Evaluation of Mixed Cropping of Oat and Hairy Vetch as Green Manure for Succeeding Corn Production

Arata Tarui, Atsushi Matsumura, Sohei Asakura, Kenji Yamawaki, Rintaro Hattori and Hiroyuki Daimon

(Graduate School of Life and Environmental Sciences, Osaka Prefecture University, 1-1, Gakuen, Naka, Sakai 5998531, Japan)

Abstract: Legume-grass mixed cropping may alleviate N starvation when incorporated as grass green manure which has a higher C/N ratio than legume manure. We focused on N and P absorption of oat in mixed cropping with hairy vetch, and investigated the effect of the mixed-cropping green manure on the growth and nutrient uptake of the succeeding corn. The total N and total P contents of oat mixed-cropped with hairy vetch were higher than those of sole-cropped oat, and dry weight in addition to N and P contents of oat were greatly increased by cutting mixed-cropped hairy vetch before blooming. Sole cropping of hairy vetch was the best green manure to enhance the growth and nutrient uptake of the succeeding corn crop, but mixed cropping of oat with hairy vetch was also highly effective. Further investigations are needed to determine the long-term effect of mixed cropping green manure on N and P sequestration as soil organic matter.

Key words: C/N ratio, Crop rotation, Grass, Legume, Nitrogen fixation, Nitrogen transfer, Phosphorus uptake.

On-site field grown green manure is a labor-and money-saving organic fertilizer considering the handling and transportation costs of conventional composts and farmyard manures. When enough maturation days have elapsed after incorporation, the succeeding crops can be supplied with much of the nutrients derived from the manure. We evaluated the positive effects on nutrient supply from summer and winter leguminous green manure crops such as *Crotalaria*, *Sesbania*, and hairy vetch (Yano et al., 1994; Ohdan and Daimon, 1998; Daimon and Kotoura, 2000; Uratani et al., 2004; Daimon, 2006; Choi and Daimon, 2008; Choi et al., 2008). These green manure legumes also reduce soil erosion (Gomez et al., 2009) and nutrient losses (Rosecrance et al., 2000), and suppress weeds (Kamo et al., 2003; Brennan et al., 2009) and parasitic nematodes (LaMondia, 2006). Thus, green manure is recently recognized as an important constituent of the environmentally friendly farming system.

Besides leguminous crops, various gramineous crops are also used as green manure. Gramineous green manure crops such as oat and rye can significantly reduce nitrogen (N) leaching from arable land, and contribute to conserve soil organic matter and maintain soil physical properties (Kuo et al., 1997; Astier et al., 2006). However, gramineous green manure crops generally provide little N to the succeeding crop, and often cause nitrogen starvation for succeeding crop growth. Because of the relatively high carbon to nitrogen ratio (C/N ratio) of gramineous crops, N immobilization in the soil often limits plant usable N during decay of the incorporated plant materials. Though N starvation of the succeeding crop could be avoided by applying chemical N fertilizer soon after incorporation, additional chemical fertilization would be undesirable for these farming systems. Leguminous green manure crops such as vetch and clover associated with rhizobia symbiotically fix atmospheric N and increase available N in the soil. However, since legumes have a relatively low C/N ratio, gramineous green manure crops are expected to contribute more to conservation of soil organic matter and soil physical properties.

The legume-grass combination has been used in several mixed cropping systems including forage and cover crops (Karpenstein-Machan and Stuelpnagel, 2000; Rauber et al., 2001; Ramos et al., 2011). Generally, grasses in mixed cropping with legumes uptake more N than in sole cropping, because of transfer from rhizodeposit-N of legume to the associated grass (Xiao et al., 2004; Rasmussen et al., 2007). Furthermore, cutting the aboveground parts of the legume during the vigorously growing stage may increase the transfer of N from the legume to the associated grass through turnover of roots and root nodules (Chesnut et al., 1980; Daimon and
Thus, the legume-grass mixed cropping system may alleviate N starvation by incorporating grass green manure crops with a higher C/N ratio.

Practical cultivation methods to establish the effective cover cropping system using mixed cropping of grasses and legumes for sustainable agriculture in North America, such as different tillage patterns have been reported (Ruffo and Bollero, 2003; Sainju et al., 2005). However, few studies have been available on dynamics of nutrients between grasses and legumes in the mixed cropping of green manure crops. There has also been little information on the effect of mixed cropped green manures on the growth and nutrient uptake of the succeeding crops. Especially in Japan, the low input production system is recently gathering concern because of the rising cost of chemical fertilizers and the requirement of sustainable soil productivity. Therefore, green manure of mixed grasses and legumes should be evaluated as both readily available and slow release organic fertilizers for several crops.

