N 90 and 180 kg ha^{-1} (Table 14). They concluded that hairy vetch and crimson clover increased tomato root growth probably due to greater amount of N supply and rye increased root growth probably because of increased soil organic matter content. Increased tomato root growth with hairy vetch mulch compared with black polyethylene mulch or bare soil were also observed by several researchers [1,2,105].

3.2.3. *Soil properties*

3.2.3.1. *Organic carbon and nitrogen*

While tillage enhances mineralization of soil organic C and N, cover crops help to maintain their levels by increasing the amount of plant residue returned to the soil [47,87,89,111]. Carbon and N inputs from cover crop residues replace soil organic

C and N lost by cultivation. Therefore, cover crops that produce higher biomass yields are also likely to maintain higher levels of soil organic C and N. The extent of the increases of organic C and N following incorporation of cover crop residues is regulated by a combination of factors, including the amount and quality of residues, rate and manner of application, soil type, frequency of tillage and climatic conditions [96,101].

The rate of decomposition of cover crop residues also influences the levels of organic C and N in the soil [19,47,48]. The decomposition rates vary with species and stage of growth of cover crops [27] due to variations in the chemical composition of the biomass [77,97]. Climatic and soil conditions can also influence the rate of decomposition [99]. Kuo et al. [47, 48] observed that the half-life of mineralization of cover crop C and N in the soil varied from 4 wk for hairy vetch to 9 wk for rye. The balance between the amount of cover crop residue applied to the soil and the rate at which it decomposes determines the levels of organic C and N in the soil [47,48,87]. Larson et al. [51] and Rasmussen et al. [78] found that changes in soil organic C were linearly related with the amount of residue applied to the soil and were independent of the type of residue.

Sainju and Singh [82] summarized literature on the effects of cover crops on soil organic C and N concentrations and found that cover crops increased organic C and N compared with no cover crop (Table 15). While Wilson et al. [116], Frye et al. [29] and Hargrove [35] observed greater organic C and N concentrations with legume than with nonlegume cover crops, Kuo et al. [46] observed greater organic C and N concentrations with nonlegume than with legume cover crops. Similarly, Sainju et al. [87] observed greater organic C and N concentrations with nonlegume (rye) than with legume (hairy vetch and crimson clover) cover crops under tomato in Georgia, USA (Table 16). They explained that because of greater biomass yields and C:N ratios (Table 9), nonlegume cover crops decompose slowly in the soil, thereby resulting in greater organic C and N concentrations than with legume cover crops. Although nonlegume cover crops had lower N accumulations than legume cover crops, nonlegumes also maintained a greater level of organic N, because organic N was closely associated with organic C [96]. They concluded that cover crops can conserve and/or maintain organic C and N concentrations in the soil better than no cover crops, with nonlegumes being more effective than legumes in improving soil quality and productivity and helping to reduce global warming by sequestering atmospheric CO_2. Sainju et al. [91] also observed greater soil organic N at 0-7.5- and 7.5-20.0-cm depths with hairy vetch than with winter weeds, although organic C was not affected (Table4).

3.2.3.2. *Potential carbon mineralization*

As with soil organic C and N, cover crops can influence PCM by adding plant residues to the soil. Sainju et al. [87] found that PCM under tomato increased with rye, hairy vetch and crimson clover compared with the control (no cover crop or N 0 kg ha^{-1}), with rye being most effective (Fig. 10). They observed that PCM increased at 30 d after incorporation of the residue, decreased at 70 d, and thereafter increased again, regardless of cover crop species. They argued that the increased PCM at 30 d was probably resulted from cover crop residue addition which increased available C for microorganisms, thereby increasing their activities. Addition of plant residue increases available C for increased microbial activities [37]. The decreased level from 30 to 70 d was probably resulted from reduced level of C substrate, as cover crop residue decomposed in the soil. The increased level after 70 d was probably resulted from rhizodeposition of organic material from tomato roots, as rhizodeposition from crop roots can significantly increase PCM [15,47,92]. They concluded that cover crops can increase microbial activities in soil, with nonlegumes being more effective than with legumes due to larger biomass or C accumulation. Similarly, Sainju et al. [91] observed that PCM at 0-7.5-cm and 7.5- 20.0-cm depths was greater with hairy vetch than with winter weeds due to larger amount of biomass added to the soil (Table 5). Increased PCM after addition of plant residue in the soil were also observed by several researchers [47,48,92].

3.2.3.3. *Potential nitrogen mineralization and inorganic nitrogen*

Cover crop residues added to the soil can also influence PNM and inorganic N levels by adding N, stimulating microbial activities, and affecting mineralization of organic N. Sainju et al. [91] observed that PNM and inorganic N increased immediately after incorporation of cover crop residues into the soil in April and May 1996 and 1997 and that their levels were greater with hairy vetch than with winter weeds (Figs 6C, 6D, 7C, and 7D). Hairy vetch increases inorganic N level in the soil because of its higher N concentration [48]. As the cover crop residue is decomposed in the soil, PNM and inorganic N levels decreased in August and September 1996 and 1997 because of decreased availability of N substrate. Similarly, Sainju et al. [87] reported that PNM and inorganic N increased at 15 to 30 d after cover crop incorporation into the soil in April and May 1996 and 1997 and that their levels were greater with hairy vetch and crimson clover than with rye or the control

Table 15. Cover crop effects on soil organic C and N concentrations [82].

Reference	Cover crop	Soil depth (cm)	Organic component C ($g \cdot kg^{-1}$)	N ($g \cdot kg^{-1}$)
Frye et al. [28]	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 [35]	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. [46]	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. [62]	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. [123]	Fallow	0-11	7.0	0.32
	Crimson clover		8.7	0.43
	Hairy vetch		10.8	0.42
Wilson et al. [116]	Initial	0-15	17.0	1.6
	Fallow		12.0	1.2
	Grasses		15.0	1.8
	Legumes		16.0	2.0

Table 16. Organic C and N concentrations in the soil at 0-30 cm depth averaged across sampling dates from April 1996 to August 1997 as influenced by cover crops and N fertilization. The significance of treatment and date of sampling was evaluated by using analysis of repeated measures [87].

	Organic C ($g\ kg^{-1}$)	Organic N ($mg\ kg^{-1}$)
Treatment		
Rye	6.19 *a*	411 *a*
Hairy vetch	5.92 *ab*	403 *ab*
Crimson clover	5.77 *b*	381 *bc*
N 0 kg ha^{-1}	4.55 *c*	347 *d*
N 90 kg ha^{-1}	5.54 *b*	356 *cd*
N 180 kg ha^{-1}	5.57 *b*	376 *bc*
Significance		
Treatment	**	***
Date of sampling (date)	***	***
Treatment x Date	*	NS

*, **, *** Significant at *P* #0.05, 0.01, and 0.001, respectively; NS, not significant.

a-d Within a column, numbers followed by the same letter are not significantly different at $P \leq 0.05$ by the least square means test.

