Hairy Vetch Becomes an Alternative Basal N Fertilizer in Low-input Fresh-market Tomato Production in a Plastic High Tunnel

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In order to establish a low-input alternative production system based on cover crops, the effectiveness of hairy vetch (*Vicia villosa* Roth; HV) incorporated as a basal nitrogen fertilizer and its effects on soil carbon (C) and nitrogen (N) content in fresh-market tomato production in plastic high tunnel was investigated in Sapporo (snow cover region), Japan. The treatments consisted of HV seeding rates (HV2, 2 kg/10 a; HV5, 5 kg/10 a) and ammonium sulfate (AS10, 10 kg N/10 a) applied as basal N fertilizers, and the Non HV (control) with no HV and ammonium sulfate. In all plots, 15 kg N/10 a were added before tomato transplanting as a controlled-release fertilizer (LPS100 41%–N) to maintain the tomato growth in the mid and late stages. HV aboveground biomass (dry weight) was 585 kg/10 a in HV2 and 719 kg/10 a in HV5. Nitrate in petiole sap was higher in HV2, HV5, and AS10 plots than in Non HV plots throughout the cultivation period with the exception of the first 2 weeks after transplanting (WAT). The Growth index (GI) was higher in HV2 (47971), HV5 (46285), and AS10 (43397) than in Non HV (39847) at 7 WAT, the beginning of the harvest. Higher marketable yields were found in tomatoes grown in HV2 (6.87 t/10 a), HV5 (6.91 t/10 a), and AS10 (6.08 t/10 a), compared with the Non HV (5.19 t/10 a). The HV plots had greater soil total and organic N than AS10 and Non HV, and slightly increased soil C after tomato production. From these results, the HV seeding rate of 2 kg/10 a will be enough to support the growth of tomatoes planted after HV production if HV grows steadily in a plastic high tunnel.

Key Words: soil carbon, soil nitrogen, tomato yield, vegetative growth.

Introduction

Chemical fertilizers have been massively used in conventional fresh-market tomato production systems to obtain high yields. For instance, more than 200 kg·ha⁻¹ of N fertilizer have been recommended for fresh-market tomato production in Hokkaido (Association of agriculture improvement and extension, 2015), and in other districts of Japan such as Chiba, where a fertilizer rate of 310 kg N·ha⁻¹ has been recommended (Tanaka, 2003). Consequently, some problems such as salt accumulation occur and excessive nitrate is prone to leach and contaminate groundwater (Meisinger et al., 1991). However, concerns about reducing environmental problems, as well as the rising demand for vegetables produced with less chemical fertilizers and pesticides have become major driving forces for the development of sustainable production systems. In Japan, reduced N

input systems have been established for environmental conservation, though these systems are reliant on chemical fertilizers. Therefore, development of low-input alternative production systems based on cover crops which have more benefits beyond yield improvement, such as improvements in environmental conditions and soil quality is of great importance.

Planting cover crops before or between cash crops can improve soil properties, thereby leading to improved soil health and yield of cash crops (Araki and Ito, 1999; Hargrove, 1986; Kuo and Jellum, 2002; Kuo et al., 1997a). As a cover crop, hairy vetch (HV) serves to fix nitrogen, recycle nutrients, reduce soil erosion and compaction, and add organic matter into the soil (Abdul-Baki and Teasdale, 2007). Tomato yield and vegetative growth were greater in HV-incorporated and mulched fields, especially in HV-mulched fields, than in no-HV fields. A large amount of supplemental N fertilizer did not show a positive effect on tomato yield in HV fields (Horimoto et al., 2002). Likewise, the yield of tomato in pots with HV and reduced supplemental N fertilizer (N0HV and N80HV, 80 kg N·ha⁻¹) was com-

