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Stable Characteristics of Cover Crops for Weed Suppression in Organic Farming Systems

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Abstract:The use of cover crops is an effective technique to control weeds, which are one of the most serious problems for crop production without using herbicides. This study investigated the characteristics of cover crops for weed suppression at an organic farming field in a snowy-cold region, Hokkaido. Nine, three and two species of cover crops comprising both Poaceae and Leguminosae were grown in 2003, 2004 and 2005, respectively, at different sowing densities from 50 to approximately 4000 seeds m^{-2}. The relationships between weed dry matter production and characteristics of cover crops, such as plant height and coverage, were investigated at 4 and 10 weeks after cover crop sowing (WAS). Correlation analysis of the weed dry weight with characteristics of cover crops revealed that the cover crop coverage at 4 WAS had a strong and stable effect on weed suppression. The cover crop coverage at 4 WAS was affected primarily by their seed weight when cover crops with a large variation in seed weight were used, and by the sowing density when cover crops with a small variation in seed weight were used. These results suggest that to achieve high weed suppression it is important to obtain higher coverage at the early growth stage of the cover crops with a heavy seed weight and high sowing density.

Key words: Coverage, Cover crop, Organic farming, Plant height, Weed suppression.

Modern intensive and highly mechanized farming systems have led to a great increase in productivity and labor efficiency in crop production. A review of recent literature, however, indicated that conventional agriculture is responsible for severe environmental problems, such as chemical residues negatively affecting biodiversity (Altieri, 1999), soil erosion (Pimentel et al., 1995), salinity and acidification of soil (Lal, 2000) and the emission of CO_2 gas due to production of agricultural chemicals (Koga et al., 2006). Therefore, a shift from conventional to sustainable agriculture, including the farming systems with reduced use of agricultural chemicals, is required to lessen these environmental burdens.

In the crop production systems with reduced or no use of agricultural chemicals, weeds are often recognized as the most detrimental threat to crop production. The use of cover crops is a relatively effective technique for controlling weeds. For instance, cover crops such as gramineous rye (*Secale cereale* L.), barley (*Hordeum bulbosum* L.) and leguminous white clover (*Trifolium repens* L.), red clover (*Trifolium pratense* L.) and other clovers have been used successfully as cover crops during the fallow season to suppress weeds (Barberi and Mazzoncini, 2001; Ross et al., 2001). Hairy vetch (*Vicia villosa* Roth), a leguminous vine cover crop, has also attracted much attention for weed control because it has an allelopathic effect (White et al., 1989; Kamo et al., 2003). In addition, some cover crops, such as marigold (*Tagetes* sp.) and wild oat (*Avena strigosa* Schreb.), have effects on populations of soil microorganisms and suppress diseases caused by endopathogenic nematodes (Topp et al., 1998; LaMondia, 1999).

In temperate cropping systems, cover crops are generally planted in fall, while the main crops are planted in the following spring. However, the pre-planted cover crop sometimes suppresses the growth of the main crop through competition for environmental resources (Box et al., 1980; Feil et al., 1997; Thorsted et al., 2006). The cover crops are usually killed by using mechanical means, such as mowing (Ateh and Doll, 1996; Garibay et al., 1997), to reduce their adverse effects on the growth of the main crop, but sometimes this may not provide sufficient control of the growth of the cover crop (Hoffman et al., 1993). Interseeding of cover crop (seeding into established vegetation of main crop) is another potential technique to avoid or decrease competition between the cover crop and main crop (Abdin et al., 2000). This technique is especially

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Table 1. Seed weight and sowing density of ten cover crops in 2003.

Cover crop[1]	Variety	Seed weight (mg)	Sowing density (seed m^{-2})
Poaceae			
winter rye	Warko	41.2	400
winter wheat	Mulch-mugi	37.0	270
winter rye	Fuyu-midori	32.9	400
oat (wild species)	Sire	17.1	586
Leguminosae			
hairy vetch	Mameya	40.7	400
purple vetch	Top-cut	29.5	166
red clover	Altaswede	1.86	1628
Persian clover	Nitro-plus	0.63	3055
white clover	Tahora	0.54	4374
Asteraceae			
marigold	Single-gold	–[2]	50
LSD (p=0.05)[3]		0.81	–

[1] Cover crop species are arranged according to the seed weight in each family.
[2] The seed weight of marigold was not measured because coated seeds were used.
[3] Abbreviation: LSD, least significant difference.

suitable in a snowy-cold climate region (Dfb) according to Koppen-Geiger climate classification (Kottek et al., 2006). For example, black medic (*Medicago lupulina* L.) and Persian clover (*Trifolium resupinatum* L.) are interseeded with winter wheat (*Triticum aestivum* L.) in New York (Hartl, 1989). Hairy vetch and lana vetch (*Vicia dasycarpa* L.) are used as interseeded cover crops for transplanted cabbage (*Brassica oleracea* L.) and cause significant weed suppression in Austria (Brainard et al., 2004). In these regions, because of the freezing temperatures, most cover crops sown in the previous fall can not survive the winter or can not produce enough biomass to suppress weeds in spring.

However, the interseeded cover crop may also reduce the growth of the main crop mainly due to the direct competition between cover crop and main crop (Scott et al., 1987; DeHaan et al., 1994; Ateh and Doll, 1996; den Hollander et al., 2007). In this technique, therefore, the species used as the cover crop is important (Muller-Scharer and Potter, 1991), and a better understanding of cover crop characteristics (species and growth pattern) and cover crop management (sowing density and sowing date) is necessary for successful inclusion of cover crops in a weed management strategy (Barberi, 2002).

