JARQ 46 (1), 15 – 25 (2012) http://www.jircas.affrc.go.jp

REVIEW
Development and Implementation of an Environmentally Conscious System for Producing Cruciferous Vegetables by Small Farms in a Hilly and Mountainous Area of Western Japan

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Abstract

We report here on the development of a system for producing cruciferous vegetables without using chemical pesticides. This system enables small-scale farmers in hilly and mountainous areas in the western region of Japan to grow products of equivalent volume and quality to those produced by standard practices. The first steps in developing the system involved modifying and creating methods to protect cruciferous vegetables against insect pests. Crops were protected from flying pests, such as the white cabbage butterfly, cabbage armyworm, diamondback moth, cabbage sawfly, leafminer fly, cabbage bug, striped flea beetle, and brassica leaf beetle using a 0.6 mm mesh screen. *Bacillus thuringiensis* preparations, the use of which is permitted by Japanese Agricultural Standards for organic plants and organic processed foods of plant origin, were used to prevent damage caused by butterfly larvae, (white cabbage butterfly, cabbage armyworm, and diamondback moth) that hatch from eggs deposited on the outer surface of the screen through which they can invade. Invasion by crawling pests, such as the striped flea and brassica leaf beetles, was suppressed by covering the ground around the greenhouse with a mulching sheet to control weeds that form the habitat for these pests. Aphids passing through the 0.6 mm mesh screen were eliminated by a banker plant system employing the aphid parasite *Diaeretiella rapae* (McIntosh), a natural predator. Solarizing the soil before cultivation destroyed the pests' larvae, pupae, or eggs residing underground, such as those of the striped flea beetle and cutworm, while pest damage by vegetable weevils was prevented by inserting our newly invented traps just underground. The second step in developing the system involved dealing with higher greenhouse temperatures during summer that would result from the 0.6 mm mesh screen cover. To keep the wet bulb globe temperature (WBGT) around the worker within acceptable limits, a battery-powered ventilator consisting of a cart, fan, solar battery, and ordinary battery was used as well as installing simple roof windows, all of which effectively lowered the WBGTs. By combining these methods, we were able to demonstrate that the system was highly effective for producing quality cruciferous vegetables in greenhouses and in open fields.

Discipline: Horticulture
Additional key words: Banker plant system, integrated pest management, insect proof screen, organic farming, solarization

Introduction

In the western region of Japan, which consists of the Kinki, Chugoku, and Shikoku districts, hilly and mountainous areas form 74% of the gross area and are where fifty-six percent of farmers in this region work, encompassing 57% of the region's farmland. Agriculture is the principal industry here, mostly involving rice production by relatively small farms. Crops other than rice, mean-

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Received 14 January 2011; accepted 22 June 2011.

while, are cultivated in rice fields because of the government's policy directing that rice production must alternate with other crops, including vegetables.

Many of the vegetables raised by small farmers are sold at farmers' markets, which have recently proliferated throughout Japan. Customers prefer vegetables from farmers' markets to those of supermarkets, because of their price, freshness, and perceived safety, while customers' ability to identify the producer is also key. Generally, customers prefer products treated minimally, or not at all, with pesticides, hence minimizing or eliminating their use is an important economic consideration for farmers.

However, farmers have been reluctant to reduce the use of pesticides because of their efficacy. We therefore attempted to establish a system for the profitable production of vegetables in suitable quantities, of the quality expected by customers, and without using chemical pesticides. We initially surveyed the types of vegetables grown and their associated insect pests in Miyama town (at present, Miyama, Nantan city) in Kyoto Prefecture, which is a typically hilly and mountainous area. Vegetables most frequently grown there included the following: cruciferous vegetables such as cabbage, Chinese cabbage, Japanese radish, turnips, komatsuna (spinach mustard), and broccoli. Solanaceous vegetables such as tomatoes, eggplant, and sweet pepper were grown less frequently. Cruciferous vegetables are often found to be infested by a variety of insect pests, hence we focused on their elimination from open fields and greenhouses. Among the significant cruciferous vegetable pests that we targeted were the striped flea beetle, *Phyllotreta striolata* (Fabricius); brassica leaf beetle, *Phaedon brassicae* Baly; cabbage bug, *Eurydema rugosa* Motschulsky; leafminer fly, *Agromyzidae* sp; cabbage sawfly, *Athalia rosae ruficornis* Jakovlev; white cabbage butterfly, *Pieris rapae crucivora* Boisduval; cabbage armyworm, *Mamestra brassicae* (Linnaeus); diamondback moth, *Plutella xylostella* (Linnaeus); cutworm, *Agrotis segetum* (Denis et Schiffermüller); turnip aphid, *Lipaphis erysimi* (Kaltenbach); green peach aphid, *Myzus persicae* (Sulzer); and vegetable weevil, *Listroderes costirostris* Schoenherr.