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parable to that in pots with the full amount of recommended N fertilizer (N240, 240 kg N·ha⁻¹) (Sugihara et al., 2013). Hairy vetch produces a large biomass rich in N and C which decompose and release high amounts of N into soil-tomato plant systems. When HV residues are incorporated in soil, a large amount of N derived from the residues (HV-N) is effectively absorbed by tomato plants within the first four weeks after transplanting (Sugihara et al., 2013). However, tomatoes are known to take up N continuously throughout the growth period (Ito et al., 1990). Thus, for sustainable tomato production using HV, additional N is required for tomato growth four weeks after transplanting. The controlled-release fertilizers such as polyolefin-coated urea S-type (LPS100) may play an important role in these systems because of their delayed and continuous N release over the whole growing season of many vegetable crops. The use of controlled-release fertilizers results in labor cost reduction with a single basal application, higher N use efficiency, and reduction in nitrate pollution (Acquaye and Inubushi, 2004; Shoji and Kanno, 1994; Shoji et al., 1991). Therefore, a combination of HV and controlled-release fertilizer is seen to be a suitable management practice in low-input systems.

There are very limited studies on the impact of HV in tomato production in plastic high tunnels. The results from outdoor tomato production with HV (Abdul-Baki et al., 1997; Horimoto et al., 2002; Kumar et al., 2005; Lu et al., 2000) indicated positive effects of HV on growth and yield of tomatoes, and the results from pot examination using HV-incorporated highlighted the possibility of N input reduction with the use of HV (Sugihara et al., 2013). The reduction of N fertilizer input is very important for sustainable tomato production, whereas the positive results reported previously were not obtained in field conditions, which are more complex and variable than pot soil. Additionally, the effects of HV-incorporated on soil C and N were not investigated. The research hypotheses were: a) the incorporation of HV may promote vigorous growth,

especially in the early growth stages, high yield and increased soil carbon and nitrogen; b) the positive effects of HV on tomatoes will be higher or similar to those of ammonium sulfate used in conventional systems. The present study was conducted to evaluate the effectiveness of HV-incorporated as a basal N fertilizer and its effects on soil C and N in tomato production under plastic high tunnel conditions.

Materials and Methods

Site and experimental design

The experiment was conducted at the Experimental Farm, Field Science Center for Northern Biosphere, Hokkaido University, Sapporo (snow cover region), Japan, from March to October 2015 (Table 1). The soil of the site is Andisol with a clay loam texture, and its chemical composition was as follows: 3.14 mg NO₃⁻-N, 0.84 mg NH₄⁺-N, 42.9 mg K₂O, 204 mg CaO, 60.5 mg MgO, and 12.7 mg P₂O₅ (Truog-L method) per 100 g dry soil taken at 0–15 cm depth before the examination. Soil pH (water, 1:2.5) and EC (1:5) were 5.8 and 42.1 mS·m⁻¹, respectively. The treatments consisted of two HV seeding rates, HV sowed at 5 kg/10 a (HV5) and 2 kg/10 a (HV2); ammonium sulfate fertilizer applied as basal N at a rate of 10 kg N/10 a (AS10) and Non HV (control; no ammonium sulfate or HV residues was applied in it). Additionally, controlled-release N fertilizer (LPS100 41%-N; JCAM AGRI. Co., Ltd., Tokyo, Japan) was added in all plots at rate of 15 kg N/10 a before tomato transplanting to supply N and maintain tomato growth in the mid and late stages. The LPS100 fertilizer is a 30 to 40-day delayed-release in water at 25°C, and then 100 days release of 80% of its total N, following a sigmoid pattern (Acquaye and Inubushi, 2004; Shoji and Kanno, 1994). The treatments were arranged in a randomized block design in three replicates.

Field preparation and chemical fertilizer application

Soil was tilled by a rotary cultivator and then the beds were raised on March 23 in 2015. The beds were

Table 1. Field operations carried out from March to October in 2015.

Month/Date	Operations
March 12	Sowing of tomato rootstock and scion cultivars
March 24	Sowing of HV
April 16	Grafting of tomato seedlings
May 29	Mowing, measurement of biomass, and chopping of HV
May 30	Incorporation of HV and chemical fertilizers
June 1	Transplanting of tomato seedlings
June 15–August 10	Measurement of nitrate in petiole sap every 2 weeks
June 15–August 24	Measurement of inorganic N every 2 weeks
June 22–August 17	Measurement of the tomato growth index every 2 weeks
July 20–September 25	Tomato harvesting every 2–3 days
October 9	Measurement of soil C and N content