Previously (Uchino et al. 2009), we investigated the effect of the cover crops, winter rye and hairy vetch, on weed suppression at an organic farming field of soybean (*Glycine max* Merr.) and maize (*Zea mays* L.) in a snowy-cold region of Hokkaido, the northern part of Japan. The weed dry weight was significantly suppressed by sowing cover crops, and the extent of weed suppression was associated with the coverage (percentage of vegetation covering area to unit soil surface area) by the main crop plus cover crop at the early growth stage of the main crop. The aim of the present study is to verify the importance of the coverage by the cover crops on weed suppression using various cover crop species with different plant characteristics and to find the characteristics of the cover crops relating to the increase of coverage. The beneficial characteristics of cover crops for interseeding with the main crop are also discussed based on the correlation analysis between cover crop characteristics and weed dry matter production.

Materials and Methods

The study was conducted for three years (2003–2005) at an organic farming field of the Field Science Center for the Northern Biosphere, Hokkaido University (Sapporo, Japan, 43°04′N, 141°20′E). The soil was Typic Udifluvent with a pH 6.5 and had 4.5% organic matter. In 2003, the nine species of cover crops, winter rye, winter wheat, oat, hairy vetch, purple vetch (*Vicia benghalensis* L.), red clover, Persian clover, white clover, and marigold, with large variations in seed weight (Table 1) were used to analyze the relationship between cover crop characteristics and weed dry matter production. These cover crops were introduced to this region as recommended by a local agricultural cooperative (Hokuren Federation of Agricultural Cooperatives, Hokkaido, Japan) or as candidate green manure crops from a seed company (Kaneko Seeds Co., Gunma, Japan). Two winter rye cultivars 'Warko' and 'Fuyu-midori' were used. The cover crops were sown according to the recommended densities as green manure in the region. In 2004 and 2005, we investigated the effect of sowing density in several cover crops; winter rye (Fuyu-midori), winter wheat and hairy vetch were sown at sowing densities of 100, 200 and 400 seeds m^{-2} in 2004, and winter rye (Fuyu-midori) and hairy vetch were sown at sowing densities of 0, 100, 200, 400, 600 and 800 seeds m^{-2} in 2005.

Seeds of cover crops were uniformly broadcasted and mixed with soil by hand on 13 June 2003, 5 July 2004 and 16 June 2005. Irrigation was applied twice before the emergence of cover crops at 7 and 9 days after sowing (DAS) in 2003 (total: 25 mm) and at 1 and 4 DAS in 2005 (total: 33 mm). The experiment was conducted at the same field for three years and arranged as a randomized complete block design with two replications in 2003 and four replications in 2004 and 2005. Each treatment plot was 1.6 m by 1.7 m, 1.8 m by 1.8 m and 1.4 m by 2.2 m in 2003, 2004 and 2005, respectively. Since the size and number of plots differed between the study period, the experimental plots were arranged randomly each year, i.e., we hypothesized that by arranging the experimental plots

randomly the effects of weed seed production in the previous year on the seed bank size was neutralized. A fully-ripened compost (total nitrogen content: 0.73% (w/w) fresh weight) was applied to the soil at 30 t ha^{-1} about 1–2 months before sowing in each year.

At two weeks after sowing (WAS), the number of cover crop seedlings in four quadrats (20 cm×20 cm) in each plot was counted and the emergence percentage of cover crops was calculated. The plant height and the cover crop coverage were recorded at 4 and 10 WAS, and the weed dry weight was measured at 10 WAS after drying at 70ºC for 72 hrs. The plant height of cover crops was measured from the soil surface to the highest point of four randomly selected plants in each plot. Cover crops and weeds were sampled from two quadrats (40 cm×20 cm) in each plot. The cover crop coverage was evaluated using digital camera images after picking up weeds from the plant community, and the average of 32 grids (8 grids×4 grids; each grid size 5 cm×5 cm) of the coverage was calculated within a 40 cm×20 cm range in 2003 and 2004. This method is a modification of a measurement for forest ecosystems (ICP Forests, 2007). In 2005, the cover crop coverage was measured by using a digital camera equipped with a near-infrared light filter and software (GAC-PS2, Kimura Oyokogei Ltd., Japan) to calculate the coverage. The calculated coverage by this method agreed closely with the evaluated coverage obtained with the digital camera images used in the previous two years ($y=1.05x-12.7$, $r=0.984^{***}$, $n=120$). Meteorological data of precipitation and daily mean air temperature were obtained from the Sapporo District Meteorological Observatory (43º04′N, 141º20′E).

Statistical analysis was conducted using the SPSS software (version 14.0J, SPSS Japan). To analyze the effect of year, we conducted a three-way analysis of variance (ANOVA) with a combined model (McIntosh, 1983) for common cover crop species, winter rye (Fuyu-midori) and hairy vetch at sowing densities 100, 200 and 400 seeds m^{-2} in 2004 and 2005. In this analysis, cover crop species and sowing density were treated as fixed effects and year was treated as a random effect. The differences between treatments were tested by the least significant difference at 5% level of probability when ANOVA was significant. Path analysis was also performed to quantify causal effects among variables. Path coefficients are shown as standardized regression coefficients. When the relationship between two variables is mediated by one or more variables, the magnitude of indirect effects is determined by multiplying the path coefficients along the pathway between the two causally related variables (Lleras, 2005).

Table 2. Precipitation and daily average air temperature during the growing seasons in 2003, 2004 and 2005.