In this study, we focused on mixed cropping of hairy vetch and oat crops, which have recently been used as winter green manure crops, and evaluated their effect on N and phosphorus (P) uptake of the succeeding summer forage corn crop. We also investigated the effect of cutting hairy vetch shoots during the vigorously growing stage of oat on the alteration of C/N ratio of oat grown as green manure.

Materials and Methods

1. Experimental site

The experiments were carried out in 2009 – 2010 at the Experimental Farm of Osaka Prefecture University in Sakai, Osaka, Japan. The soil on the farm was gray lowland soil. The soil pH, EC, concentration of inorganic N, total N, Truog-P, total P, and total carbon (C) were measured before sowing (Table 1). The previous crop was squash (Cucurbita maxima Duch) plants.

2. Experimental design and measurements

The experiment was laid out in a randomized complete block design with four treatments and three replications. Four treatments were as follows; sole cropping of oat (Avena sativa L. cv. Endax) (Sole Oat) and hairy vetch (Vicia villosa Roth cv. Mamekko) (Sole Vetch), mixed cropping of oat and hairy vetch (Mix), and mixed cropping of oat and hairy vetch which was cut before blooming (Mix + Cut). Each plot size was 1.8 × 3.6 m. The seeds were sown by hand in 6 rows with an inter-row distance of 25 cm and inter-hill distance of 10 cm on 4 December 2009. The seeding density was 4.3 g m⁻² and 2.9 g m⁻² for oat and hairy vetch in Sole Oat plot and Sole Vetch plots, respectively. For Mix and Mix + Cut plots, each crop was sown alternately in 6 rows in the plot, consisting of 3 rows of hairy vetch and 3 rows of oat, and the seeding density of each crop was half that of sole cropping. No fertilizer was applied.

In the Mix + Cut plot, hairy vetch was cut on 10 April 2010. The shoots were removed from the plot to investigate the effect of belowground residue of hairy vetch, which had many root nodules showing higher N₂ fixing activity, on the growth of the associated oat. During the growing periods, the SPAD value of the second expanded leaf of oat was measured using a chlorophyll meter (SPAD-502, Konica-Minolta Sensing, Japan) and stems were counted at approximately 10-day intervals from 3 March 2010. Leaf area index (LAI) of each plot was measured before blooming (8 April) and during blooming (1 May) of hairy vetch by using a plant canopy analyzer (LAI-2000 Plant Canopy Analyzer, LI-COR Inc., USA). Shoots of 6 oat plants grown in the middle rows of the Sole Oat and Mix plots were randomly sampled before blooming of hairy vetch to measure dry weight and N and P contents.

On 13 May 2010, shoots of oat and hairy vetch grown in all the plots were harvested, cut into about 5 cm pieces and then incorporated as green manure in each plot. Before incorporated as green manure, plants were weighed and mixed thoroughly. About 20% of total fresh weight was sampled as subsamples for analysis of C, N and P contents and also for the litter bag experiment described below. They were dried at 70°C for 48 hours, weighed and ground. Total C and N contents were measured using an NC analyzer (Vario MAX CN; Elementar Analysensysteme GmbH, Germany). For total P content, they were ashed in a muffle furnace at 550°C and determined by the vanado molybdate colorimetric method.

To collect the soil solution, we set porous cups (Mizu-Toru, Daiki Rika Kogyo, Japan) at 20 cm depth from the soil surface in each plot and collected the soil solution at about 5-day intervals after incorporating green manure. Inorganic N concentration (NO₃-N and NH₄-N) in soil solution was determined by Conway's micro-diffusion method (Conway, 1947). We evaluated the rate of decomposition of the green manure using the modified litter bag method (Maeda and Onikura, 1977; Muhr et al., 1999). A 30 g aliquot of each green manure, which had been cut into 5 cm was weighed accurately and dried at

| Table 1. Soil chemical properties at the experimental farm. |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| pH (H₂O)        | EC (dS m⁻¹)     | Inorganic N (mg kg⁻¹) | Total N (g kg⁻¹) | Truog-P (g kg⁻¹) | Total P (g kg⁻¹) | Total C (g kg⁻¹) |
| 6.8             | 0.06            | 13.5             | 2.25             | 1.05             | 3.63             | 23.4             |

Chujo, 1986a, 1986b; Paynel et al., 2001; Paynel and Cliquet, 2003).
70°C for 48 hours. It was then packed in a nonwoven fabric bag (31 x 35 cm) (litter bag) and then embedded at 10 cm depth from the soil surface on 25 May. Eight bags were embedded in each of Sole Oat, Sole Vetch, Mix and Mix + Cut plots. After 38, 68, 108, and 123 days of embedding, dry weight and contents of total N and C in the bag were determined.