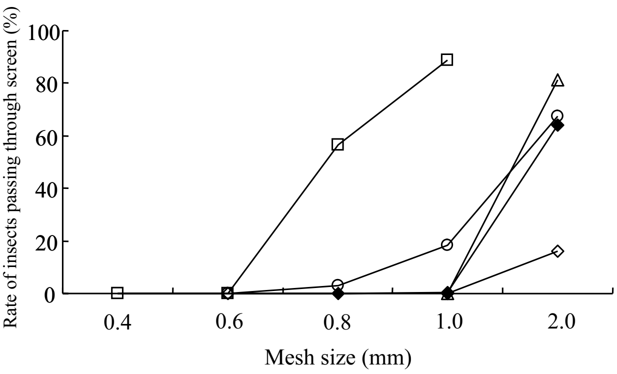


Fig. 1. Ability of major cruciferous vegetable insect pests (adults) to pass through mesh screens

Two plastic boxes were positioned adjacent and a 7-cm diameter pot containing 6–8 komatsuna plants was placed into one of the boxes, and 50 to 150 insect pests into the other. Rectangular cutouts (20 × 10 cm) were made in the adjoining sides of each box, the openings of which were covered with insect-proof screens with mesh of 0.4, 0.6, 0.8, 1.0, or 2 mm. The boxes were closed and left for 24 h at 22–25°C, at which time we counted the number of insects in the box with the komatsuna plants.

—□— : striped flea beetle,
—○— : garden pea leafminer,
—◆— : diamondback moth,
—△— : brassica leaf beetle, —◇— : cabbage sawfly

Insect proof screens

The most effective way to prevent insects from entering a greenhouse is to cover all openings with insect proof screens, which also protects field crops growing in tunnels. However, choosing screens with optimum mesh size for cruciferous vegetables was a challenge. We investigated the abilities of relatively small but important crucifer pests, specifically adult striped flea beetles, garden pea leafminers, diamondback moths, brassica leaf beetles, cabbage sawflies, and aphids, to pass through 0.4 mm to 2 mm mesh screens[8,10]. All passed through the 2.0 mm mesh screen, while the 1 mm mesh blocked only brassica leaf beetles, cabbage sawflies, and foxglove aphids. The 0.8 mm mesh screen blocked these and the

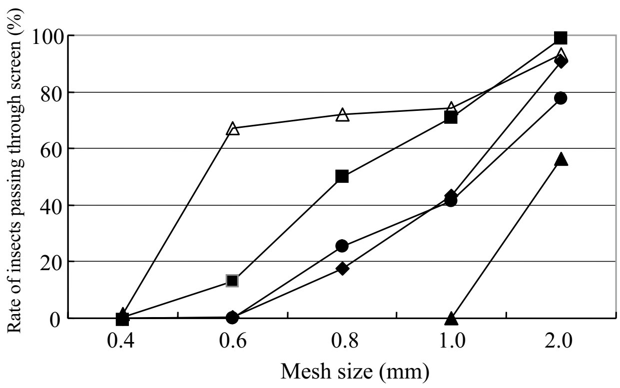


Fig. 2. Ability of alate adult aphids to pass through mesh screens

The procedures were the same as those described in the legend for Fig. 1.

—△—: cotton aphid, —■—: green peach aphid,
—◆—: turnip aphid, —●—: cabbage aphid,
—▲—: foxglove aphid.

diamondback moth, but not others. The 0.6 mm mesh screen blocked garden pea leafminers and striped flea beetles, but not cotton aphids, green peach aphids and, to a very low but significant extent, turnip aphids and cabbage aphids (Figs. 1, 2). Although the 0.4 mm mesh screen blocked the passage of all these insects, we chose the 0.6 mm mesh screen because it proved the most suitable for growing cruciferous vegetables, provided better ventilation, and was far more affordable than the 0.4 mm mesh screen. In contrast, we had to deal with aphids using a biological approach discussed later. Tiny larvae, such as those of the white cabbage butterfly, cabbage armyworm, and diamondback moth hatched from eggs deposited on the outer surface of the screen and could not be prevented from passing through even the 0.4 mm mesh screen. Spraying *Bacillus thuringiensis* preparations (BT insecticides) prevented damage by these pests. Note that the Japanese Agricultural Standards for organic plants and organic processed foods of plant origin permit the use of BT insecticide.