(N 0 kg ha^{-1}) (Figs 11 and 12). They found that, although increased temperature in the spring compared with winter weeds increased PNM and inorganic N, the peak levels with rye and control were delayed by 2 wk compared with levels with hairy vetch and crimson clover, probably due to their slower rate of decomposition. They also found a strong relationship ($r = 0.51$ to 0.83, $P \leq 0.05$, $n = 6$) between the amount of N accumulated in cover crop residues and PNM and inorganic N levels in April and May 1996 and 1997.

Nitrogen released by cover crop residues at 15 to 30 d after incorporation into the soil is critical for plant growth. Crops need a large amount of N during their active growth, especially soon after planting. Several researchers have found that N released by cover crop residues synchronized with N needs of the summer crops [48,104]. Similarly, Yaffa et al. [118] found that N released by hairy vetch residue was synchronized with N need of tomato. Lack of synchronization can result in inefficient use of N by summer crops, which results in buildup of soil residual N that can contaminate groundwater by leaching.

3.2.3.4. *Nitrate-nitrogen movement and leaching*

Because cover crops use soil residual N left after autumn harvest of the summer crop, they reduce the amount of NO_3-N available for movement in the soil profile and leaching in the groundwater [63,75]. Cover crops also use water that might otherwise dissolve NO_3-N and transport it through runoff and infiltration in the soil profile [63]. A cover crop that grows quickly and vigorously in the autumn can remove most of the soil residual NO_3-N [63]. Nonlegume cover crops grow rapidly in the autumn and therefore can reduce N leaching better than legume cover crops [63]. Sainju et al. [83] found that nonlegume cover crops, such as rye, significantly lowered autumn inorganic N level in the soil than legume cover crops, such as hairy vetch and crimson clover. As a result, nonlegume cover crops can effectively reduced N leaching compared with legume cover crops [47,61]. Sainju and Singh [82] reviewed the literature on the effects of cover crops on N leaching and found that nonlegume cover crops reduced N leaching from 29 to 93% compared with -6 to 48% by legume cover crops (Table 17). Sainju et al. [84] observed that residual soil NO_3-N at 0-120-cm soil depth after tomato harvest in autumn and its loss from autumn to following spring were greater with than without hairy vetch (Table 7 and Fig. 8). They concluded that because of higher N concentration, hairy vetch increased NO_3-N level in the soil. As a result, hairy vetch was not effective in removing residual NO_3-N and its movement within the soil profile compared with winter weeds.

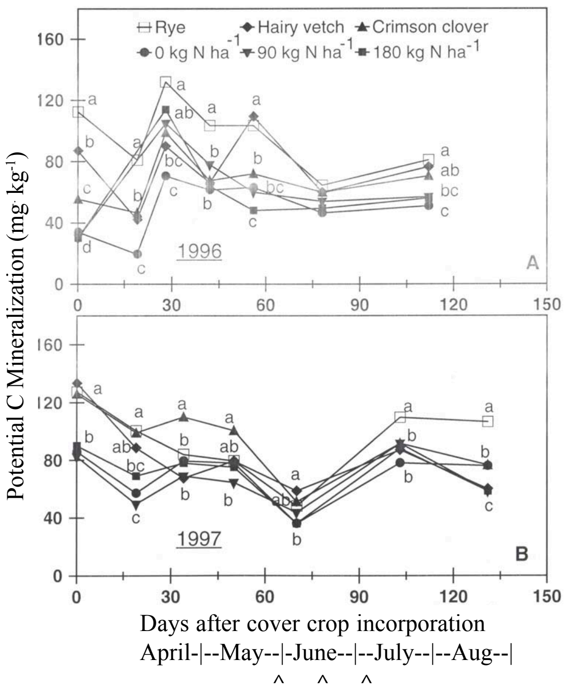

***Figure 10**.* Soil potential C mineralization at 0- to 30-cm depth from April (after cover crop incorporation) to August during tomato growing season in 1996 and 1997 as affected by cover crop species and N fertilization. The symbol ^ denotes time of N fertilization. Symbols followed by different letters within a sampling date are significantly different at $P \leq 0.05$ by the least square means test [87].

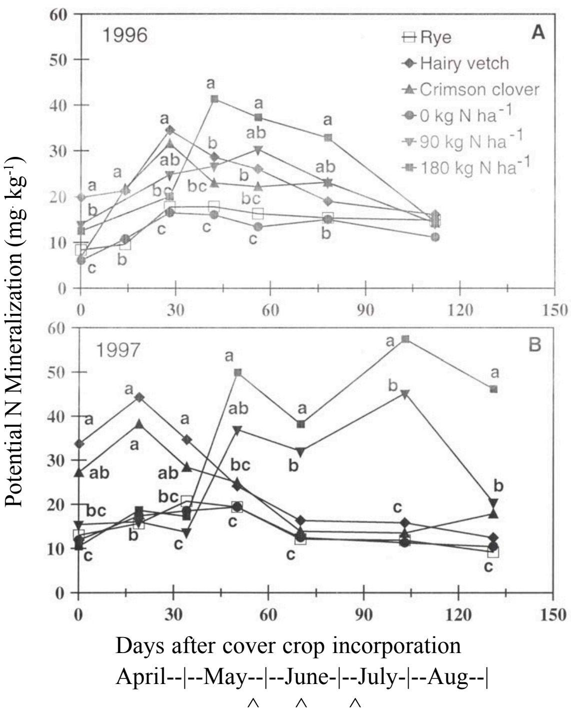

Figure 11. Soil potential N mineralization at 0- to 30-cm depth from April (after cover crop incorporation) to August during tomato growing season in 1996 and 1997 as affected by cover crop species and N fertilization. The symbol ^ denotes time of N fertilization. Symbols followed by different letters within a sampling date are significantly different at $P \leq 0.05$ by the least square means test [87].

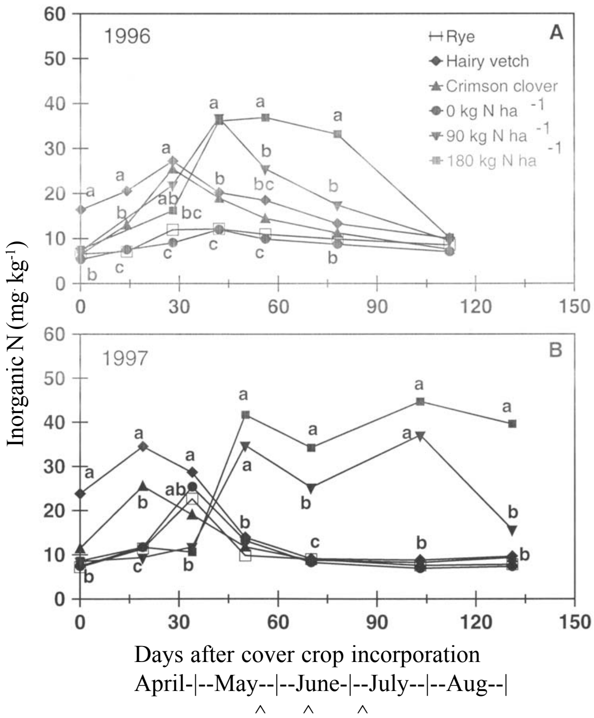

Figure 12. Soil inorganic N concentration at 0-30 cm depth from April (after cover crop incorporation) to August during tomato growing season in 1996 and 1997 as affected by cover crop species and N fertilization. The symbol ^ denotes time of N fertilization. Symbols followed by different letters within a sampling date are significantly different at $P \leq 0.05$ by the least square means test [87].