spaced 1.5 m center to center and the experimental elementary plot size was 2.4 m² (3.0 m × 0.8 m). Hairy vetch ('Mamesuke', non-overwintering cultivar; Snow Brand Seed Co., Ltd., Hokkaido, Japan) was manually sown and superficially buried just after formation of beds on March 24. The soil in Non HV and AS10 plots was left bare throughout the HV growing period; spontaneous weeds were removed by hand. HV was irrigated as needed by hand using an irrigation tube. When HV was at the flowering stage (Fig. 1), on May 29, the whole aboveground biomass was mowed 2–3 cm above soil surface by hand. Soon after, the HV biomass was weighed, and then chopped into small pieces (about 10 cm length) for easy incorporation into the soil.

Chemical fertilizers were applied and incorporated with HV residues on May 30. Ammonium sulfate (21% -N) was applied only in AS10 plots, and 20 kg/10 a of P₂O₅ as fused magnesium phosphate and 20 kg/10 a of K₂O as potassium sulfate were added in all plots.

Tomato cultivation

The seeds of the fresh-market cultivar 'Reika' and rootstock cultivar 'Friendship' were sown in sowing boxes on March 12, and seedlings were grafted using a tube grafting method on April 16. Grafted seedlings were transferred into plastic pots of 12 cm diameter. About two-month-old tomato seedlings were transplanted in plots on June 1 when the florets in the first cluster begin to bloom. Each plot contained 12 plants of which 8 in the core site were experimental plants and two in each edge were border plants. The planting density was 2667 plants/10 a with 0.5 m between tomato lines and 0.5 m between plants. After tomato transplanting, drip irrigation was installed to water the tomatoes; irrigation was carried out 2–3 times a week and was finished on September 25 after the last harvesting. For trellising of tomato plants, a hanging-string system was established at 2 weeks after transplanting (WAT). Lateral shoots were removed as they appeared allowing only the main shoot to grow and pollination occurred natu-

rally. Fruits were collected from 1 to 8 clusters, and only four fruits were allowed to set in each cluster. Pesticides were applied 2 times to prevent sucking pest infestation and to control fruit worms and late blight. Weeds were removed by hand.

Aboveground biomass, carbon, and nitrogen content of hairy vetch

Aboveground biomass yield of HV (fresh weight) was determined just after mowing, using a total plot area, 2.4 m². Soon after, HV residues were collected and oven dried at 60°C until a constant weight in order to determine their dry weight, and the C and N contents were determined by means of an elemental analyzer (Vario EL III; Elementar, Hanau, Germany). The dried residues were ground finely, and 10 mg was weighed in Sn-foil capsules for analyses using three samples in each treatment.

Soil carbon, nitrogen, and temperature

In order to investigate the effects of HV and chemical fertilizer on soil inorganic nitrogen and soil total C and N, soil was collected from 0–15 cm depth at three points in each plot and then well mixed. As a result, one sample was prepared in each plot and three samples were collected from each treatment. The soil samples were dried at room temperature, and sieved with 2 mm mesh. Soil inorganic nitrogen (NO₃⁻-N + NH₄⁺-N) was measured by using a soil analyzer (ZA-II Zen-noh; National Federation of Agricultural Cooperative Associations, Tokyo, Japan). NO₃⁻-N and NH₄⁺-N were measured by the alkali reduction-diazotization and indophenol methods, respectively. The soil total C and N were determined using an elemental analyzer (Vario EL III; Elementar). 20 mg of minced dry soil were weighed in Sn-foil capsules and then analyzed. Organic nitrogen was calculated as follows: Organic nitrogen = total nitrogen – inorganic nitrogen. The soil samples for inorganic nitrogen analyses were collected 7 times, at 0, 2, 4, 6, 8, 10, and 12 WAT, while the samples for total C

Fig. 1. Hairy vetch growing in the plastic high tunnel, May 29 in 2015 (1); and tomatoes growing in bare and HV plots in the plastic high tunnel, June 29 in 2015 (2).

and N analyses were collected before and after tomato cultivation.