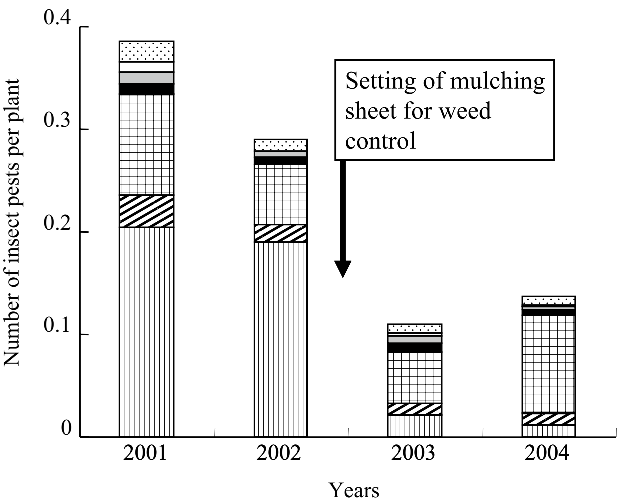


Fig. 3. Ability of mulching sheets placed around a greenhouse to control the pests inside

A 1.5-m wide section of ground around the greenhouse's perimeter was covered with mulching sheets to control weed growth at the end of 2002.
: others, : leafminer flies,
: cabbage sawflies,
: white cabbage, butterflies,
: vegetable weevils, : striped flea beetles,
: brassica leaf beetles.

Mulching sheets for weed control

The three important coleopteran pests, namely the striped flea beetle, brassica leaf beetle and vegetable weevil, invade greenhouses through narrow openings between the plastic film surrounding the house and the ground, meaning even a 0.6 mm mesh screen was ineffective in preventing their penetration. However, their range is relatively short, and they inhabit grassy places, invading greenhouse in which vegetables are grown. Mowing reduces insect numbers, but is laborious and time-consuming. Instead, we found that covering the ground around the house with 1.5 m of wide mulching sheets for weed control could control weeds and significantly reduced damage from striped flea and brassica leaf beetles, although not that due to vegetable weevils (Fig. 3)[9].

Trap for vegetable weevils

Mulching sheets for weed control failed to reduce weevil damage, since these insects reside underground. Therefore, we constructed a simple trap consisting of a vinyl chloride pipe (φ40–55 mm), into which a lengthwise 15 mm-wide cut was introduced. After capping the pipe at both ends (Fig. 4) it was placed just underground

Fig. 4. Vegetable weevil traps

so that the cutout was exposed on the surface (Fig. 4). If a vegetable weevil crawling on the ground surface drops into the trap, it cannot escape. This trap effectively reduced this pest's ability to damage crops. (Fig. 5).

Banker plant system for aphid pests

Invasion of aphid pests could not be completely prevented by using the 0.6 mm mesh screen. To suppress their infestation, a banker plant system for cruciferous vegetables was developed, which maintained a colony of a particular natural enemy in the greenhouse during crop cultivation[20]. It consisted of banker plants infested with alternative hosts, which infested the banker plant but not the crop, and the natural enemy that fed on both the target pests and the alternative hosts. The main aphid pests of cruciferous vegetables are the turnip aphid, cabbage aphid, and green peach aphid. We employed *Diaeretiella rapae* (McIntosh), the natural enemy of these aphids. Corn leaf aphids (*Rhopalosiphum maidis* (Fitch)) and barley (*Hordeum vulgare* L.) were respectively adopted as alternative hosts and the banker plants. Meanwhile, several barley plants were grown in a planter and infested with corn leaf aphids before introducing the natural enemy. A set of four such planters per 1000 m^2 effectively suppressed aphid damage to a komatsuna grown without pesticides (Fig. 6).

Soil Solarization

Insect pests such as the cabbage sawfly, striped flea beetle, brassica leaf beetle, vegetable weevil, cutworm and cabbage armyworms, spend part of their life cycles underground as eggs, larvae, or pupae, and some larvae infest crop roots. Moreover, there are usually many seeds of weeds underground, while weeds on their own hamper crop cultivation. Soil solarization can effectively eradicate insect pests and weeds in the soil[4]. In Japan, the hottest period with the most abundant sunshine is from just after the rainy season in late July to mid-August. To solarize the soil after appropriate fertilization, the field is furrowed and the ridges watered. The ridges are then covered with transparent plastic film, such as mulching and covering films, fixed securely in place and left undisturbed. The film is subsequently removed after about 1 month, just before sowing or planting seedlings. Figure 7 shows the temperature changes at three depths (10, 20 and 30 cm) from August 4 to September 3 in our field in Ayabe. The highest daily temperature exceeded 70ºC at the surface, and 50 and 45ºC, respectively, at depths of 10 and 20 cm.

Soil solarization has been considered effective in preventing soil-borne diseases[3,13,15]. Various soil-borne pathogens reside at varying depths. For example, the clubroot pathogen, *Plasmodiophora brassicae*, resides mainly above depths of 20 cm, while *Erwinia carotovo-*