Day after sowing	Precipitation (mm)			Air temperature (ºC)		
	2003	2004	2005	2003	2004	2005
0–9	31	21	35	18.6	18.5	20.3
10–19	13	37	24	16.7	22.5	18.7
20–29	16	6	40	18.0	25.3	18.0
30–39	0	2	4	17.1	25.0	22.0
40–49	13	108	99	18.4	19.8	22.8
50–59	69	18	0	21.3	20.2	24.7
60–harvest	6	67	69	20.5	18.9	22.6
Total or mean	147	258	269	18.7	21.3	21.4

Results

1. Climatic conditions

Total precipitation during the growing season was approximately 110 mm lower in 2003 than in the other two years (Table 2), but no inhibition of cover crop growth by drought was observed. Precipitation from 40 to 49 DAS in 2004 was greater than 100 mm because of a typhoon. The daily average air temperature from 10 to 49 DAS was lower in 2003 than in the other two years, causing a lower mean value of daily average air temperature during the growing season in 2003. From sowing to emergence (0–9 DAS), the daily maximum air temperature (data not shown) was usually greater than 30ºC in 2005 and the daily average air temperature was the highest in 2005 among the three years.

2. Weed growth

The main weed species for the three years were redroot pigweed (*Amaranthus retroflexus* L.), common lambsquarters (*Chenopodium album* L.) and common purslane (*Portulaca oleracea* L.). Tufted knotweed (*Persicaria longiseta* (De Bruyn) Kitag.) and black nightshade (*Solanum nigrum* L.) grew sparsely. Among the main weed species, common purslane was frequently observed at the early stages of the experiment, but it died before 10 WAS. On the other hand, redroot pigweed and common lambsquarters grew continuously until 10 WAS and were dominant throughout the study period. In the no-cover crop treatment (sowing density of 0 seed m^{-2}) in 2005, the weed dry weight reached almost 1200 g m^{-2} at the end of the experiment (Fig. 1c).

Dry matter production of weeds at 10 WAS varied greatly depending on the cover crop species and sowing density in each year (Fig. 1). In 2003, the weed dry weight was greatly suppressed by hairy vetch and two cultivars of winter rye, and was not suppressed by clovers (red clover, white clover and Persian clover) and purple vetch. Winter wheat was less effective in weed suppression compared to hairy vetch

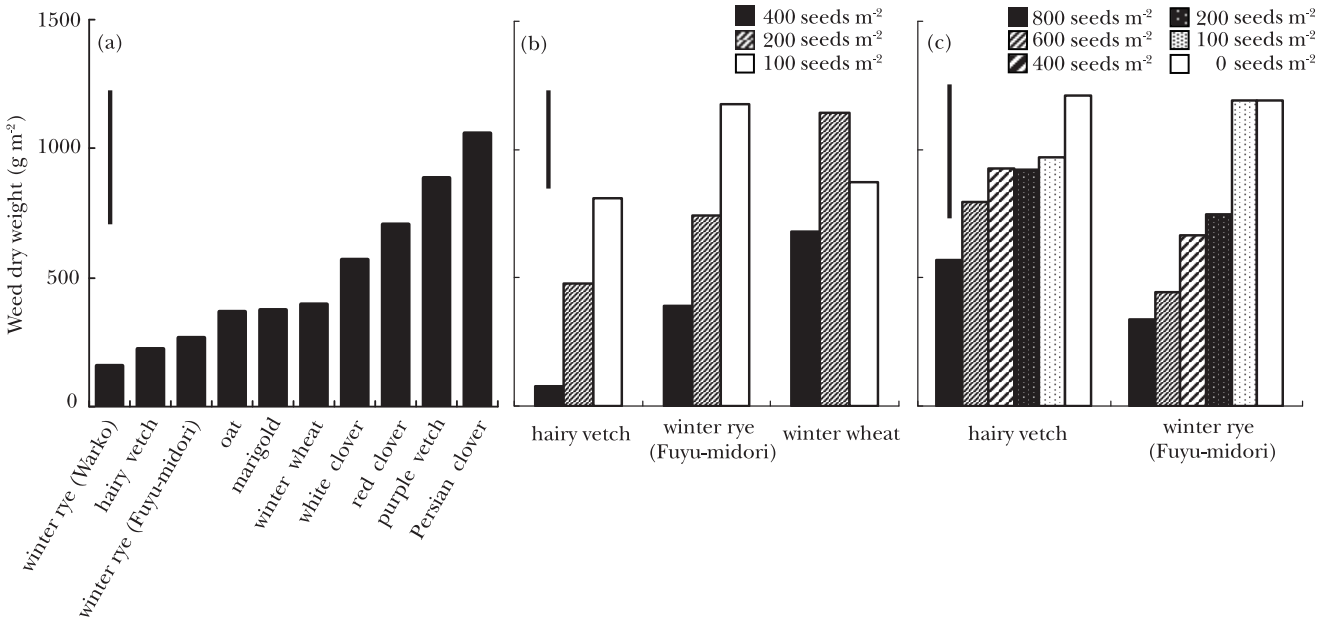


Fig. 1. Weed suppression indicated by changes in weed dry weight (a) by each cover crop in 2003; (b) by three levels of sowing density of three cover crops in 2004; (c) by six levels of sowing density of two cover crops in 2005. Weed dry weight was measured at 10 weeks after sowing. Vertical bar indicates the least significant difference (p=0.05) between treatments.

Table 3. Emergence percentage, plant height and coverage of cover crops in 2003[1].