After 20 days of incorporating green manure, 2 June 2010, seeds of corn (Zea mays L. cv. Gold-dent KD850) were sown by hand in 4 rows with inter-row distance of 40 cm and inter-hill distance of 20 cm in each plot. SPAD value of the second leaf below the uppermost expanded leaf and plant length were measured about every 10 days from 22 June. Five corn plants in each plot were randomly sampled on 22 September (112 days after sowing). They were dried, weighed and ground to determine total N and P contents.

3. Estimation of yields in mixed cropping

In order to estimate the effect of mixed cropping, we assessed the advantage of each component crop in the mixed cropping compared with the sole cropping by calculating the relative yield (RY) (Caballero et al., 1995; Rauber et al., 2001; Lithourgidis et al., 2006) as follows;

\[
RY (\text{oat}) = \frac{\text{Yield of oat in the mixed cropping}}{\text{Yield of oat in the sole cropping}}
\]

\[
RY (\text{hairy vetch}) = \frac{\text{Yield of hairy vetch in the mixed cropping}}{\text{Yield of hairy vetch in the sole cropping}}
\]

where 'Yield' is dry weight, N content, and P content at the harvesting time on 13 May. RY > 0.5 indicates positive effect on yields in the mixed cropping plot, and RY < 0.5 indicates a disadvantage by the mixed cropping.

Furthermore, in the evaluation of mixed cropping for green manure production, the advantage compared to sole cropping was assessed by calculating the relative yield total (RYT) (Caballero et al., 1995; Rauber et al., 2001; Lithourgidis et al., 2006) as follows;

\[
RYT = RY (\text{oat}) + RY (\text{hairy vetch})
\]

RYT > 1 indicates a positive effect on yield of the mixed cropping plot, and RYT < 1 indicates a disadvantage of the mixed cropping.

4. Statistical analysis

Dry weight and N and P contents of oat plants sampled before cutting of hairy vetch were analyzed by the T-test for determining significant differences in the mean of each parameter between sole cropping and mixed cropping. The other data were analyzed by a one-way ANOVA and Scheffe’s test was conducted to determine differences among treatment means, when F-values were significant.

Results and Discussion

1. Growth and uptake of N and P of green manure crops

Growth of oat was affected by mixed cropping with hairy vetch after early March. Stem number of oat was greater in the Mix plot than in the Sole Oat plot, and it markedly increased immediately after cutting of hairy vetch in early April in the Mix + Cut plot (Figs. 1a). When hairy vetch was cut, the dry weight and total N content of cut shoots were 134.4 g m⁻² and 6.7 g m⁻², respectively. SPAD values of oat leaves were highest in the Mix plot followed by the Mix + Cut and Sole Oat plots (Figs. 1b and 2b). The SPAD value in the Mix plot was 5 to 7 higher than that in the Mix + Cut plot in early May.

In the Mix plot, oat plants might be competing for light with climbing vine of hairy vetch resulting in a higher SPAD value than in the Mix + Cut plot (Fig. 3a). As shown in Table 2, the leaf area index (LAI) in the Mix plot was 3.2 before blooming of hairy vetch, and it drastically increased

![Fig. 1. Effect of cutting hairy vetch at before-blooming stage on stem number (a) and SPAD-value (b) of associated oat plants. Each value shows the mean ± SEM of three replications.](image)
at the blooming stage (7.2), indicating that competition for light between oat and hairy vetch occurred especially during the blooming stage. In fact, the hairy vetch plant utilized the oat plant as props to maintain light-interception (Fig. 3a).

Some workers reported the beneficial effect of mixed cropping with a leguminous crop on the growth and nutrient uptake of the associated gramineous crop, especially regarding N transfer from legumes (Chu et al., 2004; Xiao et al., 2004; Rasmussen et al., 2007; Li et al., 2009), whereas others described that there was no evidence of substantial transfer of legume N to the neighboring crops until the legume leaves and stems were cut or grazed (Thorsted et al., 2006; Ayres et al., 2007). In the present experiment, there was no significant difference in shoot dry weight of oat between the Sole Oat and Mix plots on 10 April, before blooming of hairy vetch growth stage (Table 3). However, the total N concentration and total N content of shoots in the Mix plot were significantly higher than those in the Sole Oat plot (Table 3). Furthermore, total P content was slightly higher in the Mix plot than in the Sole Oat plot although the difference was

---

**Table 2.** Leaf area index (LAI) of each plot before blooming (8 April) and during blooming (1 May) of hairy vetch.

| Treatment                                      | 8 April | 1 May |
|------------------------------------------------|---------|-------|
| Sole cropping of oat (Sole Oat)                | 2.4     | 2.9   |
| Sole cropping of hairy vetch (Sole Vetch)      | 4.7     | 5.7   |
| Mixed cropping (Mix)                           | 3.2     | 7.2   |
| Mixed cropping with hairy vetch cutting (Mix + Cut) | –       | 2.1   |

---

Fig. 2. Newly emerged tillers of oat in the Mix + Cut plot on 10 April (a). Arrows indicate emerged tillers. Differences in leaf color of oat between the Sole Oat (the front side) and Mix + Cut (the back side) plots (b).