Table 17. Reduction in NO_3^- leaching from soil due to cover crops [82].

Reference	Cover crop	Reduction due to cover crop (%)
Bertilsson [127]	Rape	62
Chapman et al. [122]	Sweet clover	1
	Purple vetch	10
	Mustard	80
Karrakar et al.[126]	Rye	72
McCracken et al.[61]	Rye	94
	Hairy vetch	48
Meisinger et al.[63]	Rye	29
	Hairy vetch	-6
Morgan et al.[128]	Oat	48
	Rye	62
	Timothy	33
Volk and Bell [129]	Turnip	84

3.2.3.5. *Other physical properties*

Cover crops also influence soil physical properties, such as water content, temperature, aggregation, bulk density and infiltration capacity. The mulch effect of cover crop residue can alter water content and temperature in the soil [41,96]. In the no-till system, cover crop residue can conserve soil moisture and improve tomato [1,2] and corn [17,18] yields. It can also reduce soil temperature during hot weather, thereby promoting root development in vegetables and fruits [3,41,68]. Cover crops can also improve soil aggregation, hydraulic conductivity [62,79] and water infiltration capacity [62]. Cover crops reduced soil erosion from 18 to 2 Mg ha^{-1} yr^{-1} [29] and by 62% in Ultisols and 72% in Alfisols compared with the bare soil [50].

3.3. Nitrogen fertilization

3.3.1. *Tomato production*

3.3.1.1. *Fruits*

Nitrogen fertilization can increase tomato yield and N uptake. Sainju et al. [85,86] observed that N 90 and 180 kg ha^{-1} increased tomato fresh and dry yields and N uptake compared with N 0 kg ha^{-1}, although fertilization did not influence N concentration (Tables 3 and 11). They did not found significant difference in fresh and dry yields and N uptake between N 90 and 180 kg ha^{-1} and concluded that N 90 kg ha^{-1} can sustain tomato yield and reduce potential for N leaching compared with N 180 kg ha^{-1}. Increased tomato yield with N fertilization was also observed by several researchers [64,114,115].

3.3.1.2. *Stems and leaves*

Nitrogen fertilization can increase the growth of tomato foliage. Increased fertilization, however, can produce excessive foliage at the expense of fruit production. Sainju et al. [85] observed that tomato stem dry weight and N uptake increased in N fertilization and hairy vetch compared with no fertilization and cover crop at 50, 70 and 120 d after transplanting (Figs 1B and 1 D). Similarly, N 180 kg ha^{-1} increased tomato leaf N concentration compared to N 0 and 90 kg ha^{-1} at 40 and 50 d after transplanting (Fig. 9B). Sainju et al. [86] found that N 90 and 180 kg ha^{-1} increased tomato biomass yield (dry weight of stems + leaves + fruits) and N uptake compared with N 0 kg ha^{-1} (Table 11). They found similar biomass yields and N uptake between N 90 and 180 kg ha^{-1} and concluded that N 180 kg ha^{-1} is excessive for tomato production in Georgia, USA. As a result, the higher rate of N fertilization should be discontinued to reduce the cost of N fertilization and N leaching. In an experiment on the effect of N fertilization on dry weights of tomato stems and leaves, Sainju et al. [88] found that increasing the rate of N fertilization linearly increased tomato stems and leaves dry weight and N uptake in the greenhouse and lathhouse (Table 12).

3.3.1.3. *Roots*

Nitrogen fertilization can promote tomato root growth by increasing N availability to plants. Sainju et al. [86] observed that N 180 kg ha^{-1} with moldboard plowing increased tomato root growth compared to N 0 kg ha^{-1} with moldboard plowing or to N 0 and 180 kg ha^{-1} with no-till at 26-45-cm depth (Fig. 3B). Similarly, Sainju et al. [89] found that N 90 and 180 kg ha^{-1} increased tomato root growth compared to N 0 kg ha^{-1} in 1996 and 1997 (Table 14). They found that N 90 kg ha^{-1} increased root growth as good as or better than N 180 kg ha^{-1}. They also found a strong relationship ($r = 0.82$ to 0.86, $P \leq 0.05$, n=6) between tomato minirhizotron root count and inorganic N concentration in the soil, indicating that N availability promoted root growth. In a study on the effects of hairy vetch residue and N fertilization rates on tomato root and shoot growth, Sainju et al. [88] reported that N fertilization increased length, dry weight and N uptake in tomato roots, thereby decreasing root to shoot ratio in the greenhouse and lathhouse (Table 13). Increased tomato root growth with N fertilization were also reported by several researchers [30,114,115].

3.3.2. *Soil properties*

Nitrogen fertilization increases plant biomass production. As a result, N fertilization can increase organic C and N concentrations in the soil [12,55]. Sainju et al. [91] reported that N 180 kg ha^{-1} to tomato significantly increased soil organic N compared with N 0 and 90 kg ha^{-1} after 3 yr, although it did not increase organic C (Table 4). Similarly, Sainju et al. [87] found that N fertilization to tomato increased soil organic C and N concentrations compared to no N fertilization (Table 16). Increased soil organic C and N concentrations with N fertilization to summer crops were also reported by several researchers[32,70].

Nitrogen fertilization to tomato did not influence soil PCM, although the levels varied seasonally [87,91]. In contrast, PNM and inorganic N increased immediately after N fertilization, and levels remained higher with N 180 than with 0 kg ha^{-1} throughout the tomato growth (Figs 6, 7, 10 and 11). Because 90 and 180 kg N ha^{-1} produced similar tomato yields, biomass and N uptake (Tables 3 and 11), Sainju et al. [87,91] speculated that the higher levels of PNM and inorganic N with N 180 than with 0 and 90 kg ha^{-1} at tomato harvest (Figs 6, 7, 10 and 11) may have resulted from inefficient uptake of N by tomato. Sainju et al. [84] found that residual soil N after tomato harvest in the autumn and N movement from autumn to following spring increased with increasing rate of N fertilization (Fig. 13 and Table 7). Nitrogen leaching in the groundwater increases with increased N fertilization rate [71,72,93].