Soil and air temperatures of the plastic high tunnel were measured and recorded with the aid of a data logger (midi Logger GL800; Graphtec Co., Yokohama, Japan) every hour from the establishment of HV until the end of tomato cultivation. Three sensors were set at 15 cm soil depth at three different positions in the plastic high tunnel. Similarly, three other sensors were set at 1.5 m to measure air temperature around tomato plants.

Nitrate concentration in leaf petioles

The nitrate concentration in the leaf petioles just below the first cluster was determined by means of a reflection photometer RQ flex (Merck Co., Ltd., Darmstadt, Germany). One gram of petioles was macerated with 49 mL of deionized water (Sakaguchi et al., 2004), and the diluted solution was used for analyses. The leaf petiole samples were collected four times, at 2, 4, 8, and 10 WAT.

Tomato growth and yield

The growth index [GI = Plant length (cm) × Number of expanded leaves × Stem diameter (mm)] (Soma, 1993) was measured using 4 plants in each plot at 7 WAT (July 20), at the beginning of the harvest. The stem diameter was measured 2–3 cm above the grafted portion, while plant length was measured from the grafted portion to the last expanded leaf of the growing tip, and then the number of completely expanded leaves was collected by counting. Tomato yield was determined using mature tomatoes (red-ripe fruits) harvested from 8 plants per plot every 2–3 days from July 20 to September 25. Fruits with no physiological disorders (cracking, scarring, misshapen fruit, blossom-end rot) and weight over 100 g were considered marketable fruits.

Statistical analyses

All tomato and soil characteristics were subjected to statistical analyses using R software, and mean values were evaluated at 5% probability of significance using Tukey's test. However, for HV, mean values were evaluated using the *t*-test. Values represent the mean of three replications.

Results and Discussion

Soil and air temperature

Soil temperature at the root zone (15 cm depth) and air temperature were recorded (Table 2). The monthly mean air temperatures varied from 17.8°C in May to a maximum of 25.1°C in July. However, the monthly mean soil temperatures were more stable, varying from 18.2°C in May to 23.5°C in August. Generally, temperatures were lower by mid-June and higher in July and August, compared with ordinary years. The soil and air temperature in the plastic high tunnel observed in June, July, and August were suitable for tomato cultivation. The optimum root temperature for mineral uptake and tomato growth is 20°C to 30°C (Maletta and Janes, 1987; Teasdale and Abdul-Baki, 1995; Tindall et al., 1990), while the optimum air temperature is 18°C to 25°C (Heuvelink and Dorais, 2005).

Aboveground biomass of hairy vetch

The HV grew for 64 days, and was mowed in late May. At the mowing time, some plants were flowering. Aboveground biomass weights (dry weight) of HV at seeding rates of 2 kg/10 a and 5 kg/10 a were 585 kg/10 a and 719 kg/10 a, respectively (Table 3). The C:N ratio was lower than 20 which suggested rapid decomposition of organic residues after incorporation into the soil (Brady and Weil, 2007).

Soil carbon and nitrogen

The HV plots had slightly lower soil inorganic nitrogen (SIN) at week 0, before transplanting (Fig. 2). The AS10 and HV5 plots exhibited higher SIN (8.95 mg/

Table 2. Mean air and soil temperature in the plastic high tunnel measured during hairy vetch and tomato cultivation in 2015.

Month	Mean temperature (°C)	
	Air ^z	Soil ^y
May	17.8	18.2
June	18.6	20.5
July	25.1	22.3
August	24.2	23.5

^z Air temperature measured at 1.5 m height.

^y Soil temperature measured at 15 cm depth.

Table 3. Aboveground biomass, carbon, and nitrogen content of hairy vetch.

Hairy vetch ^z	Fresh weight ^y (kg/10 a)	Dry weight (kg/10 a)	N content (%)	N incorporated (kg/10 a)	C:N ratio
HV2	5850	585	4.3	25.2	9.6
HV5	7190	719	4.3	30.9	9.6
<i>t</i> -test	NS ^x	NS	—	NS	—

^z HV2, hairy vetch sowed at a seeding rate of 2 kg/10 a; and HV5, hairy vetch sowed at a seeding rate of 5 kg/10 a.

^y Measured just after moving of hairy vetch using a total plot area of 2.4 m².

^x NS: not significant.