Fig. 3. The vines of hairy vetch climbed up oat plants in early April (a). Improvement of light interception of oat after cutting of hairy vetch (b).
needed to provide a significant amount of N from legume to a partner crop, and also that apparent N transfer was not observed even if legume shoots were cut in several pasture legumes, because belowground N was used for regrowth of shoots after cutting. On the other hand, several researchers reported that significant N transfer definitely occurred through decomposition of the root systems, and it could be enhanced particularly when the legume shoots were removed (Daimon and Chujo, 1986a, 1986b; Pappa et al., 2006; Thorsted et al., 2006).

Speculation and discussion on N transfer from the legume to mixed cropped grass should take into consideration to clarify the complex mechanisms such as exudation of nitrogenous compounds through root system turnover and mycorrhizal hyphal network function, and also they should be defined from the viewpoint of quantitative evaluation. Ta et al. (1986) reported that fixed N was the main source of N excreted from nodulated roots in a winter legume, *Medicago sativa*. Viera-Vargas et al. (1995) also estimated that more than 30% of accumulated N in grass *Brachiaria* was derived from N fixed by the associated summer legumes.

In the present study, we could not quantify the amount not significant. These data indicated that mixed cropping with hairy vetch enhanced the growth and nutrient uptake of the oat plant grown as green manure. After cutting of hairy vetch shoots on 10 April, light interception by hairy vetch vines to oat shoots suddenly disappeared (Fig. 3b), and then new tillers emerged (Fig. 2a).

The values of RY in dry weight, total N content and total P content of oat shoots in the Mix plots at the harvesting time were 0.43, 0.67 and 0.62, respectively, whereas those in the Mix + Cut plot were 0.79, 1.04 and 0.99, respectively (Table 4).

There was also a definite difference in growth, and N and P uptake of hairy vetch shoots between the Sole Vetch and Mix plots. RY in dry weight, total N content and total P content of hairy vetch shoots in the Mix plot were 0.92, 0.93 and 0.77, respectively (Table 5). As described above, the hairy vetch plant in the Mix plot utilized the oat plant as props to maintain light-interception (Fig. 3a), which might increase the RY of hairy vetch in the Mix plot. On the other hand, oat plants might strongly compete for light with hairy vetch.

Trannin et al. (2000) reported that the longer-term decaying of roots and root nodules of legumes is generally

---

### Table 3. Dry weight and N and P contents of oat shoots sampled on 10 April 2010.

| Treatment            | Dry weight (g plant⁻¹) | Total N content (mg g⁻¹) | Total P content (mg plant⁻¹) |
|----------------------|-------------------------|--------------------------|------------------------------|
| Sole cropping (Sole Oat) | 10.2                    | 8.8                      | 4.8                          |
| Mixed cropping (Mix)  | 9.3                     | 13.2                     | 5.9                          |
|                      | **                      | **                       | ns                           |
|                      | ns                      | ns                       | ns                           |

Values are means of three replications.

**, Significant difference at 1% level.

ns, Not significant.

### Table 4. Effect of cutting hairy vetch at before-blooming stage on dry weight and N and P contents of oat shoots sampled on 13 May 2010.

| Treatment                                                  | Dry weight (g m⁻²) | Total N content (mg g⁻¹) | Total P content (mg g⁻¹) |
|------------------------------------------------------------|---------------------|--------------------------|--------------------------|
| Sole cropping (Sole Oat)                                   | 573 a               | 8.5 c                    | 4.1 c                    |
| Mixed cropping (Mix)                                       | 246 c               | 13.2 a                   | 6.0 a                    |
| Mixed cropping with hairy vetch cutting (Mix + Cut)        | 454 b               | 11.1 b                   | 5.1 b                    |
| **                                                        |                      | **                       | ns                       |
| ns                                                        |                      | ns                       | ns                       |

Means in the same column followed by same letter are not significantly different at 5% level according to Scheffe’s test.