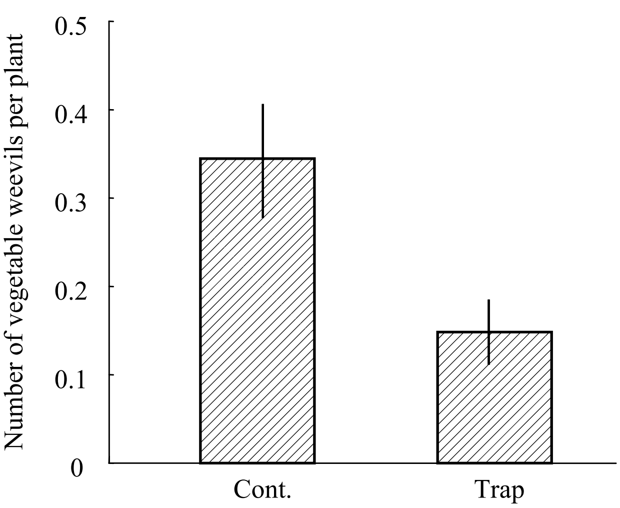


Fig. 5. Effect of setting traps in reducing the density of vegetable weevils on komatsuna plants cultured without pesticides in a greenhouse

Vertical lines indicate standard errors. The densities of adults and larvae of vegetable weevils were determined twice a month from December 2004 to April 2005. The difference between the treatments was significant at $P = 0.01$ by t-test.

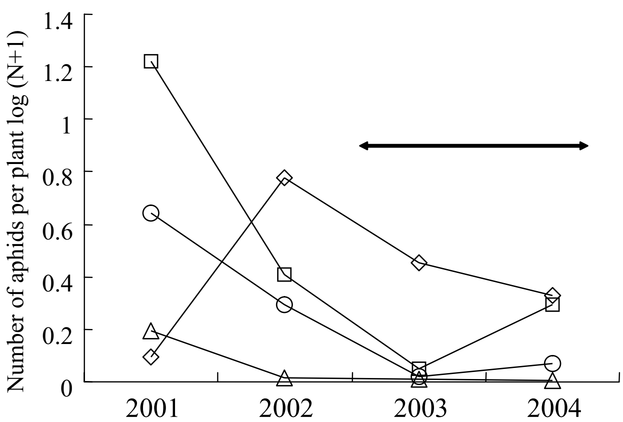


Fig. 6. Effect of a greenhouse banker plant system on aphid densities on komatsuna plants cultured without pesticides

The banker plant system employed *Diaeretiella rapae* as the natural enemy, corn leaf aphids as the alternative host, and barley (*Hordeum vulgare* L.) as the banker plant. The horizontal arrow indicates the time intervals during which the systems were used in greenhouses 3 and 4.

—◇—: House 1, —□—: House 2,
—△—: House 3, —○—: House 4.

ra, the etiological agent of soft rot, is found below 30 cm[7]. Shimizu et al[16] reported that more than 230 hours at 40ºC was required to kill *P. brassicae*. In our 2004 experiment (Fig. 7), soil temperatures exceeding 40ºC lasted 305 and 157 h in total at depths of 10 and 20 cm, respectively. This result suggests *P. brassicae* ground infestation would not have been eradicated.

Moderating temperatures in greenhouses during summer

In greenhouses with all openings covered by 0.6 mm mesh screens, temperatures become very high during the day in summer due to restricted ventilation. ISO 7243 states that workers' health is endangered when working in structures in which the wet bulb globe temperature (WBGT) exceeds 32.5ºC[14]. Figure 8 shows changes in the WBGT in greenhouses with and without 0.6 mm mesh screens during a hot summer. The WBGT in a screened greenhouse exceeded 32.5ºC from 8 a.m. to 4 p.m., and was approximately 3–7ºC higher than that in an unscreened greenhouse during the same time[17]. We

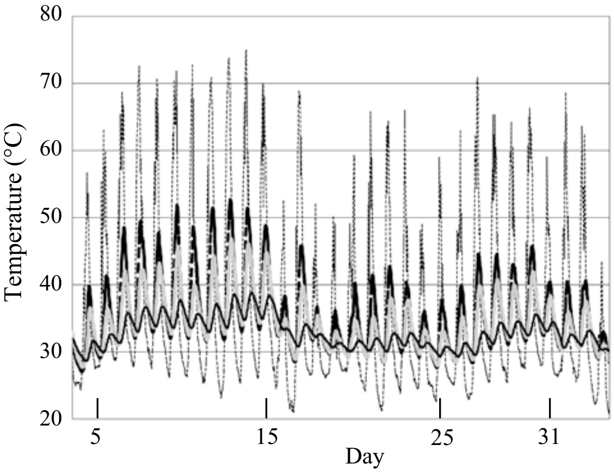


Fig. 7. Temperature of solarized soil at different depths during August 2004
Solarization was started on 4 August and ended on 3 September, 2004.
----- : Surface, — — : 10cm deep, —— :20cm, —— : 30cm.