Cover crop[2]	Emergence percentage (%)	Plant height (cm)		Coverage (%)	
		4 WAS	10 WAS	4 WAS	10 WAS
winter rye (Warko)	89.5	27.3	37.4	78.6	76.6
hairy vetch	65.5	36.4	67.4	57.9	67.3
winter rye (Fuyu-midori)	90.5	31.4	43.9	66.4	85.0
oat	75.0	38.4	132.3	60.8	73.9
marigold	64.0	24.8	77.3	13.0	49.3
winter wheat	63.5	24.1	38.5	31.4	54.7
white clover	17.0	10.9	23.4	19.5	24.7
red clover	8.5	9.9	25.5	1.4	20.9
purple vetch	26.5	23.0	68.1	1.8	11.2
Persian clover	18.5	11.8	34.5	11.2	27.9
LSD (p=0.05)	28.1	8.9	25.4	23.0	44.3

[1] Abbreviations: LSD, least significant difference; WAS, weeks after sowing.
[2] Cover crop species are arranged according to the weed dry weight in Figure 1a.

and winter rye both in 2003 and 2004. Winter rye suppressed weeds at similar levels in both 2004 and 2005, but hairy vetch suppressed weeds more effectively in 2004 than in 2005. In 2004 and 2005, the weed dry weight was more greatly suppressed as the sowing density of cover crops increased.

3. Cover crop growth

(1) Experiment in 2003

Table 3 shows the emergence percentage, plant height and cover crop coverage at 4 and 10 WAS in 2003. Although there was no significant correlation between seed weight and germination percentage under constant temperature in a growth chamber, there was a significant positive correlation between seed weight and emergence percentage in the field ($r=0.784$, $p<0.01$, $n=9$, with the exception of the coated seed cover crop marigold), i.e., emergence percentage was higher in cover crops with a heavy seed weight than in cover crops with a light seed weight. The low emergence percentage of purple vetch was presumed to be caused by inferior seed quality, because the germination percentage in a growth chamber

Table 4. Emergence percentage, plant height and coverage of cover crops in 2004[1].

Cover crop	Sowing density (seed m^{-2})	Emergence percentage (%)	Plant height (cm)		Coverage (%)	
			4 WAS	10 WAS	4 WAS	10 WAS
hairy vetch	400	89.5	36.6	41.0	87.0	82.5
	200	97.3	41.1	42.0	77.6	68.8
	100	89.1	38.3	41.3	60.6	72.2
winter rye (Fuyu-midori)	400	55.5	31.3	36.4	55.2	71.1
	200	47.3	26.0	33.1	44.1	61.1
	100	57.8	26.1	29.0	19.9	32.7
winter wheat	400	51.4	26.4	25.8	57.6	48.2
	200	55.9	22.8	27.3	35.4	19.7
	100	64.8	20.8	28.0	19.0	22.7
LSD (p=0.05)		16.4	4.4	5.9	12.7	14.8
Mean value of each cover crop						
hairy vetch		91.9	38.7	41.4	75.1	74.5
winter rye (Fuyu-midori)		53.5	27.8	32.9	39.8	55.0
winter wheat		57.4	23.3	27.0	37.3	30.2
LSD (p=0.05)		11.4	2.5	6.8	7.3	8.5
Mean value of each sowing density						
	400	65.4	31.4	34.4	66.6	67.3
	200	66.8	30.0	34.1	52.4	49.9
	100	70.6	28.4	32.8	33.2	42.5
LSD (p=0.05)		NS	NS	NS	7.3	8.5

[1]Abbreviations: LSD, least significant difference; NS, not significant; WAS, weeks after sowing.

was lower than 40% for purple vetch, but it was more than 80% for the other species (data not shown).

The plant height of oat was significantly higher than that of the other cover crops at 10 WAS. Among Poaceae, the increase of the plant height from 4 WAS to 10 WAS was more significant in oat than in the other species, because oat does not require vernalization to elongate stems. In contrast, spring-planted winter rye and winter wheat did not elongate stems because of the absence of vernalization and the plant height was low even at the late growth stage. The plant height of vine-like cover crops, such as hairy vetch and purple vetch, was comparatively high at 10 WAS, because they climbed up the weeds.

The cover crop coverage at 4 WAS was significantly higher in oat, two cultivars of winter rye and hairy vetch than in red clover, Persian clover, purple vetch and marigold. Especially, the coverage by winter rye reached 79% (Warko) and 66% (Fuyu-midori) at 4 WAS and these values remained high until 10 WAS. Among leguminous plants, hairy vetch had the highest coverage at 4 and 10 WAS, but the coverage by clovers and purple vetch increased only slightly from 4 WAS to 10 WAS and was less than 30% even at 10 WAS.

(2) Experiments in 2004 and 2005

In 2004, the emergence percentage of hairy vetch was significantly higher than that of winter rye and winter wheat (Table 4). Hairy vetch had a significantly higher plant height and coverage than the other two cover crops at 4 and 10 WAS. The coverage by winter wheat did not increase from 4 WAS to 10 WAS and was very low at 10 WAS, because the tiller number of winter wheat (6.6 $plant^{-1}$) was significantly lower than that of winter rye (10.1 $plant^{-1}$, $p < 0.001$), and some wheat plants died at 10 WAS. The mean coverage by the three cover crops increased significantly as the sowing density increased at both 4 and 10 WAS.

In 2005, the emergence percentage of winter rye was significantly higher than that of hairy vetch (Table 5). Hairy vetch had a significantly higher plant height than winter rye at 4 and 10 WAS. Although winter rye had a significantly higher coverage than hairy vetch at 4 WAS, there was no significant difference between the two cover crop species at 10 WAS. The mean plant height of the two cover crops was significantly higher at the sowing density of 600 seeds m^{-2} at 4 WAS, but did not differ significantly between sowing densities at 10 WAS. The mean coverage by the two cover crops increased significantly as the sowing

Table 5. Emergence percentage, plant height and coverage of cover crops in 2005[1].