### Table 5. Effect of mixed cropping with oat (Mix) on dry weight and of N and P contents of associated hairy vetch sampled on 13 May 2010.

| Treatment          | Dry weight (g m⁻²) | Total N content (mg g⁻¹) | Total P content (mg g⁻¹) |
|--------------------|---------------------|--------------------------|--------------------------|
| Sole cropping (Sole Vetch)   | 501 a               | 37.9 a                   | 6.2 a                    |
| Mixed cropping (Mix)         | 461 a               | 36.9 a                   | 5.1 a                    |
| **                       |                      | **                       | ns                       |
| ns                       |                      | ns                       | ns                       |

Means in the same column followed by same letter are not significantly different at 5% level according to Scheffe’s test.
of N transferred from belowground parts of hairy vetch. However, we observed change in leaf color immediately after cutting hairy vetch (Fig. 1b), and higher value of RY (1.04) in total N content of oat plant in the Mix + Cut plot (Table 4). As described above, the value of RY > 0.5 indicates the positive effect of the mixed cropping on yield and N content of oat, and 1.04 in the Mix + Cut plot was extremely high. Therefore, we thought that increase of these parameters found immediately after cutting might be due to decaying of belowground parts of hairy vetch. The amounts of N transferred should be examined using a $^{15}$N tracer method.

In addition, Johansen and Jensen (1996) reported that transfer of P from pea to barley in the mixed cropping occurred, when pea plants were dying due to removal of shoots. In the present experiment, RY in total P contents of oat in the Mix and the Mix + Cut plots were higher than 0.5 (Table 4), suggesting that higher P accumulation in oat in the Mix + Cut plot was extremely high. Therefore, we thought that increase of these parameters found immediately after cutting might be due to decaying of belowground parts of hairy vetch. The amounts of N transferred should be examined using a $^{15}$N tracer method.

In this study, we estimated the amounts of N and P transferred from green manure to the succeeding corn crop, when oat and hairy vetch were mixed cropped as green manures. As described above, N uptake by oat plants was significantly increased by mixed cropping with hairy vetch and the beneficial effect of mixed cropping was enhanced by cutting of hairy vetch before blooming.

The mean RYT values for dry weight, total N content and total P content calculated according to the data in Tables 4 and 5 were 1.34, 1.61 and 1.39, respectively. The values of total N and P contents in the Mix plot were higher than in the Sole Oat, Sole Vetch and Mix + Cut plots (Table 6).

### 2. Growth and uptake of N and P of the succeeding corn crop

The inorganic N concentration in soil solution after incorporation of oat and hairy vetch in the Mix plot was kept high until mid June, while that in the Mix + Cut plot was low (Fig. 4). Low concentration of N in all plots after 22 June might be due to N uptake by the succeeding corn that grew vigorously during those days.

During the early growth stages of corn (22 June – 1 July), the SPAD values of leaves were higher in the Sole Vetch and Mix plots than in the Mix + Cut plot, and was lowest in the Sole Oat plot (Fig. 5a). The plant length of corn was also longer in the Sole Vetch and Mix plots than in the Sole Oat and Mix + Cut plots (Fig. 5b). In the litter bag experiment shown in Fig. 6, the remaining percentage of N and C in the green manure was lower in the Mix + Cut plot than in the Sole Oat plot. It might be due to lower C/N ratio of oat in the Mix + Cut plot (36.6) than in the Sole Oat plot (48.3) (Table 6). This demonstrated that Mix + Cut is a desirable method to control the C/N ratio of oat.

As reported previously, the higher C/N ratio of incorporated materials results in temporal N starvation during early growth of the succeeding crop through decomposition of incorporated green manure by microorganisms in the soil (Kuo and Sainju, 1998; Rosecrance et al., 2000, Chaves et al., 2004). In addition, a low C/P ratio might also be critical for rapid decomposition of the incorporated materials (Lupwayi et al., 2007). In this

Table 6. Amounts of oat and hairy vetch incorporated as green manures in each plot.

| Treatment                                  | Dry weight (g m$^{-2}$) | Total N content (g m$^{-2}$) | Total P content (g m$^{-2}$) | C/N ratio | C/P ratio |
|--------------------------------------------|-------------------------|-----------------------------|-----------------------------|-----------|-----------|
| Sole cropping of oat (Sole Oat)            | 449                     | 3.8                         | 1.8                         | 48.3      | 100.7     |
| Sole cropping of hairy vetch (Sole Vetch)  | 393                     | 14.5                        | 2.4                         | 11.0      | 66.0      |
| Mixed cropping (Mix)                       |                         |                             |                             |           |           |
| Oat                                        | 189                     | 2.5                         | 1.1                         | 31.2      | 68.5      |
| Hairy vetch                                | 362                     | 13.4                        | 1.9                         | 11.4      | 83.6      |
| Total                                      | 551                     | 15.9                        | 3.0                         | 13.5      | 76.5      |
| Mixed cropping with hairy vetch cutting (Mix + Cut) | 350                     | 3.9                         | 1.8                         | 36.6      | 80.6      |
experiment, the concentration of inorganic N in soil solution after incorporation of oat and hairy vetch (Mix plot) was higher than that in the Sole Oat plot (Fig. 4). These results also indicate that hairy vetch functions as a supplier of N after incorporation.