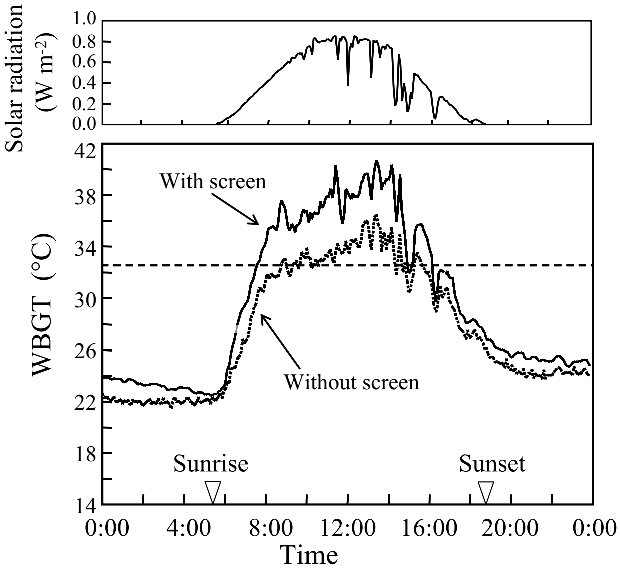


Fig. 8. WBGT values in a greenhouse covered with a 0.6 mm mesh screen
WBGT was measured at a point 1.6 m high in the center of the greenhouse on 23 August, 2003. Maximum wind velocity was 2.8 m s^{-1}.

Fig. 9. Roof windows for lowering WBGT values
Five roof windows 0.5-m wide and 2-m long were attached to a 110-m^2 greenhouse. The ratio of total roof window area to floor area of the house was 0.045.

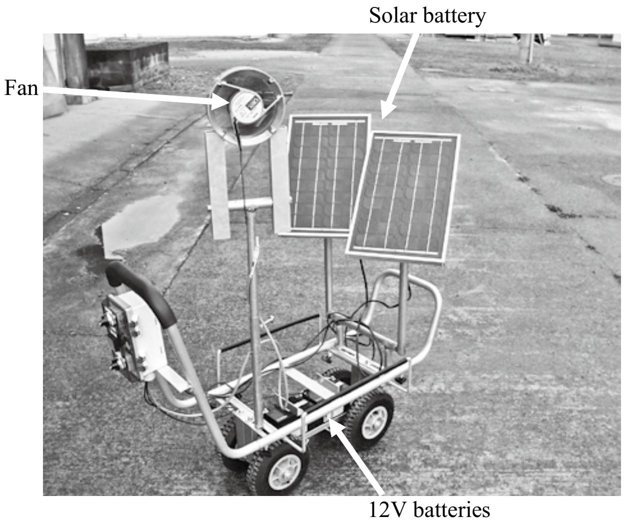


Fig. 10. Solar-powered forced airflow system

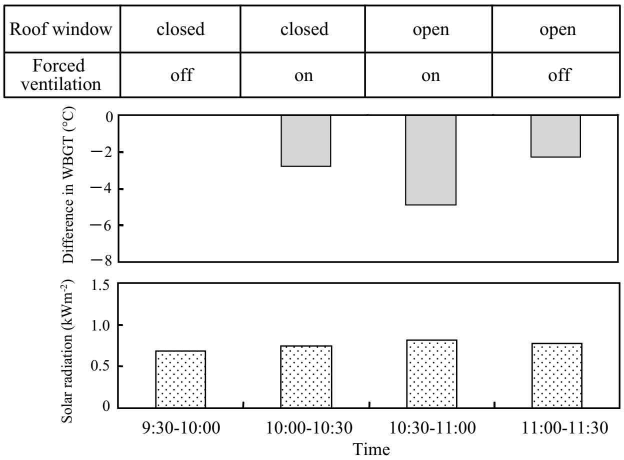


Fig. 11. Effects on WBGT of forced ventilation and roof windows installed in a greenhouse

A measurement was taken on August 26, 2004. Solar radiation values are mean measurements taken over 30-min intervals.

Table 1. Business analysis of komatsuna production in organic farming by the production system of cruciferous vegetables for greenhouse cultivation

	Marketable yield (kg)[1)]	Sales (yen)[1)]	Operating costs (yen)[1)]	Income (yen)[1)]	Total labor time (h)[1)]	Income per work hour[1)]
System[2)]	851	468,058	179,035	289,023	190	1,521
Control[3)]	447	245,810	114,300	131,510	225	585

[1)] These figures are for 1 cropping per 10 a.
[2)] Production by the established system.
[3)] Production by the farmer's usual practice.

decreased the WBGT by installing roof windows (Fig. 9) to promote natural ventilation. We also developed a battery-powered ventilator (Fig. 10) consisting of a cart, fan, and solar cell plus an ordinary battery[18]. This system, combined with the roof windows, lowered the WBGT by approximately 5ºC on warm days (Fig. 11)[19].

Greenhouse cultivation system

We combined all the above measures to produce cruciferous vegetables in a greenhouse and engaged a farmer who had been producing komatsuna year-round by organic (pesticide-free) farming in a greenhouse. As a control, komatsuna plants untreated with pesticides were cultivated in the farmer's other greenhouses with their openings covered by 1 mm mesh insect proof screens. Other cultivation conditions such as fertilization were the same in all the houses and in line with the farmer's usual practice.