Cover crop	Sowing density (seed m^{-2})	Emergence percentage (%)	Plant height (cm)		Coverage (%)	
			4 WAS	10 WAS	4 WAS	10 WAS
hairy vetch	800	43.1	36.1	119.3	61.9	85.1
	600	45.1	42.4	121.4	56.0	71.1
	400	36.0	38.3	127.8	40.1	50.3
	200	41.0	31.1	119.5	28.5	56.0
	100	35.9	33.2	123.1	16.0	46.9
winter rye (Fuyu-midori)	800	56.0	32.8	43.3	91.6	91.0
	600	65.3	36.3	36.5	87.1	82.8
	400	74.1	32.8	41.1	84.2	84.6
	200	72.7	29.5	42.1	56.1	61.4
	100	64.8	30.1	23.5	32.5	15.6
LSD (p=0.05)		17.3	6.1	23.1	14.5	32.9
Mean value of each cover crop						
hairy vetch		40.2	36.2	122.2	40.5	61.9
winter rye (Fuyu-midori)		66.6	32.3	37.3	70.3	67.1
Significance		***	**	***	***	NS
Mean value of each sowing density						
	800	49.5	34.4	81.3	76.8	88.0
	600	55.2	39.4	78.9	71.6	77.0
	400	55.1	35.5	84.4	62.2	67.5
	200	56.8	30.3	80.8	42.3	58.7
	100	50.4	31.6	73.3	24.3	31.3
LSD (p=0.05)		NS	4.3	NS	10.2	23.2

[1]Abbreviations: LSD, least significant difference; NS, not significant; WAS, weeks after sowing.
** Significant at 1% level of probability.
*** Significant at 0.1% level of probability.

Table 6. Mean squares from combined analysis of variance for emergence percentage, plant height and coverage of cover crops for 2004 and 2005[1,2].

Source of variation	df	Emergence percentage (%)	Plant height (cm)		Coverage (%)	
			4 WAS	10 WAS	4 WAS	10 WAS
year (Y)	1	4166***	7^{NS}	21510***	2522***	1796*
Error A	6	97	16	271	25	276
cover crop (C)	1	92^{NS}	616^{NS}	27922^{NS}	104^{NS}	842^{NS}
sowing density (D)	2	29^{NS}	43^{NS}	226^{NS}	4751*	3805^{NS}
C×D	2	134^{NS}	9^{NS}	186^{NS}	334^{NS}	2350^{NS}
C×Y	1	15237**	168^{NS}	18854**	12568**	1494^{NS}
D×Y	2	62^{NS}	9^{NS}	60^{NS}	99^{NS}	248^{NS}
C×D×Y	2	115^{NS}	49^{NS}	94^{NS}	99^{NS}	417^{NS}
Error B	30	146	16	102	107	397

[1]Analysis was done for common cover crop species hairy vetch and winter rye (Fuyu-midori) for two years at sowing densities 100, 200 and 400 seeds m^{-2}.
[2]Abbreviations: NS, not significant; WAS, weeks after sowing; df, degree of freedom.
* Significant at 5% level of probability.
** Significant at 1% level of probability.
*** Significant at 0.1% level of probability.

density increased at both 4 and 10 WAS.

Table 6 shows the mean squares of combined analysis with two cover crops at three plant densities in 2004 and 2005. The effect of year was significant for all characteristics of cover crops, except for the plant height at 4 WAS. The emergence percentage and the cover crop coverage were significantly lower, and the plant height was significantly higher in 2005 than in 2004 (Tables 4, 5). The interaction between crop species and year was significant for the emergence percentage, the plant height at 10 WAS and the coverage at 4 WAS. The emergence percentage and the coverage at 4 WAS were higher in 2005 than in 2004 for winter rye, but were significantly lower in 2005 than in 2004 for hairy vetch. The low emergence percentage in hairy vetch in 2005 was probably caused by higher temperatures from sowing to emergence than in 2003 and 2004 (Table 2). The plant height of winter rye at 10 WAS was similar in 2004 and 2005, but that of hairy vetch was greater in 2005 than in 2004, because hairy vetch was beaten down by a typhoon just before sampling in 2004.

Table 7. Correlation coefficients between weed dry weight at 10 WAS and plant height, coverage and multiplied dominance ratio (=plant height×coverage) of cover crops at 4 and 10 WAS in 2003 (n=10), 2004 (n=9) and 2005 (n=10)[1].

Characteristics of cover crops	Year		
	2003	2004	2005
Plant height			
4 WAS	−0.704*	-0.627^{NS}	-0.188^{NS}
10 WAS	-0.239^{NS}	-0.664^{NS}	0.247^{NS}
Coverage			
4 WAS	−0.808**	−0.845**	−0.882***
10 WAS	−0.855**	−0.829**	−0.937***
Multiplied dominance ratio			
4 WAS	−0.784**	−0.799**	−0.870**
10 WAS	-0.551^{NS}	−0.805**	-0.136^{NS}

[1]Abbreviations: NS, not significant; WAS, weeks after sowing.
* Significant at 5% level of probability.
** Significant at 1% level of probability.
*** Significant at 0.1% level of probability.