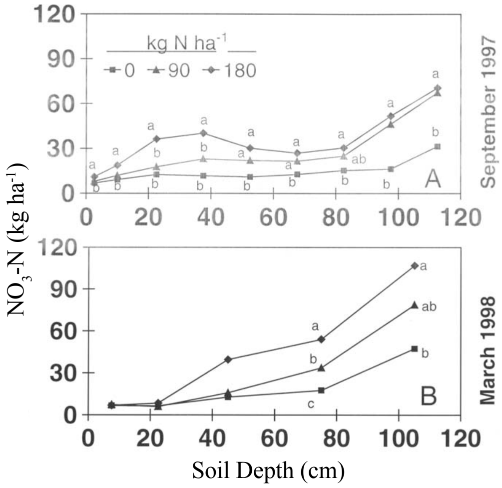

Figure 13. Soil NO_3-N with depth in the autumn (September 1997) and spring (March 1998) as influenced by N fertilization. Nitrate content at a particular depth is plotted at the mid-point of the depth range. Symbols followed by different letter at a particular depth are significantly different at $P \leq 0.05$ by the least square means test [84].

4. Sustainable Production

Because of higher demands of tomatoes, poor management practices, such as intensive tillage and heavy rate of fertilization, were used to produce large yields of tomato in the last few decades. Little attentions were paid on fertility and productivity of soil and the subsequent environmental damages. Intensive tillage and heavy rate of fertilization increased soil erosion, organic matter mineralization and soil and nutrient losses, which increasingly contaminated surface and groundwater. Similarly, excessive application of animal manures rich in N and P increased surface runoff and leaching of these nutrients, causing eutrophication in lakes and rivers. Today, agriculture contributes one of the largest sources of NO_3-N contamination in the groundwater [23,34,100]. Furthermore, higher rate of fertilization has led to the increased development of unproductive acidic soils that need to be limed heavily in order to produce a reasonable crop yield. Liming, however, adds extra cost in crop production.

Recent research in the development of management practices on tomato production suggests that improved management practices, such as conservation tillage, cover cropping and reduced rate of N fertilization, can be used not only to sustain tomato yield but also to improve soil and water quality. Conservation tillage can reduce the degradation of soil aggregates, incorporation of plant residues and loss of soil organic matter compared with conventional tillage. Cover crops can recycle soil residual N, fix atmospheric C and/or N and supply them to the soil so that C and N storage in the soil can be increased compared with no cover crops. These management practices cannot only decrease N leaching from agricultural soils and help to reduce global warming but also help to improve soil quality and productivity by influencing its physical, chemical and biological properties. Similarly, reduced rate of N fertilization can sustain tomato yields and reduce the cost of fertilization and potential for N leaching compared with full rate of N fertilization. Reduced rate of N fertilization can also increase plant biomass yield and improve soil organic matter compared with no N fertilization. A combination of conservation tillage, cover cropping and reduced rate of N fertilization is needed to sustain tomato yields, improve soil and water quality and help to reduce global warming.

Sainju et al. [85,86,91] found that, in Georgia, USA, conservation tillage, such as chisel till, produced tomato yields similar to that produced by conventional tillage, such as moldboard till. Chisel till also increased concentrations of organic C and N in the soil compared with moldboard till. No-till maintained the highest levels of organic C and N compared with chisel and moldboard till but it reduced tomato yield. Similarly, Sainju et al. [87,89] observed that legume cover crops, such as hairy vetch and crimson clover, increased tomato yields compared with nonlegume cover crops, such as rye, or no cover crop. Legume cover crops produced tomato yields equivalent to that produced by N 90 and 180 kg ha^{-1} fertilizations. While rye decreased tomato yield, it maintained the highest levels of soil organic C and N compared hairy vetch, crimson clover and N 0, 90 and 180 kg ha^{-1}. Similarly, N 90 kg ha^{-1} produced tomato yields similar to that produced by N 180 kg ha^{-1}. Sainju et al. [84] also found that chisel till reduced the movement and loss of soil residual NO_3-N relative to moldboard till under tomato but no-till increased the loss. In contrast, the movement and loss of soil residual NO_3 increased with increased rate of N fertilization. Based on these findings, it can be concluded that sustainable management practices containing a combination of conservation tillage, a mixture of legume and nonlegume cover crops and reduced rate of N fertilization can be used to sustain tomato yield, maintain soil fertility and productivity, improve water quality and help reduce global warming. Further research on the use of such management practices is needed at various locations which have mild winter that can support cover crop growth.

5. Economical Implications

Before a sustainable management practice can be implemented, it needs to be cost-effective. This means that for a farmer or producer to implement such practice, its economic benefit should outweigh the cost of using it. Although the practice may have many benefits, such as sustaining crop yields, improving soil and water quality, controlling pests and diseases, or helping to reduce global warming, its economic benefit is usually measured in terms of crop yields while ignoring other benefits. This is because of increasing difficulty and longer time required to measure those benefits. In such cases, benefits averaged across years should be used to calculate the annual returns. Other social factors, such as acceptability of practices to the growers, should also be considered before a practice is fully implemented.

A grower should know all the hidden benefits and costs associated with management practices, besides crop production. If the person does not understand the benefits, he/she should be trained. For example, the total returns from crop production systems should include returns not only from grain yields but also from the production of straw used for animal feed and litter. If the grower decides to incorporate straw into the soil, it may supply C to the soil and enrich soil C storage, which may improve soil quality and productivity. It may also help to reduce global warming by sequestering atmospheric C in the soil. In return, a person may be able to get C credit from the government when C storage in the soil improves. When conservation tillage is used, it may save money for the producers by reducing the energy required for tillage and the depreciation cost of the equipment compared conventional tillage. When a cover crop is grown, it may provide many benefits in terms of improving soil, water and environmental qualities, besides increasing crop yields. Similarly, using the reduced rate of N fertilization can reduce the cost of fertilization and N leaching. Growing cover crops, however, may have some disadvantages. For example, it may cost more to buy seeds and the extra energy required to incorporate cover crop biomass in the soil. Some places may not be suitable to grow cover crops because of harsh winter. In that case, other management practices may be used and their economic analysis evaluated. The cost of buying seeds for summer crops and cover crops, fertilizers, pesticides and equipments used for growing crops should be fully taken into account when calculating the cost/benefit ratio. The grower should be able to understand these costs and benefits when the economic analysis of a practice is evaluated.

Frye et al. [29] observed substantial economic return 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, USA. 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} fertilizer N was added, the net return of corn production with cover crop residue 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. [41] observed a greater economic return in tomato production using hairy vetch mulch than using polyethylene mulch or bare soil. Because of soil N enrichment by legumes and improving soil and water quality by nonlegumes, a mixture of legume and nonlegume cover crops may provide the highest economic returns. However, due to limited data on the use of mixed cover crop system on crop production, soil and water quality and pest and disease control, more research is needed on the use of such practice before a thorough economic analysis is made. Use of such cover crops in a conservation tillage system along with the reduced rate of N fertilization compared with conventional tillage system also needs to be economically evaluated before recommending the practice to the producers.