100 g and 5.44 mg/100 g, respectively) compared with other treatments at 2 WAT. However, the SIN in HV2 plots was found to be lower at 2 WAT and then increased until 6 WAT. As expected, ammonium sulfate in the AS10 plots released N rapidly after application into the soil (Schnier et al., 1987). Its effects were seen until 4 WAT and after that period its SIN levels were comparable to that of the Non HV plots until the end of measurement period. Although all plots showed a decreasing trend, generally SIN in HV plots tended to be higher compared with Non HV and AS10 plots throughout the measurement period. This pattern suggests that although much of its N was released in the first 4–6 weeks after application, the N release continued for long period due to decomposition of residues that were initially resistant to microbial degradation (Hue and Silva, 2000). In this regard, Sugihara et al. (2016) reported that HV applied in the previous year contributed slightly to the tomato growth when planted in the following year, especially in the early growth stages. The increased SIN in the first weeks after residue incorporation may indicate that HV is suitable to be used as a nitrogen source for the early growth stages of tomatoes.

Before tomato cultivation, the total and organic nitro-

Fig. 2. Inorganic nitrogen concentration in soil during tomato cultivation. Vertical bars represent standards errors ($n = 3$). Means followed by the same letters in each week are not significantly different at 5%, Tukey's test. NS: not significant.

gen were higher in Non HV (285 mg/100 g and 280 mg/100 g) and AS10 plots (277 mg/100 g and 272 mg/100 g) compared with HV2 (263 mg/100 g and 259 mg/100 g) and HV5 plots (251 mg/100 g and 247 mg/100 g) (Table 4). However, after tomato cultivation, total and organic nitrogen were higher in HV and lower in Non HV and AS10 plots. In comparison with the period before tomato cultivation, soil organic nitrogen increased by 14.3% and 7.29% in HV2 and HV5, whereas it decreased by 9.93% and 18.2% in AS10 and Non HV, respectively, after tomato cultivation. Similarly, soil carbon increased by 0.34% and 0.40% in HV2 and HV5 plots, respectively. In contrast, soil carbon decreased by 0.50% and 1.37% in AS10 and Non HV plots, respectively. The increased soil carbon with the HV treatments may have resulted from the incorporation of their residues into the soil (Sainju et al., 2000). Sainju et al. (2015) also reported an increase in soil organic carbon and soil total nitrogen with cover crops (hairy vetch, rye, and hairy vetch + rye) at 0–30 cm depth under sorghum cultivated as a bioenergy crop. In this study, HV was more effective in increasing soil organic and total nitrogen than soil carbon. These results were consistent with those reported in previous studies (Kuo et al., 1997a, b; Sainju et al., 2003).

Nitrate concentration in leaf petioles

The nitrate concentration in petiole sap was higher in HV and AS10 plots compared with Non HV at 4, 8, and 10 WAT (Table 5). No differences among means were observed at 2 WAT. The highest nitrate in petiole sap was observed at 4 WAT in HV5, HV2, and AS10 plots (4775 mg·L⁻¹ for HV5, and 4492 mg·L⁻¹ for HV2 and AS10), and then decreased after 10 WAT. The nitrate concentration in petiole sap is one of the indicators of vegetative growth in tomatoes and is used to determine topdressing time because nitrate concentration in soil is reflected in that of petiole sap (Horimoto et al., 2002). In addition, nitrate concentration reflects the nutrient status of the whole plant and the probable yield of almost all crops (Tanaka, 2003). In this study, nitrate con-

Table 4. Effect of hairy vetch and chemical fertilizer on soil carbon and nitrogen after tomato cultivation.