4. Relationship between cover crop characteristics and weed suppression

Correlations of the plant height, the coverage and multiplied dominance ratio (=plant height×coverage) of cover crops at 4 WAS and 10 WAS with the weed dry weight at 10 WAS were analyzed for each year (Table 7). The correlation coefficient between the plant height of cover crops and the weed dry weight was not significant except at 4 WAS in 2003. The tallest cover crop, oat, did not suppress weeds efficiently compared with the shorter cover crops such as the two cultivars of winter rye, in 2003 (Table 3; Fig. 1). On the other hand, the cover crop coverage at both 4 WAS and 10 WAS showed significant correlations with the weed dry weight for each year (Table 7). The multiplied dominance ratio correlated significantly with the weed dry weight except at 10 WAS in 2003 and 2005, but these correlation coefficients were not high compared to those for the coverage. These results imply that the weed growth was suppressed more effectively by the cover crops with high coverage in the early growth stage (i.e., 4 WAS), even when the plant height was low in each year.

The cover crop coverage at 4 WAS was expected to be affected by the seed characteristics of cover crops. Figure 2 shows the relationships of the seed characteristics of cover crops with the cover crop coverage at 4 WAS in 2003 (except for purple vetch because of its inferior seed quality with an extremely low germination percentage even in a growth chamber). Since we used cover crops with large variations in seed weight, even at the high sowing density,

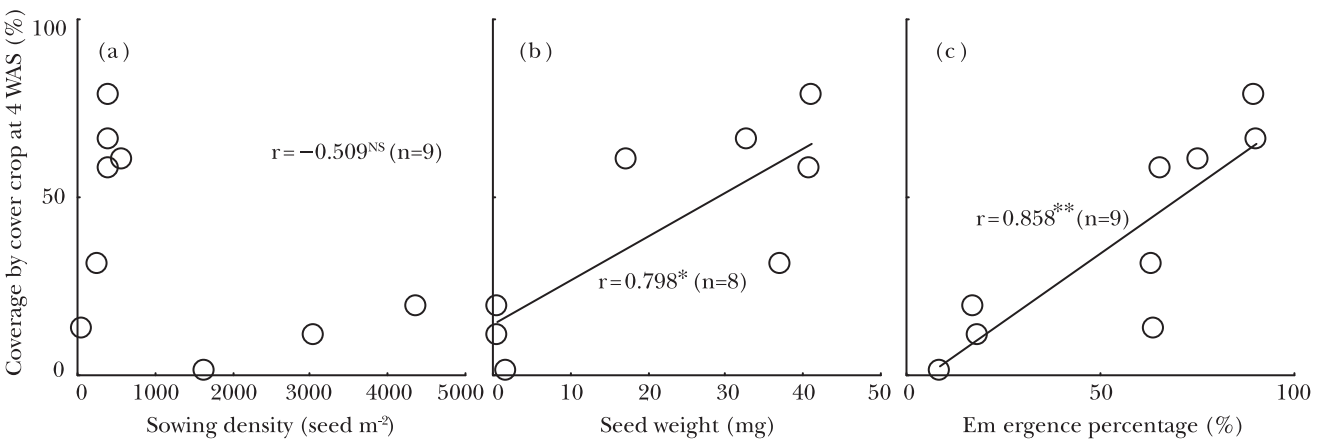


Fig. 2. Relationships between coverage by cover crop at 4 weeks after sowing and seed characteristics of cover crops, including (a) sowing density, (b) seed weight and (c) emergence percentage in 2003. Purple vetch was excluded from the statistical analyses because of its inferior seed quality, and marigold was excluded from (b) because coated seeds were used. * Significant at 5% level of probability; ** Significant at 1% level of probability; NS, not significant.

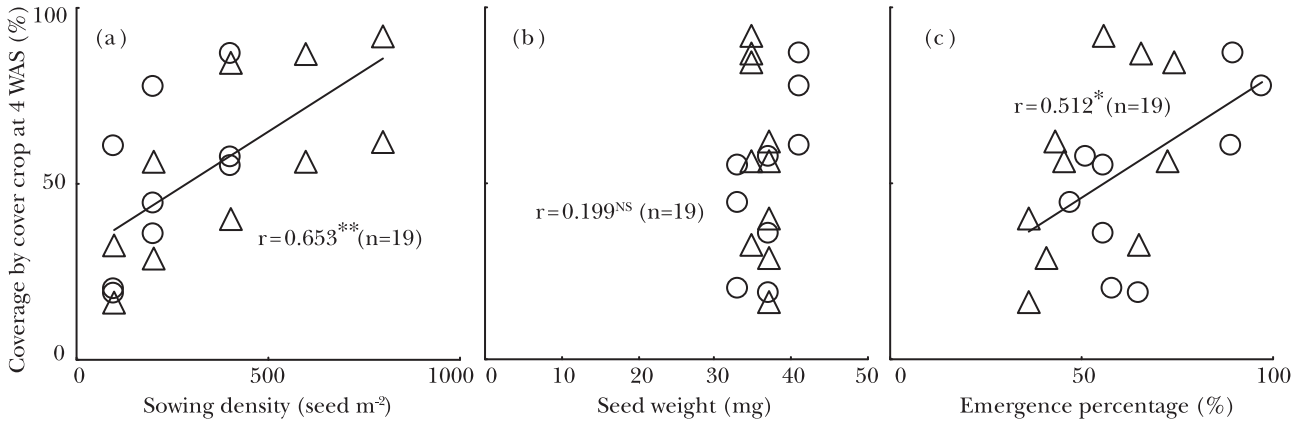


Fig. 3. Relationships between coverage by cover crop at 4 weeks after sowing and seed characteristics of cover crops, including (a) sowing density, (b) seed weight and (c) emergence percentage in 2004 and 2005. Correlation coefficients combining both the years are shown. The data of sowing density 0 seed m^{-2} in 2005 is not included. ○ , 2004; △ , 2005.* Significant at 5% level of probability; ** Significant at 1% level of probability; NS, not significant.

