INTEGRATED MANAGEMENT OF PADDY WEEDS IN JAPAN

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ABSTRACT

The area planted in rice in Japan in 1991 was 2.03 million ha for lowland paddy rice, and 16,000 ha for upland rice. Most paddy fields were transplanted by machine, using young seedlings in nursery boxes. Only 7,440 ha were dry- or wet-seeded. Japanese rice farmers usually apply herbicides twice each growing season to their transplanted fields. Of the recommended herbicides, the so-called "one-shot herbicides" have been the most popular in recent years.

The average total cost of weed control in Japanese paddy fields in 1990 was US$445/ha, of which US$201 was for labor, including the labor cost of spraying herbicide as well as manual weeding. Applied herbicides cost on average US$244/ha. Manual weeding is still common among small-scale rice farmers in Japan, and rotary weeders are also sometimes used. Cultural methods are effective in controlling propagules of perennial paddy weeds. Winter cultivation, especially plowing, has been found to be effective in drying out the tubers of perennial species so that they die. Crop rotation in paddy fields, growing alternate crops of soybean etc. and rice, was also useful in reducing paddy weeds during soybean culture, and upland weeds during paddy rice culture.

Integrated weed management (IWM) also plays a role in intensive Japanese rice cultivation, in order to reduce excessive chemical applications, avoid environmental pollution and reduce weeding costs. However, weed control at present in paddy fields is mainly based on chemical herbicides.

In future, we expect that the number of large-scale farmers will increase in response to new government policies, and that these farmers will be willing to cultivate crops rotationally in their paddy fields. They will therefore be able to control paddy weeds more effectively by ecological or cultural methods. Furthermore, the successful development of bioherbicides is expected to enable rice farmers to decrease chemical applications from two applications to a single application during each cropping season.

RICE CULTIVATION IN JAPAN

Of the 5.20 million ha of agricultural land in Japan in 1991, 2.03 million ha was planted in paddy rice (it should in fact have been 2.83 million ha according to the governmental policy restricting rice production). The most common method of planting rice, found in 99% of the total paddy area, is to use machinery to transplant young seedlings at the 2.0-5.0 leaf stage. Only 1% of fields were transplanted by hand. The transplanting of 'infant seedlings' at the 1.0-2.0 leaf stage or direct seeding is not yet common in Japan, and was found in only 625 ha and 7,440 ha, respectively. Of the latter, 4,945 ha were dry seeded, and 2,495 ha were wet seeded. There were also 16,000 ha of upland rice in 1991, all of which were dry seeded.

CURRENT METHODS OF WEED MANAGEMENT

Methods of weed management in agricultural fields in Japan differ according to the crop. Mainly chemical methods are used for paddy rice; chemical, mechanical and cultural methods are used for upland crops (including fruits and nuts); while manual,

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physical and cultural methods are used for vegetables and forage crops.

In paddy rice cultivation, manual weeding is still frequently carried out by small-scale farmers, particularly to eradicate barnyard grass. Rotary weeders are not common today, although some farmers like to use them to control perennial weeds which are tolerant of pre- or early post-emergence herbicides. However, a great deal of heavy labor is needed to operate them. Many farmers cultivate their paddy fields in late autumn or winter after harvesting the rice, to incorporate the rice straw or for other purposes. This is effective in reducing the number of perennial weeds by bringing their tubers or other propagules up to the soil surface, where they die during the cold, dry winter.

However, Japanese paddy farmers expect to control weeds in their fields mainly by the use of chemicals. They usually apply herbicides twice to each rice crop. They often supplement these by applying non-selective herbicides after harvesting rice or before planting it, to control regrowth from weed stubble or the growth of spring weeds.

Control of paddy weeds in Japan is therefore rather expensive. The cost of weed management includes herbicides, sprayers, and the labor required to spray chemicals, weed manually or weed with rotary weeders. Changes in the time required for weeding in Japanese paddy fields over 20 years is indicated in Fig. 1. In 1990, the 24 man-hours per ha required for weeding had a labor cost of US$201/ha (at a rate of US$8.3 per hour). The cost of herbicides in 1990 was US$244/ha, while the cost of the sprayers used to apply them was considered a very moderate annual expense because farmers could use them for all kinds of pesticides over several years. The total cost for weed control in Japanese paddy fields in 1990 was about US$445/ha. This represents 4.6% of the total cost of rice production (US$9,714/ha or US$1828/mt of brown rice), most of which was spent on machinery and labor.