The dry weight of leaves and stems (stover) and ears of corn plants at harvest varied with the preceding cropping pattern (Table 7). The yield of corn was higher in both the Sole Vetch and Mix plots than in the Sole Oat plot, and the dry weight of stover in the Mix + Cut plot was significantly heavier than that in the Sole Oat plot. Although sole cropping of hairy vetch (Sole Vetch) was the best to enhance nutrient uptake of the succeeding corn crop, there was no significant difference in total N and P contents of stover between the Sole Vetch and Mix plots. This indicated that the half stand of hairy vetch in the Mix plot enhanced the N and P uptake of the succeeding corn as well as that in the Sole Vetch plot where double stands of hairy vetch were grown. This is achieved by the higher RY of hairy vetch in this experiment (Table 5 compared with Table 4). Dry matter yield and N and P contents of the succeeding corn were higher in the Mix plot than in the Sole Oat and Mix + Cut plots on the average as shown by the values in parentheses in Table 7.
3. Conclusion

Our results showed that dry matter production of green manure was the highest in the Mix plot. Sole cropping of hairy vetch was the best method to enhance the growth and nutrient uptake of the succeeding corn crop, but mixed cropping green manure was also highly effective. It was clarified that cutting hairy vetch shoots before blooming reduced the C/N ratio of oat. The belowground residue of hairy vetch that contained plenty of N might act as a readily available N fertilizer for oat crop. We showed here the short-term effect of mixed cropping green manure on the succeeding crop. Further investigations are needed to determine the long-term effect of green manure production by mixed cropping of grass and legume, on N and P sequestration as soil organic matter.

Acknowledgements

We thank Dr. Araki, Hokkaido University, for his valuable comments. Thanks are also due to Mrs. Nishida and Koido, Osaka Prefecture University, for their technical field assistance.

References

Astier, M., Maass, J.M., Etchevers-Barra, J.D., Pena, J.J. and de Leon Gonzalez, F. 2006. Short-term green manure and tillage management effects on maize yield and soil quality in an Andisol. Soil Till. Res. 88: 153-159.

Ayres, E., Dromph, K.M., Cook, R., Ostle, N. and Bardgett, R.D. 2007. The influence of below-ground herbivory and defoliation of a legume on nitrogen transfer to neighbouring plants. Funct. Ecol. 21: 256-263.
Brennan, E.B., Boyd, N.S., Smith, R.F. and Foster, P. 2009. Seeding rate and planting arrangement effects on growth and weed suppression of a legume-oat cover crop for organic vegetable systems. Agron. J. 101: 970-988.

Caballero, R., Goicoechea, E.L. and Hernaiz, P.J. 1995. Forage yields and quality of common vetch and oat sown at varying seeding ratios and seeding rates of vetch. Field Crops Res. 41: 135-140.

Chaves, B., De Neve, S., Hofman, G., Boecckx, P. and Van Cleemput, O. 2004. Nitrogen mineralization of vegetable root residues and green manures as related to their biochemical composition. Eur. J. Agron. 21: 161-170.

Chesnutt, D.M.B., Bartholomew, P.W. and Binnie, R.C. 1980. The interaction of perennial ryegrass and timothy in mixtures and their reaction to clover and nitrogen in cut swards. Grass Forage Sci. 35: 281-286.

Choi, B. and Daimon, H. 2008. Effect of hairy vetch incorporated as green manure on growth and N uptake of sorghum crop. Plant Prod. Sci. 11: 211-216.

Choi, B., Ohe, M., Harada, J. and Daimon, H. 2008. Role of belowground parts of green manure legumes, Crotalaria spectabilis and Sesbania rostrata, in N uptake by the succeeding tendergreen mustard plant. Plant Prod. Sci. 11: 116-123.

Chu, G.X., Shen, Q.R. and Cao, J.L. 2004. Nitrogen fixation and N transfer from peanut to rice cultivated in aerobic soil in an intercropping system and its effect on soil N fertility. Plant Soil 263: 17-27.

Conway, E.J. 1947. Microdiffusion Analysis and Volumetric Error. 2nd edition, Crosby Lockwood and Son, London.

Cu, S.T.T., Hutson, J. and Schuller, K.A. 2005. Mixed culture of wheat (Triticum aestivum L.) with white lupin (Lupinus albus L.) improves the growth and phosphorus nutrition of the wheat. Plant Soil 272: 143-151.

Daimon, H. and Chujo, H. 1986a. Plant growth and fate of nitrogen in mixed cropping, intercropping and crop rotation. 2. Nitrogen content of wheat in association with pea or broad bean. Jpn. J. Crop Sci. 55: 162-170**.

Daimon, H. and Chujo, H. 1986b. Plant growth and fate of nitrogen in mixed cropping, intercropping and crop rotation. 3. Nitrogen content of corn in association with soybean, cowpea or kidney bean. Jpn. J. Crop Sci. 55: 171-178**.