We compared the yields of marketable products, sales, operating costs, income, total labor hours, and income per work-hour with that of the farmer's usual practice (Table 1). The marketable yields and sales of komatsuna produced by our system were 1.9-fold higher than that of the farmer's usual practice. Although the operating cost of our system was 1.57-fold higher, it yielded 2.2-fold more income than the farmer's practice. Via our system, the farmer's time for harvest and preparation was extended due to increased marketable yields, but time was saved by eliminating insect pests and weed control, resulting in an income per work-hour value 2.6-fold greater than that of the farmer's usual practice[12].

Field cultivation system

We developed a system for the field cultivation of cruciferous vegetables as discussed above by performing soil solarization, installing 0.6 mm mesh insect proof screens, and applying BT insecticides. Ridges were prepared in early summer and solarized until the day of sowing or planting seedlings in late August to early autumn. Just after sowing or planting, the ridges were completely covered so that 0.6 mm mesh insect proof screens, secured by stays, covered the tunnels. For 1.1 m wide ridg-

Fig. 12. Screen-tunnel culture

es, the use of 2.4 m stays and 2.3 m wide screens proved effective. The hem of the screen had to be buried[5] to eliminate openings between the screen and ground through which insect pests could invade (Fig. 12). If we found damage by butterfly larvae, BT insecticides were applied to the crops through the screen (once a month, or 2 to 3 times per cropping season).

Table 2 shows the results for cultivating cabbage, Chinese cabbage, Japanese radish, and turnips at the Ayabe research station[1]. The conditions for the test and control plots were identical except for the omission of solarization and tunneling for the latter. For both conditions, no chemical fertilizers or pesticides were applied, and only commercial 100% organic fertilizer was used. We tested two commercial varieties of each vegetable. Butterfly larvae severely damaged cabbages and Chinese cabbages in control plots (Fig. 13), and the yields of mar-

Table 2. Results for trial cultivation of cabbage, Chinese cabbage, Japanese radish, and turnip by the production system for open culture

Cabbage

Variety	Treatment	Number of products[1)]	Mean weight of the products (kg)	Mean level of pest damage[2)]	Rate of marketable products (%)
Bloodyball	System	46	1.5	0.17	98
	Control	38	1.0	1.39	40
Kinkei 201	System	47	1.3	0.04	96
	Control	41	0.9	1.06	40

Chinese cabbage

Variety	Treatment	Number of products[1)]	Mean weight of the products (kg)	Mean level of pest damage[2)]	Rate of marketable products (%)
Daifuku	System	38	3.7	0.50	84
	Control	37	2.5	1.82	14
Musou	System	34	4.3	0.74	85
	Control	33	3.0	1.62	32

Japanese radish

Variety	Treatment	Yield (kg/a)	Mean weight of products (kg)	Pest damage to the crop surface[3)]	Rate of marketable products (%)
YR Kurama	System	714	2.04	0.18	90
	Control	536	1.29	0.98	50
Yakusha-yokocho	System	660	1.98	0.09	88
	Control	426	1.00	0.83	61