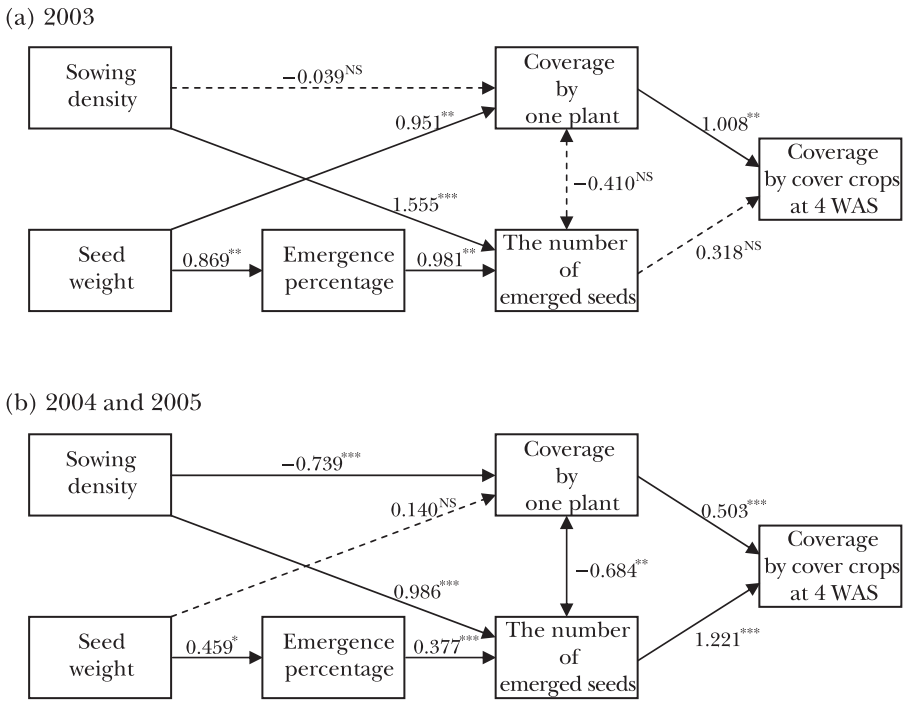


Fig. 4. Path coefficient analysis of coverage at 4 weeks after sowing (WAS) and seed characteristics of cover crops (a) in 2003 (n=8, except for purple vetch and marigold because of the inferior seed quality and the use of coated seeds, respectively) and (b) in 2004 and 2005 (n=19, except for sowing density 0 seed m^{-2} in 2005). The solid lines indicate significant relationships and the dashed lines indicate non-significant relationships. The single-headed arrows indicate path coefficients, and the double-headed arrows indicate simple correlation coefficients. * Significant at 5% level of probability; ** Significant at 1% level of probability; *** Significant at 0.1% level of probability; NS, not significant.

the light seed weight cover crops (Table 1), such as clovers, had a markedly low coverage relative to the other cover crops (Table 3). Therefore, the sowing density did not correlate significantly with the cover crop coverage. However, the seed weight and the emergence percentage of cover crops were significantly and positively correlated with the coverage by the crops.

In 2004 and 2005, we used three and two cover crops, respectively, that had comparatively heavy seed weights. Unlike in 2003, the sowing density and the emergence percentage correlated significantly and positively with the cover crop coverage at 4 WAS, however, this was not the

case for the seed weight (Fig. 3).

Figure 4 shows a path coefficient diagram to clarify the causal relationships between the seed characteristics of cover crops and the coverage at 4 WAS. In this diagram, the cover crop coverage at 4 WAS is hypothesized to be dependent upon two variables, the coverage by one plant and the number of emerged seeds. The number of emerged seeds was calculated by multiplying the two variables, the sowing density and the emergence percentage, and the coverage by one plant was calculated by dividing the cover crop coverage at 4 WAS by the number of emerged seeds. We also hypothesized that the sowing density and seed weight were initial variables, because when we use cover crops, we can adjust these only two characteristics, i.e., we can change the sowing density by increasing/decreasing seed number and also can change the seed weight by selecting other cover crop species.

In 2003, the coverage by one plant had a significant positive effect on the cover crop coverage at 4 WAS, but the number of emerged seeds did not (Fig. 4a). In addition, the coverage by one plant was affected significantly and positively by the seed weight but not by the sowing density. This diagram, therefore, indicates that the cover crop coverage at 4 WAS became higher by the increase of seed weight primarily via increasing the coverage by one plant, when we used cover crops with large variation in seed weight.

In 2004 and 2005, unlike 2003, both the coverage by one plant and the number of emerged seeds had a significant positive effect on the cover crop coverage at 4 WAS (Fig. 4b). This positive effect on the cover crop coverage was stronger for the number of emerged seeds than for the coverage by one plant according to the standardized regression coefficients. The number of emerged seeds was affected significantly and positively by both sowing density and seed weight via emergence percentage, but this positive effect was stronger for sowing density than for seed weight. The sowing density also had a negative indirect effect on the cover crop coverage at 4 WAS via the coverage by one plant ($-0.739\times0.503=-0.371$), but this negative effect was weaker than the positive indirect effect on the coverage at 4 WAS via the number of emerged seeds ($0.986\times1.221=1.203$). This diagram, therefore, demonstrates that the cover crop coverage at 4 WAS became higher by the increase of sowing density primarily via increasing the number of emerged seeds, when we used cover crops with small variation in seed weight.