References

[1]Abdul-Baki, A.A. and J.R. Teasdale (1993). A no-tillage tomato production system using hairy vetch and subterranean clover mulches. *HortScience* 28:106-108.

[2]Abdul-Baki, A.A., J.R. Teasdale, R. Lorcak, D. J. Chitwood and R.N. Huettel (1996). Fresh-market tomato production in a low-input alternative system using cover crop mulch. *HortScience* 31:65-69.

[3]Agamuthu, P. and W.J. Broughton (1986). Factors affecting the development of the rooting system in young oil palms. *Agricultural Ecosystem Environment* 17:173-180.

[4]Allison, F.E. (1955). The enigma of soil nitrogen balance sheets. *Advances in Agronomy* 7:213-250.

[5]Balesdent, J.A., A. Mariotti and D. Boisgontier (1990). Effects of tillage on soil organic carbon mineralization estimated from ^{13}C abundance in maize fields. *Journal of Soil Science* 41:584-596.

[6]Bauder, J.W., G.W. Randall and R.T. Schuller (1985). Effect of tillage with controlled wheel traffic on soil properties and root growth of corn. *Journal of Soil and Water Conservation* 40:382-385.

[7]Bauder, J.W., G.W. Randall and J.B. Swan (1981). Effects of four continuous tillage systems on mechanical impedance of a clay loam soil. *Soil Science Society of America Journal* 45:802-806.

[8]Bauer, A. and A.L. Black (1994). Quantification of the effect of soil organic matter content on soil productivity. *Soil Science Society of America Journal* 58:185-193.

[9]Beattie, J.H., W.R. Beattie and S.P. Doolittle (1942). Production of tomatoes for canning and manufacturing. *Farmers Bulletin 1901*.

[10]Bhagat, J.W. and C.L. Acharya (1987). Effect of soil management on rainfed wheat in northern India. I. Hydrothermal regime and root growth. *Soil and Tillage and Research* 9:65-77.

[11]Bland, W.L. and W.A. Dugas (1988). Root length density from minirhizotron observations. *Agronomy Journal* 80:271-275.

[12]Blevins, R.L., G.W. Thomas, M.S. Smith, W.W. Frye and P.L. Cornelius (1983). Changes in soil properties after continuous non-tilled and conventionally tilled corn. *Soil and Tillage Research* 3:135-136.

[13]Box, J.E. Jr. (1996). Modern methods of root investigation. In Waisel, Y., A. Eshel and U. Kafkafi (eds). *Plant Roots: The Hidden Half*. Marcel Dekker, New York, 2nd ed, pp. 193-237.

[14]Brower, R. and C.T. de Wit (1969). A simulation model for plant growth with special attention to root growth and its consequences. In Whittington, W.J. (ed.). *Root Growth.* Butterworth, London, pp. 224-244.

[15]Buyanovsky, G.A., G.H. Wagner and C.J. Gantzer (1986). Soil respiration in a wheat ecosystem. *Soil Science Society of America Journal* 50: 338-344.

[16]Cambardella, C.A. and E.T. Elliott. (1993). Carbon and nitrogen distribution in aggregate from cultivated and native grassland soils. *Soil Science Society of America Journal* 57:1071-1076.

[17]Clark, A.J., A.M. Decker, J.J. Meisinger and M.S. McIntosh (1997). Kill date of vetch, rye, and vetch-rye mixture: II. Soil moisture and corn yield. *Agronomy Journal* 89:434-441.

[18]Clark, A.J., A.M. Decker, J.J. Meisinger, F.R. Mulford and M.S. McIntosh (1995). Hairy vetch kill date effects on soil water and corn production. *Agronomy Journal* 87:579-585.

[19]Dalal, R.C. and R.J. Mayer (1986). Long-term trends in fertility of soils under continuous cultivation and cereal cropping in southern Queensland. II. Total organic carbon and its rate of loss from the soil profile. *Australian Journal of Soil Research* 24:281-292.

[20]Doran, J.W. (1987). Microbial biomass and mineralizable nitrogen distributions in no-tillage and plowed soils. *Biology and Fertility of Soils* 5:68-75.

[21]Doran, J.W. and T.B. Parkin (1994). Defining and assessing soil quality. In Doran, J.W., D.C. Coleman, D.F. Bezdicek and B.A. Stewart (eds). *Defining Soil Quality for a Sustainable Environment.* Soil Science Society of America, Madison, WI., Special Publication 35, pp. 3-21.

[22]Errebhi, M., C.J. Rosen, S.C. Gupta and D.E. Birong (1998). Potato yield response and nitrogen leaching as influenced by nitrogen management. *Agronomy Journal* 90:10-15.

[23]Ferguson, R.B., C.A. Shapiro, G.W. Hergert, W.L. Kranz, N.L. Klocke and D.H. Krull (1991). Nitrogen and irrigation management practices to minimize nitrate leaching from irrigated corn. *Journal of Production Agriculture* 4:186-192.

[24]Food and Agriculture Organization of the United Nations (FAO) (2001). *FAOSTAT Agriculture data*. FAO, Rome, Italy.

[25]Frankenberger, W.T., Jr. and H.M. Abdelmagid (1985). Kinetic parameters of nitrogen mineralization rates of leguminous crops in corporated into soil. *Plant and Soil* 87:257-271.

[26]Franzluebbers, A.J., F.M. Hons and D.A. Zuberer (1995a). Soil organic carbon, microbial biomass, and mineralizable carbon and nitrogen in sorghum. *Soil Science Society of America Journal* 59:460-466.

[27]Franzluebbers, A.J., F.M. Hons and D.A. Zuberer (1995b). Tillage and crop effects on seasonal soil carbon and nitrogen dynamics. *Soil Science Society of America Journal* 59:1618-1624.

[28]Frye, W.W., J.H. Herbeck and R.L. Blevins (1986). Nitrogen from legume cover crops for no-tillage corn. *1986 Grain Research.* University of Kentucky, Lexington, KY.

[29]Frye, W.W., W.G. Smith and R.J. Williams (1985). Economics of winter cover crops as a source of nitrogen for no-till corn. *Journal of Soil and Water Conservation* 40:246-249.

[30]Garton, R.W. and I.E. Widders (1990). N and P preconditioning of small plug seedlings influences growth and yield of processing tomatoes. *HortScience* 25:655-657.

[31]Gould, W.A. (1983). *Tomato Production, Processing, and Quality Evaluation*. AVI Publishing Co., Westport, CT.

[32]Gregorich, E.G., B.H. Ellert, C.F. Drury and B.C. Liang (1996). Fertilization effects on soil organic matter turnover and corn residue carbon storage. *Soil Science Society of America Journal* 60:472-476.