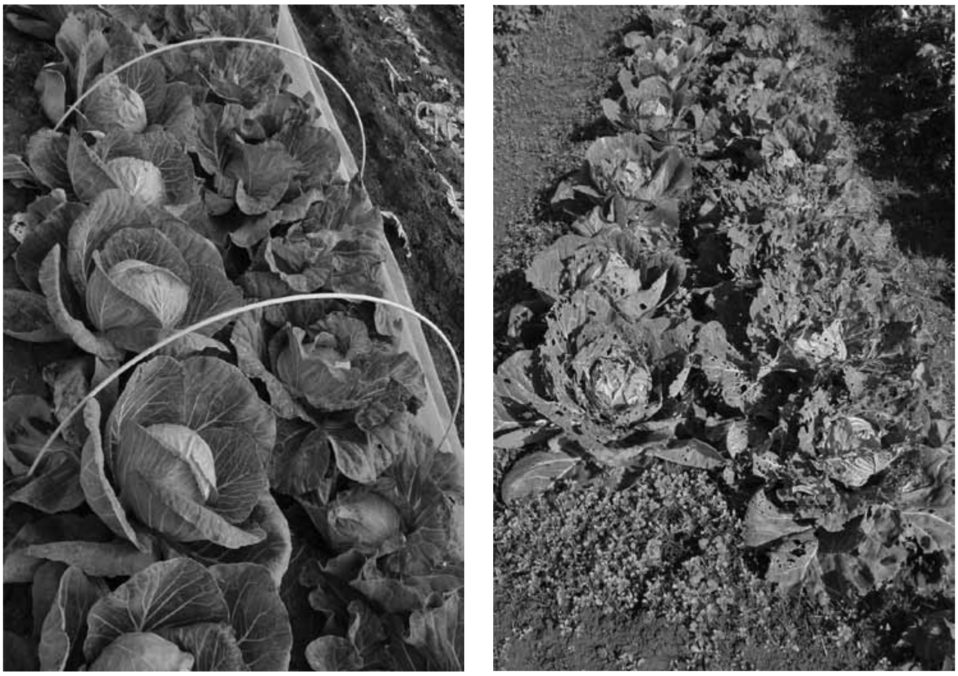
Turnips

Variety	Treatment	Yield (kg/a)	Mean weight of products (kg)	Pest damage to the crop surface[3)]	Rate of marketable products (%)
Swan	System	300	275	0.3	93
	Control	194	245	1.3	42
Kyousenmai	System	355	325	0.0	96
	Control	251	293	0.8	53

1) Total number of harvested products

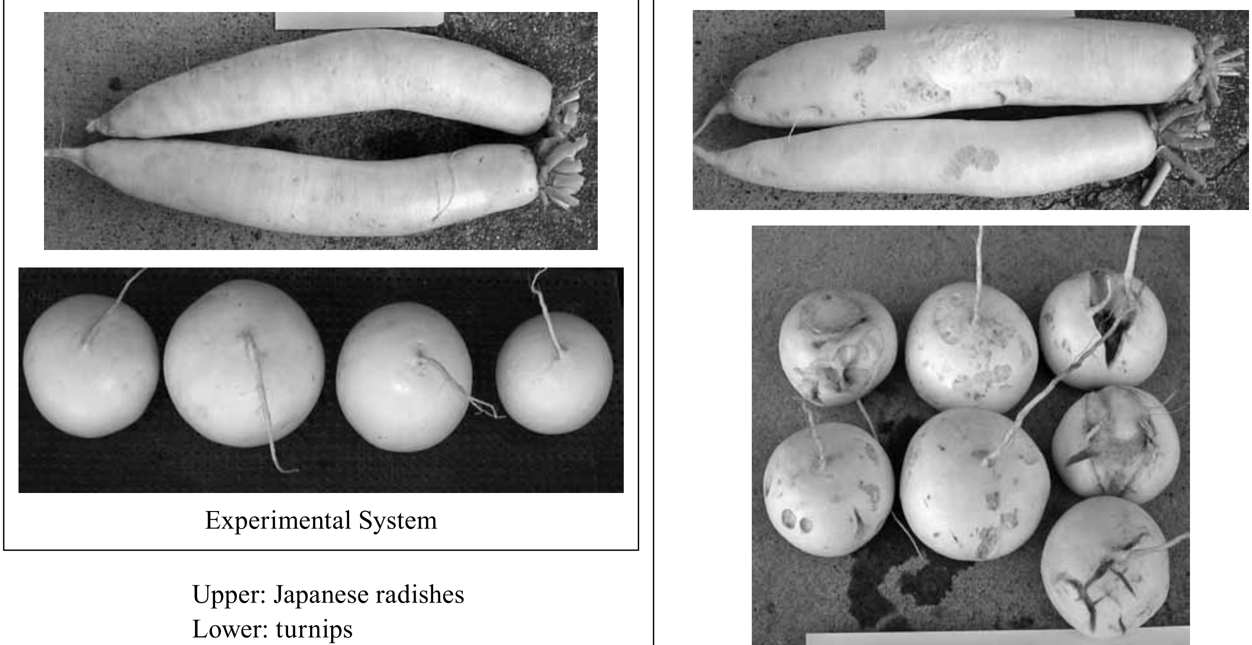
2) Products with no pest damage were assigned a "0." Those with slight damage were assigned "1," and those with heavy damage were assigned "2."
The mean level of pest damage was calculated by dividing the sum of the points of all products by the total number of harvested products.

3) Products with unhurt surface were assigned point 0. Those with slightly damaged surfaces were given 1 point and those with severely damaged surfaces were given 2 points.
Pest damage to the crop surface was calculated by dividing the sum of the points of all products by the total number of harvested products.



Experimental System Control

Fig. 13. Comparison of crops produced by the experimental system relative to the control



Experimental System

Upper: Japanese radishes
Lower: turnips

Control

Fig. 14. Comparison of crops produced by the experimental system relative to the control

Table 3. Experimental cabbage cultivation by individual farmers

Farmer	Culture area (m^2)	The number of seedlings planted	The number of times of BT treatments	The number of products harvested	The number of products damaged by insect pests	The number of products sent to market	Rate of marketable products (%)
No. 1	25	110	3	110	1	109	99
No. 2	97	292	2	292	6	292	100
No. 3	27	100	1	92	10	82	82
No. 4	60	141	2	141	0	141	100
No. 5[1)]	34	140	2	82	0	82	59
No. 6	22	85	2	85	0	85	100
No. 7	37	70	2	65	10	54	77
No. 8	28	97	1	97	1	97	100
No. 9	53	280	2	275	6	263	94

