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-
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* Boisdval; 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.

**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. 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...
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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.

**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

![Setting of mulching sheet for weed control](image)

**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.

![Vegetable weevil traps](image)

**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. 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 m² 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. 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 70°C at the surface, and 50 and 45°C, respectively, at depths of 10 and 20 cm.

Soil solarization has been considered effective in preventing soil-borne diseases. Various soil-borne pathogens reside at varying depths. For example, the clubroot pathogen, *Plasmodiophora brassicae*, resides mainly above depths of 20 cm, while *Erwinia carotovora*-
ra, the etiological agent of soft rot, is found below 30 cm². Shimizu et al. reported that more than 230 hours at 40°C was required to kill \( P. brassicae \). In our 2004 experiment (Fig. 7), soil temperatures exceeding 40°C 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 32.5°C. 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 32.5°C from 8 a.m. to 4 p.m., and was approximately 3–7°C higher than that in an unscreened greenhouse during the same time. We

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**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-m² greenhouse. The ratio of total roof window area to floor area of the house was 0.045.
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. This system, combined with the roof windows, lowered the WBGT by approximately 5°C on warm days (Fig. 11). 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.

**Greenhouse 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-
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es, the use of 2.4 m stays and 2.3 m wide screens proved effective. The hem of the screen had to be buried1 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 station1. 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-

![Fig. 12. Screen-tunnel culture](image)

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

<table>
<thead>
<tr>
<th>Cabbage</th>
<th>Mean weight of products (kg)</th>
<th>Mean level of pest damage (%)</th>
<th>Rate of marketable products (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Variety</td>
<td>Treatment</td>
<td>Number of products</td>
<td></td>
</tr>
<tr>
<td>Bloodyball</td>
<td>System</td>
<td>46</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td>Control</td>
<td>38</td>
<td>1.0</td>
</tr>
<tr>
<td>Kinkei 201</td>
<td>System</td>
<td>47</td>
<td>1.3</td>
</tr>
<tr>
<td></td>
<td>Control</td>
<td>41</td>
<td>0.9</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>Chinese cabbage</th>
<th>Mean weight of products (kg)</th>
<th>Mean level of pest damage (%)</th>
<th>Rate of marketable products (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Variety</td>
<td>Treatment</td>
<td>Number of products</td>
<td></td>
</tr>
<tr>
<td>Daifuku</td>
<td>System</td>
<td>38</td>
<td>3.7</td>
</tr>
<tr>
<td></td>
<td>Control</td>
<td>37</td>
<td>2.5</td>
</tr>
<tr>
<td>Musou</td>
<td>System</td>
<td>34</td>
<td>4.3</td>
</tr>
<tr>
<td></td>
<td>Control</td>
<td>33</td>
<td>3.0</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>Japanese radish</th>
<th>Yield (kg/a)</th>
<th>Mean weight of products (kg)</th>
<th>Pest damage to the crop products surface (%)</th>
<th>Rate of marketable products (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Variety</td>
<td>Treatment</td>
<td>Yield (kg/a)</td>
<td>Mean weight of products to the crop products</td>
<td>Rate of marketable products (%)</td>
</tr>
<tr>
<td>YR Kurama</td>
<td>System</td>
<td>714</td>
<td>2.04</td>
<td>0.18</td>
</tr>
<tr>
<td></td>
<td>Control</td>
<td>536</td>
<td>1.29</td>
<td>0.98</td>
</tr>
<tr>
<td>Yakusha-yokocho</td>
<td>System</td>
<td>660</td>
<td>1.98</td>
<td>0.09</td>
</tr>
<tr>
<td></td>
<td>Control</td>
<td>426</td>
<td>1.00</td>
<td>0.83</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Turnips</th>
<th>Yield (kg/a)</th>
<th>Mean weight of products (kg)</th>
<th>Pest damage to the crop products surface (%)</th>
<th>Rate of marketable products (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Variety</td>
<td>Treatment</td>
<td>Yield (kg/a)</td>
<td>Mean weight of products to the crop products</td>
<td>Rate of marketable products (%)</td>
</tr>
<tr>
<td>Swan</td>
<td>System</td>
<td>300</td>
<td>275</td>
<td>0.3</td>
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<td></td>
<td>Control</td>
<td>194</td>
<td>245</td>
<td>1.3</td>
</tr>
<tr>
<td>Kyousenmai</td>
<td>System</td>
<td>355</td>
<td>325</td>
<td>0.0</td>
</tr>
<tr>
<td></td>
<td>Control</td>
<td>251</td>
<td>293</td>
<td>0.8</td>
</tr>
</tbody>
</table>

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

Experimental System

Control

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

Experimental System

Upper: Japanese radishes
Lower: turnips

Control
Marketable 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). 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 cru-

| Table 3. Experimental cabbage cultivation by individual farmers |
|-----------------|-------------|-----------------|-----------------|
| Farmer          | Culture area (m²) | 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*          | 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                      |

*Bacterial soft-rot infection
ciferous 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\(^a\). 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\(^2\) or hot water\(^1\) 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. Mizazawa, 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.

References


68 [In Japanese].