[33]Hallberg, G.R. (1989). Nitrate in groundwater in the United States. In Follett, R.F. (ed.). *Nitrogen Management and Groundwater Protection*, Elsevier, Amsterdam, pp. 35-74.

[34]Hallberg, G. R., R.D. Libra and B.E. Hoyer (1985). *Non-point source contamination of groundwater in Karst carbonate aquifers in Iowa. Perspectives on non-point source pollution.* United States Environmental Protection Agency, Washington, D.C.

[35]Hargrove, W.L. (1986). Winter legumes as a nitrogen source for no-till grain sorghum. *Agronomy Journal* 78:70-74.

[36]Havlin, J.L., D.E. Kissel, L.D. Maddux, M.M. Claasen and J.H. Long (1990). Crop rotation and tillage effects on soil organic carbon and nitrogen. *Soil Science Society of America Journal* 54:448-452.

[37]Hu, S., N.J. Grunwald, A.H.C. van Bruggen, G.R. Gamble, L.E. Drinkwater, C. Shennan and M.W. Demment (1997). Short-term effects of cover crop incorporation on soil carbon pool and nitrogen availability. *Soil Science Society of America Journal* 61:901-911.

[38]Kaiser, E.A. and O. Heinemeyer (1993). Seasonal variations of soil microbial biomass carbon within the plough layer. *Soil Biology and Biochemistry* 25:1649-1655.

[39]Karlen, D.L., G.E. Varvel, G.E. Bullock and R.M. Cruse (1994). Crop rotations for the 21st century. *Advances in Agronomy* 53:1-45.

[40]Kaspar, T.C., H.J. Brown and E.M. Kassmeyer (1991). Corn root distributions as affected by tillage, wheel traffic, and fertilizer placement. *Soil Science Society of America Journal* 55:1390-1394.

[41]Kelly, T.C., Y.C. Lu, A.A. Abdul-Baki and J.R. Teasdale (1995). Economics of hairy vetch mulch system for producing fresh market tomatoes in the Mid-Atlantic region. *Journal of American Society of Horticultural Science* 120:854-860.

[42]Kingham, H.G. (1973). *The U.K. Tomato Manual*. Grower Books, London.

[43]Klepper, B., R.K. Belford and R.W. Rickman (1984). Root and shoot development in winter wheat. *Agronomy Journal* 76:117-122.

[44]Klepper, B. and R.W. Rickman (1990). Modeling crop root growth and function. *Advances in Agronomy* 44:113-132.

[45]Kucuk, O. (2001). Phase II randomized clinical trial of lycopene supplementation before radical prostatectomy. *Cancer Epidemiology, Biomarkers, and Prevention* 10:861-868.

[46]Kuo, S., E.J. Jellum and U.M. Sainju (1995). The effect of winter cover cropping on soil and water quality. *Proceeding Western Nutrient Management Conference,* Salt Lake City, UT, pp. 56-64.

[47]Kuo, S., U.M. Sainju and E.J. Jellum (1997a). Winter cover crop effects on soil organic carbon and carbohydrate. *Soil Science Society of America Journal* 61:145-152.

[48]Kuo, S., U.M. Sainju and E.J. Jellum (1997b). Winter cover cropping influence on nitrogen in soil. *Soil Science Society of America Journal* 61:1392-1399.

[49]Lal, R. and J.M. Kimble (1997). Conservation tillage for carbon sequestration. *Nutrient Cycling in Agroecsystem* 49:243-253.

[50]Langsdale, G.W., R.L. Blevins, D.L. Karlen, D.K. McCool, M.A. Nearing, E.L. Skidmore, A.W. Thomas, D.D. Tyler and J.R. Williams (1991). Cover crop effects on soil erosion by wind and water. In Hargrove, W.L. (ed.). *Cover Crops for Clean Water.* Soil and Water Conservation Society, Ankeny, IA, pp. 15-22.

[51]Larson, W.E., C.E. Clapp, W.H. Pierre and Y.B. Morachan (1972). Effects of increasing amounts of organic residues on continuous corn. II. Organic carbon, nitrogen, phosphorus, and sulfur. *Agronomy Journal* 64:204-208.

[52]Leskovar, D.I. and D.J. Cantliffe (1993). Comparison of plant establishment method, transplanting, or direct seeding on growth and yield of bell pepper. *Journal of American Society of Horticultural Science* 118: 17-22.

[53]Leskovar, D.I., D.J. Cantliffe and P. Stofella (1989). Pepper root growth and its relation to shoot growth in response to nitrogen. *Journal of Horticultural Science* 64:711-716.

[54]Leskovar, D.I. and P.J. Stofella. (1995). Vegetable seedling root system: Morphology, development, and importance. *HortScience* 30:1153-1159.

[55]Liang, B.C. and A.F. Mackenzie. (1992). Changes in soil organic carbon and nitrogen after six years of corn production. *Soil Science* 153:307-313.

[56]Liang, B.C. and A.F. Mackenzie. (1994). Changes of soil nitrate-nitrogen and denitrification as affected by nitrogen fertilizer on two Quebec soils. *Journal of Environmental Quality* 23:521-525.

[57]Liang, B.C., M. Remillard, and A.F. Mackenzie. (1991). Influence of fertilizer, irrigation, and nongrowing season precipitation on soil nitrate-nitrogen under corn. *Journal of Environmental Quality* 20:123-128.

[58]Linville, K,W. and G.E. Smith. (1971). Nitrate content of soil cores from corn plots after repeated nitrogen fertilization. *Soil Science* 112:249-255.

[59]Lorenz, O.A. and D.N. Maynard. (1980). *Knotts' Handbook for Vegetable Growers. 2nd ed*. Wiley Interscience, New York.

[60]Lowrance, R. and D. Smittle. (1988). Nitrogen cycling in a multiple crop-vegetable production system. *Journal of Environmental Quality* 17:158-162.

[61]McCracken, D.V., M.S. Smith, J.H. Grove, C.T. Macknown and R.L. Blevins (1994). Nitrate leaching as influenced by cover cropping and nitrogen source. *Soil Science Society of America Journal* 58:1476-1483.

[62]McVay, K.A., D.E. Radcliffe and W.L. Hargrove (1989). Winter legume effects on soil properties and nitrogen fertilizer requirements. *Soil Science Society of America Journal* 53:1856-1862.

[63]Meisinger, J.J., W.L. Hargrove, R.L. Mikkelsen, Jr., J.R. Williams and V.W. Benson. (1991). Effects of cover crops on groundwater quality. In Hargrove, W.L. (ed.). *Cover Crops for Clean Water.* Soil and Water Conservation Society, Ankeny, IA, pp. 57-68.

[64]Melton, R.R. and R.J. Dufault (1991). Tomato seedling growth, earliness, yield, and quality following pretransplant nutritional conditioning and low temperature. *Journal of American Society of Horticulture* 116:421-425.