Discussion

1. Effect of cover crop characteristics on weed suppression

In the present study, the plant height of cover crops had less effect on the weed dry weight at 10 WAS (Table 7). However, the plant height is generally thought to be one of the factors influencing the competition between plants. For example, Appleby et al. (1976) compared yield reductions by weeds among four winter wheat cultivars, and concluded that the plant height of winter wheat is correlated positively with its competitiveness against weeds. Jennings and de Jesus (1968) also found that taller cultivars had higher competitiveness than shorter cultivars by comparing five rice cultivars. The reason for the discrepancy between the results of the present study and the previous reports may be that one crop species with a similar plant type (leaf number, leaf length, leaf area, etc.) was used in the previous studies, while different crop species with large variations in plant type were used in our study. In the present study, characteristics other than the plant height of cover crops had a significant effect on weed suppression.

The multiplied dominance ratio is considered to be one important indicator for the intensity of competition between weeds and crops (Kobayashi et al., 2003). In the present study, however, the correlation coefficients between multiple dominance ratio of cover crops and weed dry weight were not consistently significant, mainly due to a weak correlation between the plant height of cover crops and the weed dry weight (Table 7). This difference between the results of our study and previous study may be related to the difference in weed species dominated in the fields. Further experiments should be needed to address this issue in details.

Two cultivars of winter rye with high coverage from 4 WAS could suppress weed dry matter production sufficiently (Fig. 1) in spite of their low plant height (Tables 3, 4, 5). Therefore, we suggest that weeds can be controlled by increasing the coverage by the cover crop from the early growth stage, even if the plant height is low. These characteristics of the cover crop may be beneficial for inclusion into mixed cropping or intercropping system, especially when plant height of the main crop is higher than that of the cover crops. This may be because competition for light between the main crop and cover crop is small due to the low plant height of the cover crop. However, the weed dry weight in the present study was not so light even in the most suppressed treatment in each year (161, 76 and 336 g m^{-2} in 2003, 2004 and 2005, respectively). If the same amount of weeds grows in the crop production systems, the yields of the main crop may be decreased. Therefore, it is important to integrate the use of cover crops with proper crop management practices, such as late sowing of cover crops (Uchino et al., 2009), for successful inclusion of the cover crop into the main crop production systems.

Peachy et al. (1999) reported that the degree of weed suppression depends on soil cover crop coverage. Bilalis et al. (2003) investigated the correlation between percentage

of soil cover by crop residue (dead mulch) and the weed dry weight and found a significant negative correlation between them. In addition, Teasdale and Mohler (1993) studied the effect of the crop residue of rye and hairy vetch on weed growth, and concluded that these two cover crops suppress weed emergence because of the reduction of light transmittance derived from soil covering. A close relationship between the coverage and weed suppression was also found in our previous study in the intercropping system with main crops and cover crops (Uchino et al., 2009). In the present study, the cover crop coverage at both 4 and 10 WAS correlated significantly with weed dry weight at 10 WAS for three years, whereas there were no significant correlations between the plant height and the weed dry weight (Table 7). The cover crop coverage is, therefore, considered to be a more accurate characteristic than the plant height of cover crops to evaluate weed suppression by cover crops.

It is noteworthy that the procedure to measure the coverage is simple and nondestructive. Investigations using the coverage requires only pictures taken above the plant communities in the experimental field, which requires less than one minute for each plot. After taking the pictures, the coverage can be analyzed at any time on a computer. Rasmussen et al. (2007), who investigated suitable light conditions, camera tilt angles and image analysis methods to estimate leaf cover by using a digital camera, also reported the conciseness of the coverage measurements.

In addition, the present study suggests that the weed growth may be suppressed more effectively with an increase in the sowing density of cover crops, because the weed dry weight was lighter at a higher sowing density due to the increased cover crop coverage irrespective of the plant height (Tables 4, 5; Fig. 1). In 2005, when the temperatures from sowing to emergence were high, however, the emergence percentage and the coverage by hairy vetch decreased markedly and did not suppress weed growth even at a higher sowing density (Table 5; Fig.1). This may be caused by the differences in optimum temperature for germination between hairy vetch and weeds. The optimum germination temperature for hairy vetch is 15−23ºC (Brar et al., 1991; Mosjidis and Zhang, 1995), and 35ºC for redroot pigweed (Steckel et al., 2004). Further investigations are needed to clarify the effect of temperature on weed suppression by cover crops.

2. Effects of seed characteristics of cover crops on the coverage at the early growth stage

The path coefficient diagram in 2004 and 2005 revealed the positive effect of sowing density on the cover crop coverage by increasing the number of emerged seeds, when we used cover crops with small variation in seed weight (Fig. 4b). The path coefficient diagram in 2003 also indicated that seed weight had a positive effect on the cover crop coverage at 4 WAS by increasing the coverage by one plant (Fig. 4a). This positive relationship between the seed weight and the coverage at the early growth stage is well supported by Wulff (1986) and Jurado and Westoby (1992) who reported that the heavy seed-weight species are superior to the light seed-weight species because of better growth at the seedling stage and at the late growth stages. Light seed-weight species are reportedly more susceptible to the change in microsite (litter distribution and composition etc.) and the fluctuation of microclimate (soil temperature and moisture etc.) than heavy seed-weight species (Winn, 1985). These results suggest that to increase the cover crop coverage at their early growth stage it is important not only to increase the sowing density but also to use cover crop species with a heavy seed weight.

The superiority of cover crops with a heavy seed weight in the present study may be related to the light seed weight of dominant weeds in our field (e.g. seed weight of redroot pigweed was 0.39 mg). The early growth of weeds with a light seed weight was considered to be inferior to that of cover crops with a heavy seed weight for the same reason as explained above. However, the effect of cover crops in fields dominated by weeds with a heavy seed weight is not clear in our results and should be addressed in further experiments.

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