Daimon, H. and Kotoura, S. 2000. Incorporation of Crotalaria spectabilis grown at a high seeding rate inhibits the growth of the succeeding wheat crop. J. Agron. Crop Sci. 185: 137-144.

Daimon, H. 2006. Traits of the genus Crotalaria used as a green manure legume on sustainable cropping systems. Jpn. J. Agric. Res. Q. 40: 299-305.

Gardner, W.K. and Boundy, K.A. 1983. The acquisition of phosphorus by Lupinus albus L. 4. The effect of interplanting wheat and white lupin on the growth and mineral composition of the two species. Plant Soil 70: 391-402.

Gomez, J.A., Gema G.M., Giraldez, J.V. and Fereres, E. 2009. The influence of cover crops and tillage on water and sediment yield, and on nutrient, and organic matter losses in an olive orchard on a sandy loam soil. Soil Till. Res. 106: 137-144.

Hauggaard-Nielsen, H., Ambus, P. and Jensen, E.S. 2001. Temporal and spatial distribution of roots and competition for nitrogen in pea-barley intercrops – a field study employing P-32 technique. Plant Soil 236: 63-74.

Hauggaard-Nielsen, H., Gooding, M., Ambus, P., Corre-Hellou, G., Crozet, Y., Dahlmann, C., Dibet, A., von Fragsvold, P., Pritsneri, A., Monti, M. and Jensen, E.S. 2009. Pea-barley intercropping for efficient symbiotic N₂-fixation, soil N acquisition and use of other nutrients in European organic cropping systems. Field Crops Res. 113: 64-71.

Johansen, A. and Jensen, E.S. 1996. Transfer of N and P from intact or decomposing roots of pea to barley interconnected by an arbuscular mycorrhizal fungus. Soil Biol. Biochem. 28: 73-81.

Kamh, M., Horst, W.J., Amer, F., Mostafa, H. and Maier, P. 1999. Mobilization of soil and fertilizer phosphate by cover crops. Plant Soil 211: 19-27.

Kamo, T., Hiradate, S. and Fujii, Y. 2003. First isolation of natural cyanamide as a possible allelochemical from hairy vetch Vicia villosa. J. Chem. Ecol. 29: 275-283.

Karpensen-Machan, M. and Stuelpennag, R. 2000. Biomass yield and nitrogen fixation of legumes monocropped and intercropped with rye and rotation effects on a subsequent maize crop. Plant Soil 218: 215-222.

Keerthisinghe, G., Hocking, P.J., Ryan, P.R. and Delhaize, E. 1998. Effect of phosphorus supply on the formation and function of proteoid roots of white lupin (Lupinus albus L.). Plant Cell Environ. 21: 467-478.

Kuo, S., Sainju, U.M. and Jellum, E.J. 1997. Winter cover crop effects on soil organic carbon and carbohydrate in soil. Soil Sci. Soc. Amer. J. 61: 145-152.

Kuo, S. and Sainju, U.M. 1998. Nitrogen mineralization and availability of mixed leguminous and non-leguminous cover crop residues in soil. Biol. Fertil. Soils 26: 346-353.

LaMondia, J.A. 2006. Management of lesion nematodes and potato early dying with rotation crops. J. Nematol. 38: 442-448.

Li, H., Shen, J., Zhang, F., Clairotte, M., Drevon, J.J., Le, C.E. and Hinsinger, P. 2008. Dynamics of phosphorus fractions in the rhizosphere of common bean (Phaseolus vulgaris L.) and durum wheat (Triticum turgidum durum L.) grown in monocropping and intercropping systems. Plant Soil 312: 139-150.

Li, Y.F., Ran, W., Zhang, R.P., Sun, S.B. and Xu, G.H. 2009. Facilitated legume nodulation, phosphate uptake and nitrogen transfer by legume nodulation, phosphate uptake and nitrogen transfer by arbuscular inoculation in an upland rice and mung bean intercropping system. Plant Soil 315: 285-296.

Lithourgidis, A.S., Vasilakoglou, I.B., Dhima, K.V., Dordas, C.A. and Yiakoulaki, M.D. 2006. Forage yield and quality of common vetch mixtures with oat and triticale in two seeding ratios. Field Crops Res. 99: 106-113.

Lupwayi, N.Z., Clayton, G.W., O’Donovan, J.T., Harker, K.N., Turkington, T.K. and Soon, Y.K. 2007. Phosphorus release during decomposition of crop residues under conventional and zero tillage. Soil Till. Res. 95: 231-239.

Maeda, K. and Onikura, Y. 1977. A method to determine phosphorus content of corn in association with soybean, cowpea or kidney bean. Jpn. J. Chem. Ecol. 244: 137-144.