[65]Merrill, S.D., A.L. Black and A. Bauer (1996). Conservation tillage affects root growth of dry land spring wheat under drought. *Soil Science Society of America Journal* 60:575-583.

[66]Murphy, S.L. and A.J.M. Smucker (1995). Evaluation of video image analysis and line-intercept methods of measuring root systems of alfalfa and ryegrass. *Agronomy Journal* 87:865-868.

[67]National Research Council (NRC) (1978). Occurrence and transport of nitrate in the environment. In *Nitrates: An Environmental Assessment*. National Academic of Science, Washington, D.C., pp. 103-605.

[68]Newenhouse, A.C. and M.N. Dana (1989). Grass living mulch for strawberries. *Journal of American Society of Horticultural Science* 114:859-862.

[69]Nonnecke, I.N. (1989). *Vegetable Production*. Van Nostrand Reinhold, New York.

[70]Omay, A.B., C.W. Rice, L.D. Maddux and W.B. Gordon (1997). Changes in soil microbial and chemical properties under long-term crop rotation and fertilization. *Soil Science Society of America Journal* 61:1672-1678.

[71]Owens, L.B., W.M. Edwards and P.W. Van Keuren (1994). Groundwater nitrate levels under fertilized grass and grass-legume pasture. *Journal of Environmental Quality* 23:752-758.

[72]Pang, X.P., S.C. Gupta, J.F. Moncrief, C.J. Rosen and H.H. Cheng (1998). Evaluation of nitrate leaching potential on Minnesota glacial outwash soils using the CERES-maize model. *Journal of Environmental Quality* 27:75-85.

[73]Paustian, K., O. Andren, H.H. Janzen, R. Lal, P. Smith, G. Tian, H. Tiessen, M. Van Noordwijk and P.L. Woomer (1997). Agricultural soils as a sink to mitigate CO_2 emissions. *Soil Use and Management* 13:230-244.

[74]Pierce, L.C. (1963). *Tomatoes*. Iowa State University, Ames, IA, Pamphlet No. 299.

[75]Power, J.F. and J.W. Doran (1988). Role of crop residue management in nitrogen cycling and use. In Hargrove, W.L. (ed.). *Cropping Strategies for Efficient Use of Water and Nitrogen.* American Society of Agronomy, Madison, WI, Special Publication 51, pp. 101-113.

[76]Power, J.F. and J.S. Schepers (1989). Nitrate contamination of groundwater in North America. *Agricultural Ecosystem Environment* 26:165-187.

[77]Quemada, M. and M.L. Cabrera (1995). Carbon and nitrogen mineralized from leaves and stems of four cover crops. *Soil Science Society of America Journal* 59:471-477.

[78]Rasmussen, P.E., R.R. Allmaras, C.R. Rhoade and N.C. Roger, Jr. (1980). Crop residue influences on soil carbon and nitrogen in a wheat-fallow system. *Soil Science Society of America Journal* 44:596-400.

[79]Roberson, E.B., S. Saring and M.K. Firestone (1991). Cover crop management of polysaccaride-mediated aggregation in an orchard soil. *Soil Science Society of America Journal* 55:734-739.

[80]Sainju, U.M. and R.E. Good (1993). Vertical root distribution in relation to soil properties in New Jersey Pinelands forest. *Plant and Soil* 150:87-97.

[81]Sainju, U.M. and P.J. Kalisz (1990). Characteristics of "coal bloom" horizons in undisturbed forest soils in eastern Kentucky. *Soil Science Society of America Journal* 54:879-882.

[82]Sainju. U.M. and B.P. Singh (1997). Winter cover crops for sustainable agricultural systems: Influence on soil properties, water quality, and crop yields. *HortScience* 32:21-28.

[83]Sainju, U.M., B.P. Singh and W.F. Whitehead (1998). Cover crop root distribution and its effects on soil nitrogen cycling. *Agronomy Journal* 90:511-518.

[84]Sainju, U.M., B.P. Singh, S. Rahman and V.R. Reddy (1999). Soil nitrate-nitrogen under tomato following tillage, cover cropping, and nitrogen fertilization. *Journal of Environmental Quality* 28:1837-1844.

[85]Sainju, U.M., B.P. Singh, S. Rahman and V.R. Reddy (2000a). Tillage, cover crop, and nitrogen fertilization influence tomato yield and nitrogen uptake. *HortScience* 35:217-221.

[86]Sainju, U.M., B.P. Singh, S. Rahman and V.R. Reddy (2000b). Tomato root growth is influenced by tillage, cover cropping, and nitrogen fertilization. *HortScience* 35:78-82.

[87]Sainju, U.M., B.P. Singh and W.F. Whitehead (2000c). Cover crops and nitrogen fertilization effects on soil carbon and nitrogen and tomato yield. *Canadian Journal of Soil Science* 80:523-532.

[88]Sainju, U.M., S. Rahman and B.P. Singh (2001a). Evaluating hairy vetch residue as nitrogen fertilizer for tomato in soilless medium. *HortScience* 36:90-93.

[89]Sainju, U.M., B.P. Singh and W.F. Whitehead (2001b). Comparison of the effects of cover crops and nitrogen fertilization on tomato yield, root growth, and soil properties. *Scientia Horticulturae* 91:201-214.

[90]Sainju, U.M., B.P. Singh and W.F. Whitehead (2002a). Long-term effects of tillage, cover crops, and nitrogen fertilization on organic carbon and nitrogen concentrations in sandy loam soils in Georgia, USA. *Soil and Tillage Research* 63:167-179.

[91]Sainju, U.M., B.P. Singh and W.F. Whitehead (2002b). Soil organic matter and tomato yield following tillage, cover cropping, and nitrogen fertilization. *Agronomy Journal* 94:594-602.

[92]Salinas-Garcia, J.R., F.M. Hons and J.E. Matocha (1997). Long-term effects of tillage and fertilization on soil organic matter dynamics. *Soil Science Society of America Journal* 61:152-159.

[93]Sexton, B.T., J.F. Moncrief, C.J. Rosen, S.C. Gupta and H.H. Cheng (1996). Optimizing nitrogen and irrigation inputs for corn based on nitrate leaching and yield on a coarse-textured soil. *Journal of Environmental Quality* 25:982-992.

[94]Sheenan, C. (1992). Cover crops, nitrogen cycling, and soil properties in semi-irrigated vegetable production systems. *HortScience* 27:749-754.

[95]Singh, B.P. and U.M. Sainju (1998). Soil physical and morphological properties and root growth. *HortScience* 33:966-971.

[96]Smith, M.S., W.W. Frye and J.J. Varco (1987). Legume winter cover crops. *Advances in Soil Science* 7:95-139.

[97]Staaf, H. and B. Berg (1981). Plant litter input to soil. In Clark, F.E. and T. Rosswall (eds.). *Terrestrial Nitrogen Cycles: Processes, Ecosystem Strategies, and Management Impacts.* Swedish Natural Science Research Council, Stockholm, pp. 147-162.