[1)] Bacterial soft-rot infection

ketable products harvested were 40 and 14-32% for cabbage and Chinese cabbage, respectively. In striking contrast, the test plots were not damaged by butterfly larvae. Marketable product yields exceeded 96 and 84% for cabbage and Chinese cabbage, respectively. The mean weights of the marketable products of both cabbage varieties from control plots were below the common level due to butterfly larvae damage, while those in the test plots were up to the level. Similarly, Japanese radish and turnip yields in the control plots were below standard, while those in the test plots were up to standard. Significant portions of both products in the control plots showed severe surface damage and were rendered unmarketable by ground-dwelling insects, likely larvae of the striped flea beetle (Fig. 14). In contrast, we observed little such damage in our system's test plots. Weeding was required in the control, but not the test plots (Fig. 13).

Nine farmers located in Miyama town conducted experimental cabbage cultivation using our system along with 100% organic fertilizer and only BT insecticide as pesticide (Table 3)[2]. Six farmers harvested marketable cabbages of good quality from 94-100% of the seedlings planted. The rates of pest-damaged products did not exceed 2.2%. Two farmers' cultivation (Nos. 3 and 7 in Table 3) rates of marketable products were around 80%. Spraying BT insecticide was delayed, which may have contributed to these lower rates. Farmer No. 5's 59% yield was due to an outbreak of bacterial soft rot. Cabbages had been cultured just before this experiment started, and bacterial soft rot had previously broken out. This fact reveals that the soil solarization performed before cultivation was not effective enough to disinfect the soil infected with the bacterial soft rot pathogen.

Conclusion and future studies

This study established methods for controlling almost all significant cruciferous vegetable insect pests. We prevented invasion by adult white cabbage butterflies, cabbage armyworms, diamondback moths, cabbage sawflies, leafminer flies, cabbage bugs, striped flea beetles, and brassica leaf beetles with 0.6 mm mesh insect proof screens. Invasion of striped flea beetles and brassica leaf beetles, which come crawling from weeds around the greenhouses, was prevented by covering the ground with 1.5 m wide mulching sheets to control weed growth around the greenhouse. Specially designed traps prevented weevil infestation, and a banker plant system controlled aphids. Underground-dwelling insect pests and weeds were eradicated by solarization. BT insecticides curbed damage by butterfly larvae, such as those of the white cabbage butterfly, diamondback moths, and the cabbage armyworm, which hatch from eggs deposited on the outer surface of the screen and invade the greenhouses or tunnels. By installing roof windows combined with a battery-powered forced airflow system, we reduced the WBGT during summer in greenhouses covered with 0.6 mm mesh screens.

By combining these methods, we developed a system for profitably producing cruciferous vegetables of high quality and quantity without using chemical pesticides. These systems can be applied to produce most cruciferous vegetables. Several kinds of 100% organic fertilizer containing known amounts of nitrogen, phosphate, and potassium are commercially available and can be used in our system in compliance with the Japanese Agricultural Standards for organic plants and organic processed foods of plant origin. Another key aspect of this new system is its affordability for small farms.

The insect pests studied here, as well as others, infest cruciferous vegetables grown in many parts of the world, including the highlands of most tropical countries[6]. We believe that our system is capable of eradicating insect pests from farms located in these areas, as well as in the whole of Japan.

The following problems, however, remain to be resolved: 1. *Diaeretiella rapae* and corn leaf aphids, both of which constitute the banker plant system, are not yet commercialized, but are found widely in fields in Japan; 2. Soil solarization is not effective enough to disinfect soil harboring soil-borne pathogens that cause diseases such as clubroot and soft rot. Furthermore, solarization is effective only when performed during summer in temperate zones similar to those in Japan. Soil disinfection techniques using steam[21] or hot water[11] have been developed and practiced to a limited extent. However, these require equipment that is too expensive for most small-scale farmers. Inexpensive soil disinfection techniques that can be performed as needed during the year must be developed to eradicate soil-borne diseases, insect pests and weeds. 3. We require more effective pesticide-free methods to control diseases like downy mildew that are transmitted above ground. At present cultural control such as planting crops at a proper density may be the only approach for this problem. When these problems have been solved, the environmentally conscious and organic production of cruciferous vegetables will likely spread more widely.

Acknowledgments

We greatly appreciate the contribution by the late Dr. Kazuo Tanaka as the leader for the first three years of this project. We are also grateful to Mr. and Mrs. Minazasa, Mr. and Mrs. Kido, Mr. Tsugio Shimizu, Mr. Kazuo Hirai, Mr. and Mrs. Kaisou and other farmers in Miyama town who cooperated with us and performed the experimental cultivation. We are also grateful to the officials of Miyama town office, especially Mr. Tadakazu Ohzawa, who cooperated with us in organizing farmers who tested our system. Finally, we would like to thank the staff of the Ayabe Research Station for their support.

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