Monti, M. and Jensen, E.S. 2009. Pea-barley intercropping for efficient symbiotic N₂-fixation, soil N acquisition and use of other nutrients in European organic cropping systems. Field Crops Res. 113: 64-71.

Muhr, L., Tarawali, S.A., Peters, M. and Schultzke-Kraft, R. 1999. Forage legumes for improved fallows in agropastoral systems of subhumid West Africa. II. Green manure production and decomposition after incorporation in the soil. Trop. Grassl. 33: 234-244.
Ohdan, H. and Daimon, H. 1998. Growth of Crotalaria juncea and Sesbania cannabina under different underground water levels and their nitrogen contribution to the succeeding spinach plant. *Jpn. J. Crop Sci.* 67: 467-472*.

Pappa, V.A., Rees, R.M. and Watson, C.A. 2006. Nitrogen transfer between clover and wheat in an intercropping experiment. *Aspet. Appl. Bio.* 79: 291-295.

Paynel, F., Murray, P.J. and Cliquet, J.B. 2001. Root exudates: a pathway for short-term N transfer from clover and ryegrass. *Plant Soil* 229: 235-243.

Paynel, F. and Cliquet, J.B. 2003. N transfer from white clover to perennial ryegrass, via exudation of nitrogenous compounds. *Agronomie* 23: 503-510.

Ramos, M.E., Altieri, M.A., Garcia, P.A. and Robles, A.B. 2011. Oat and oat-vetch as rainfed fodder cover crops in semiarid environments: Effects of fertilization and harvest time on forage yield and quality. *J. Sustain. Agri.* 35: 726-744.

Rasmussen, J., Eriksen, J., Jensen, E.S., Esbensen, K.H. and Hogh-Jensen, H. 2007. In situ carbon and nitrogen dynamics in ryegrass-clover mixtures: Transfers, deposition and leaching. *Soil Biol. Biochem.* 39: 804-815.

Rauber, R., Schmidtke, K. and Kimpel-Freund, H. 2001. The performance of pea (*Pisum sativum* L.) and its role in determining yield advantages in mixed stands of pea and oat (*Avena sativa* L.). *J. Agron. Crop Sci.* 187: 137-144.

Rosecrance, R.C., McCarty, G.W., Shelton, D.R. and Teasdale, J.R. 2000. Denitrification and N mineralization from hairy vetch (*Vicia villosa* Roth) and rye (*Secale cereale* L.) cover crop monocultures and bicultures. *Plant Soil* 227: 283-290.

Ruffo, M.L. and Bollero, G.A. 2003. Modeling rye and hairy vetch residue decomposition as a function of degree days and decomposition days. *Agron. J.* 95: 900-907.

Sainju, U.M., Whitehead, W.F. and Singh, B.P. 2005. Biculture legume-cereal cover crops for enhanced biomass yield and carbon and nitrogen. *Agron. J.* 97: 1403-1412.

Ta, T.C., Macdowall, F.D.H. and Faris, M.A. 1986. Excretion of nitrogen assimilated from N\textsubscript{2} fixed by nodulated roots of alfalfa (*Medicago sativa*). *Can. J. Bot.* 64: 2063-2067.

Thorsted, M.D., Olesen, J.E. and Weiner, J. 2006. Mechanical control of clover improves nitrogen supply and growth of wheat in winter wheat/white clover intercropping. *Eur. J. Agron.* 24: 149-155.

Tranmin, W.S., Urquiaga, S., Guerra, G., Ibijbijen, J. and Cadisch, G. 2000. Interspecies competition and N transfer in a tropical grass-legume mixture. *Biol. Fertil. Soils* 32: 441-448.

Uratani, A., Daimon, H., Ohe, M., Harada, J., Nakayama, Y. and Ohdan, H. 2004. Ecophysiological traits of field-grown *Crotalaria incana* and *C. pallida* as green manure. *Plant Prod. Sci.* 7: 449-455.

Vera-vargas, M.S., Souto, C.M., Urquiaga, S. and Boddey, R.M. 1995. Quantification of the contribution of N\textsubscript{2} fixation to tropical forage legumes and transfer to associated grass. *Soil Biol. Biochem.* 27: 1193-1200.

Xiao, Y., Li, L. and Zhang, F. 2004. Effect of root contact on interspecific competition and N transfer between wheat and faba bean using direct and indirect \textsuperscript{15}N techniques. *Plant Soil* 262: 45-54.

Yano, K., Daimon, H. and Mimoto, H. 1994. Effect of sunn-hemp and peanut incorporated as green manures on growth and nitrogen uptake of the succeeding wheat. *Jpn. J. Crop Sci.* 63:137-143.

* In Japanese with English abstract.
** In Japanese with English summary.
*** In Japanese.