Treatments ^z	Before tomato cultivation				After tomato cultivation				Organic nitrogen change ^x (%)	Carbon change ^w (%)
	Nitrogen (mg/100 g)			Total carbon (%)	Nitrogen (mg/100 g)			Total carbon (%)		
	Inorganic	Organic	Total		Inorganic	Organic	Total			
Non HV	5.06 (0.19) a ^y	280 (4) a	285 (4) a	6.48 (0.17)	1.86 (0.08) c	229 (3) c	231 (3) c	5.11 (0.10)	−18.2	−1.37
AS10	5.18 (0.21) a	272 (3) a	277 (3) a	6.07 (0.39)	1.82 (0.11) c	245 (6) bc	247 (6) bc	5.57 (0.09)	−9.93	−0.50
HV2	3.63 (0.56) b	259 (9) ab	263 (9) ab	5.85 (0.16)	2.62 (0.08) b	296 (7) a	299 (7) a	6.19 (0.46)	14.3	0.34
HV5	3.95 (0.13) ab	247 (6) b	251 (6) b	5.77 (0.19)	3.26 (0.04) a	265 (2) ab	268 (2) ab	6.17 (0.38)	7.29	0.40

^z Plots of HV2 and HV5 incorporated hairy vetch sowed at seeding rate of 2 and 5 kg/10 a, respectively; AS10 was fertilized with 10 kg N/10 a of ammonium sulfate; and Non HV (control) had no HV and ammonium sulfate.

^y Means followed by same letters are not significantly different at 5%, Tukey's test. Brackets indicate standard errors ($n = 3$).

^x Calculated as follows: (A-B)/B; A—after tomato cultivation, B—before tomato cultivation.

^w Difference of soil carbon after and before tomato cultivation.

Table 5. Nitrate concentration in leaf petioles just below the first cluster during tomato cultivation.

Treatments ^z	Nitrate in petiole sap (mg·L ⁻¹)			
	WAT ^y			
	2	4	8	10
Control	2867 (93)	3417 (220) b ^x	2025 (75) b	trace ^w
AS10	3000 (58)	4492 (110) a	4050 (86) a	2850 (29) b
HV2	2733 (130)	4492 (156) a	4283 (159) a	3987 (79) a
HV5	2550 (76)	4775 (14) a	3933 (72) a	3525 (52) a

^z Plots of HV2 and HV5 incorporated hairy vetch sowed at seeding rates of 2 and 5 kg/10 a, respectively; AS10 was fertilized with 10 kg N/10 a of ammonium sulfate; and the Non HV (control) had no HV and ammonium sulfate.

^y Weeks after transplanting. Brackets indicate the standard errors (n=3).

^x Means followed by the same letters in each week are not significantly different at 5%, Tukey's test.

^w Nitrate concentration less than 250 mg·L⁻¹.

Fig. 3. Effect of hairy vetch and chemical fertilizer on plant length. Vertical bars represent standard errors (n = 3). Means followed by the same letters in each week are not significantly different at 5%, Tukey's test. NS: not significant.

Fig. 4. Effect of hairy vetch and chemical fertilizer on the number of expanded leaves. Vertical bars represent standard errors (n = 3). Means followed by the same letters in each week are not significantly different at 5%, Tukey's test. NS: not significant.

centration was close to the minimum level of the optimal nitrate values (4000 to 7000 mg·L⁻¹) suggested by Sakaguchi et al. (2004) at 4 to 8 WAT in HV and AS10 plots. Thus, HV and AS10 plots exhibited nitrate values within the proper range for one month. After 8 WAT, nitrate concentration in leaf petiole sap decreased rapidly in AS10, but nitrate sap in HV plots was still close to 4000 mg·L⁻¹. Therefore, HV may contribute to reduce N input from chemical fertilizers. Although controlled-release fertilizer (LPS100) was applied to all plots, the nitrate concentration in Non HV plots was below the detection limit of 250 mg·L⁻¹ at 10 WAT; in contrast, AS10 plots exhibited a higher nitrate concentration until the end of the measurement period. One possible reason for this discrepancy may be the quick senescence of the lower leaves used for analyses in Non HV plots, probably due to a lower N concentration in soil in the first 4 WAT compared with AS10 plots.