[98]Staben, M.L., D.F. Bezdicek, J.L. Smith and M.F. Fauci (1997). Assessment of soil quality in conservation research program and wheat fallow soils. *Soil Science Society of America Journal* 61:124-130.

[99]Stanford, G. and S.J. Smith (1972). Nitrogen mineralization potential of soils. *Soil Science Society of America Proceeding* 36:465-472.

[100]Stanley, C.D., R.E. Green, M.A. Khan and L.T. Santo (1990). Nitrogen fertilization rate and soil nitrate distribution for micro-irrigated sugarcane. *Soil Science Society of America Journal* 54:217-222.

[101]Stevenson, F.J. (1982). Origin and distribution of nitrogen in soil. In Stevenson, F.J. (ed.). *Nitrogen in Agricultural Soils.* Soil Science Society of America, Madison, WI, pp. 1-42.

[102]Stivers, L.J. and C. Sheenan (1991). Meeting the nitrogen needs for processing tomatoes through winter cover cropping. *Journal of Production Agriculture* 4:330-335.

[103]Stofella, P.J., M.L. Di Paola, A. Pardossi and F. Tognoni (1988). Root morphology and development of bell peppers. *HortScience* 23:1074-1077.

[104]Stute, J.K. and J.L. Posner (1995). Synchrony between legume nitrogen release and corn demand in the upper Midwest. *Agronomy Journal* 87:1063-1069.

[105]Teasdale, J.R. and A.A. Abdul-Baki (1995). Soil temperature and tomato growth associated black polyethylene and hairy vetch mulches. *Journal of American Society of Horticultural Science* 120:848-853.

[106]Thomas, G.W., R.L. Blevins, R.E. Phillips and M.A. McMahon (1973). Effect of a killed sod mulch on nitrate movement and corn yield. *Agronomy Journal* 65:736-739.

[107]Tollner, E.W., W.L. Hargrove and G.W. Langdale (1984). Influence of conventional and no-till practices on soil physical properties in the southern Piedmont. *Journal of Soil and Water Conservation* 39:73-76.

[108]Tyler, D.D. and G.W. Thomas (1977). Lysimeter measurements of nitrate and chloride losses from soil under conventional and no-tillage corn. *Journal of Environmental Quality* 6:63-66.

[109]United State Department of Agriculture (USDA) (1963). Composition of Foods. USDA Agricultural Handbook No. 7.

[110]University of Georgia (1995). *Commercial Tomato Production and Management.* Cooperative Extension Service, University of Georgia, Athens, GA, Bulletin 1116.

[111]Varvel, G.E. (1994). Rotation and nitrogen fertilization effects in changes in soil carbon and nitrogen. *Agronomy Journal* 86:319-325.

[112]Viets, F.G. (1965). The plant's need for and use of nitrogen. In Bartholomew, W.V. and F.E. Clark (eds.). *Soil Nitrogen*. Soil Science Society of America Journal, Madison, WI, Agronomy Monograph 10, pp. 503-549.

[113]Voorhees, W.B. (1983). Relative effectiveness of tillage and natural forces in alleviating wheel-induced soil compaction. *Soil Science Society of America Journal* 47:129-133.

[114]Weston, L.A. and B.H. Zandstra (1989). Transplant age and N and P nutrition effects on growth and yield of tomatoes. *HortScience* 24:88-90.

[115]Widders, I.E. (1989). Pretransplant treatment of N and P influence growth and elemental accumulation in tomato seedlings. *Journal of American Society of Horticultural Science* 114:416-420.

[116]Wilson, G.F., R. Lal and B.N. Okigbo (1982). Effects of cover crops on soil structure and on yield of subsequent arable crops grown on an eroded Alfisol. *Soil and Tillage Research* 2:233-250.

[117]Yadav, S.N. (1997). Formulation and estimation of nitrate-nitrogen leaching from corn cultivation. *Journal of Environmental Quality* 26:808-814.

[118]Yaffa, S., U.M. Sainju and B.P. Singh (2000). Fresh market tomato yield and soil nitrogen as affected by tillage, cover cropping, and nitrogen fertilization. *HortScience* 35:1258-1262.

[119]Clark, A.J., A. M. Decker and J.J. Meisinger (1994). Seeding rate and kill date effects on hairy vetch-cereal rye cover crop mixtures for corn production. *Agron. J.* 86:1065-1070.

[120]Ebelhar, S. A., W. W. Frye and R. L. Blevins (1984). Nitrogen from legume cover crops for no-tillage corn. *Agron. J.* 76:51-55.

[121]Huntington, T. G., J. H. Grove and W. W. Frye (1985). Release and recovery of nitrogen from winter annual cover crops in no-till corn production. *Commun. Soil Sci. Plant Anal.* 16:193-211.

[122]Chapman, H. D., G. F. Liebig and D. S. Rayner (1949). A lysimeter investigation of nitrogen gains and losses under various systems of covercropping and fertilization and a discussion of error sources. *Hilgardia* 19:57-95.

[123]Touchton, J. T., D. H. Rickerl, R. Rodriguez-Kabana and W.B. Gordon (1984). Full season and double cropped cotton as affected by tillage, starter fertilizer, in-row subsoiling, and nematicide, 1-year results. In Touchton, J. T. and R. E. Stevenson (eds). *Proc. 7th Annual Southeast No-Tillage Systems Conference.* Headland, AL 10 July 1984. Alabama Agri. Exp. Stn., Auburn Univ. Auburn, AL. pp. 54-57.

[124]Decker, A. M., Clark, A. J., Meisinger, J. J., Mulford, F. R. and McIntosh, M. S. (1994). Legume cover crop contributions to no-tillage corn production. *Agron. J.* 86. 126-135.

[125]Kamprath, E. J., Chandler, W. V. and Krantz, B. A. (1968). Winter cover crops. Their effects on corn yields and soil properties. *North Carolina Agricultural Experiment Station, Technical Bulletin* 129.

[126]Karrakar, P.E., Bortner, C. E. and Fergus, E. N. (1950). Nitrogen balance in lysimeters as affected by growing Kentucky bluegrass and certain legumes separately and together. *Kentucky Agricultural Experimental Station Bulletin* 557.

[127]Bertilsson, G. (1988).Lysimeter studies on nitrogen leaching and nitrogen balance as affected by agricultural practices. *Acta Agric. Scandi.* 38:3-11.

[128]Morgan, M. F., Jacobson, M. G. M. and LeCompte, S.B.Jr. (1942). Drainage water losses from a sandy soil as affected by cropping and cover crops. *Connecticut Agricultural Experiment Station Bulletin* 466.

[129]Volk, G. M. and Bell, C. E. (1945). Some major factors in the leaching of calcium, potassium, sulfur, and nitrogen from sandy soils: a lysimeter study. *Florida Agricultural Experiment Station Bulletin* 416.