Growth index and tomato yield

Plant length increased vigorously over the period of measurement, especially in HV plots (linear trend) (Fig. 3). However, the effect of the treatments was not significant at 3 to 5 WAT, and after that period, plant

length in HV plots was longer than in AS10 and Non HV plots. Although no significant difference was seen in the initial 5 WAT, plant length tended to be longer in AS10 and HV plots (125 cm in AS10, 120 cm in HV2, 118 cm in HV5), especially in AS10 than in Non HV plots (113 cm). Similarly, the number of expanded leaves increased linearly during the measurement period, especially for HV (Fig. 4). There was no significant difference in two sampling dates (7 and 11 WAT). Overall, the tomatoes in HV plots displayed a higher number of expanded leaves compared with AS10 and Non HV plots. The effect of HV and AS10 on GI was statistically significant at 7 WAT (July 20) (Table 6). The GI values were 47971 and 46285 in HV2 and HV5, higher than 43397 and 39847 in AS10 and Non HV plots, respectively. It is necessary to ensure a GI of 40000–70000 at the beginning of harvesting time to obtain an average yield (Fujiwara, 2000; Soma, 1993). The GI in HV and AS10 plots was over 40000, and within the recommended range at the beginning of the harvest on July 20. Horimoto et al. (2002) reported similar results. Tomato growing in plots incorporating HV with supplemental N fertilizer showed higher GI (GI over 40000) than non-HV plots with similar supplemental N fertil-

Table 6. Effect of hairy vetch and chemical fertilizer on the growth index at 7 WAT, the beginning of the harvest.

Treatments ^z	GI ^y
Non HV	39847 (386) c ^x
AS10	43397 (1303) b
HV2	47971 (462) a
HV5	46285 (1348) ab

^z Plots of HV2 and HV5 incorporated hairy vetch sowed at seeding rates of 2 and 5 kg/10 a, respectively; AS10 was fertilized with 10 kg N/10 a of ammonium sulfate; and the Non HV (control) had no HV and ammonium sulfate.

^y Growth index was calculated as a product of plant length, number of expanded leaves, and stem diameter.

^x Means followed by the same letters are not significantly different at 5% Tukey's test. Brackets indicate the standard errors (n=3).

izer at the beginning of the harvest on July 6. The increased plant length, number of expanded leaves, and stem diameter (data not shown) or GI in HV plots compared with AS10 and Non HV plots suggest that HV-N promotes tomato growth more effectively.

Similar and higher marketable yields were observed in HV plots, 6.87 t/10 a in HV2 and 6.91 t/10 a in HV5, respectively. The next higher marketable yield was 6.08 t/10 a in AS10, and the lowest was observed in Non HV plots, 5.19 t/10 a. However, unmarketable yields were not statistically different; 0.67 t/10 a in HV2, 0.41 t/10 a in HV5, 0.61 t/10 a in AS10, and 0.63 t/10 a in Non HV plots (Fig. 5). Increased tomato yield with HV than with no HV was reported in previous studies (Kumar et al., 2005; Sainju et al., 1999; Teasdale and Abdul-Baki, 1997).

The results of the present study clarified that besides the benefits of HV on plant growth and tomato yield previously reported, incorporation of its residues into the soil may increase soil carbon and nitrogen in the short-term. Therefore, HV is an important biological tool for sustainable tomato production systems because it produces a large biomass rich in N with a low C:N ratio that decomposes rapidly and releases N to tomatoes, thereby reducing the N fertilizer input. Additionally, it improves yield and soil quality.

In conclusion, the incorporation of HV residues in soil reduced N input in 38%, even though good vegetative growth and high marketable yield were obtained. Under plastic high tunnel conditions, HV residues effectively increased soil organic nitrogen, and slightly increased soil carbon. Thus, the research hypotheses were fully supported by the data. HV may be used as an alternative basal N fertilizer, and the combination of HV with controlled-release fertilizer may be one of the better strategies for fresh-market tomato production in low-input alternative systems because of its agronomic, economic, and environmental merits.

Further research is needed on HV (incorporated and mulched) effects on soil physical and biological proper-

Fig. 5. Effect of hairy vetch and chemical fertilizer on marketable and unmarketable yields. Vertical bars represent standard errors (n = 3). Means followed by the same letters are not significantly different among treatments at 5%, Tukey's test. NS: not significant.

ties, as well as on nitrate leaching and greenhouse gas emissions in fresh-market tomato production systems. Additionally, research on the N release pattern from LPS100 in soil and its effectiveness in tomato production is needed because LPS100 was designed for rice production in paddy fields, and also considering the cool climate of Hokkaido, north part of Japan.

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