Dry-seeded rice receives three herbicide applications, one pre-emergence and one post-emergence under dry conditions, with the third application a few days after the fields are flooded, 20 to 30 days after seeding. Manual weeding of barnyard grass before flooding is common in dry-seeded rice fields. Wet-seeded rice is given two applications of herbicide, one pre-emergence and one early post-emergence.

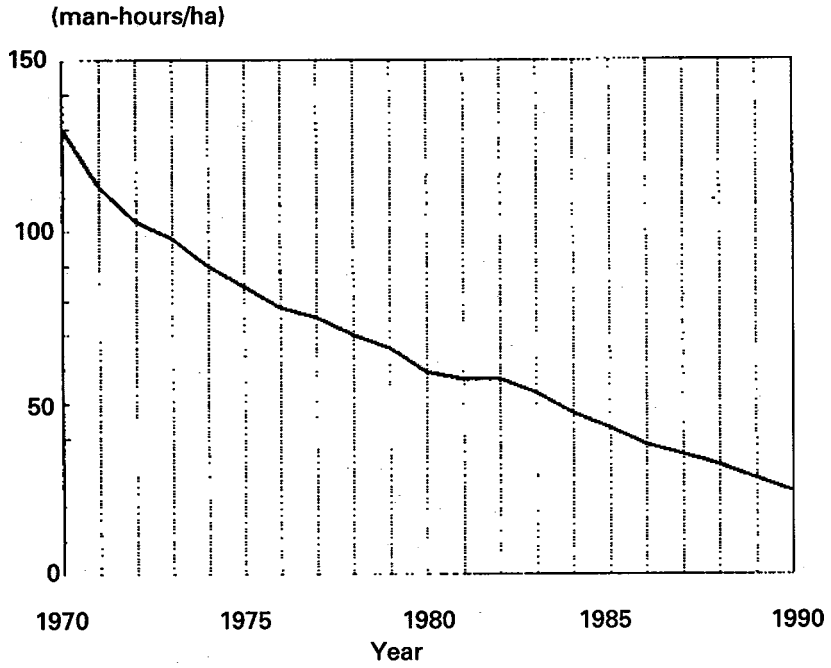

Fig. 1. Changes in weeding hours per ha in Japanese paddy fields. Note that weeding hours include those spent spraying herbicides as well as manual and mechanical weeding.

Herbicides are applied to upland crops on average about 1.2 times per cropping season, usually to the soil before the seedlings emerge. Upland rice may have one or two herbicide applications, one pre- and one post-emergence, and weeds may be eradicated by hand or by mechanical cultivation.

REGISTERED HERBICIDES USED FOR RICE IN JAPAN

The main registered herbicides for rice which have been introduced into, or developed in, Japan are listed in Table 1 (although the registration of a few of these has already been cancelled). Most of them are for transplanted rice, and they are usually sold in the market as mixtures of two or three active ingredients which can control annual and perennial

Table 1. Main registered herbicides for rice (including combination products) in Japan

Year	For paddy rice		For upland rice, dry-seeded rice and levees
	Single herbicides	*Combination products*	
1950	2,4-D		
	MCPA		
	Pentachlorophenol (PCP)		Simazine
1960			Diuron, Dalapon
	Propanil	*PCP • MCPA*	Propanil
	Nitrofen, MCPCA		Prometryn, Diquat
	2,4,5-T		
1965	Chlornitrofen (CNP)		Paraquat
	Swep		Swep, Trifluralin
	ACN	*Swep• MCPA*	
		Thiobencarb • simetryn	
1970	Thiobencarb	*Thiobencarb • CNP, Molinate • simetryn*	
	Oxadiazon	*Simetryn • MCPA - thioethyl*	
	Butachlor, Chlomethoxyfen		*Thiobencarb • prometryn*
	Daimuron		*MCPA • propanil • dalapon*
1975	Bentazon	*Dimethametryn • piperophos • bentazone*	Oxadiazon
		Bentazon • 2,4-D	
		Thiobencarb • simetryn • MCPB	
	Pyrazolate, Naproanilide		
1980		*Oxadiazon • butachlor*	Glyphosate
	Bifenox		*Propanil • dalapon*
		Pyrazolate • butachlor	
	Pretilachlor		
		Pyrazolate • pretilachlor	Bialaphos, Glufosinate
1985	Pyrazoxyfen, Dimepiperate		*Diquat • paraquat*
		Pyrazoxyfen • pretilachlor	
	Mefenacet, Bromobutide		
	Benzofenap, *Bensulfuronmethyl (BSM) • thiobencarb*		
		BSM • mefenacet, BSM • dimepiperate	
		BSM • pretilachlor	
	Quinclorac,	*BSM • esprocarb*	
1990	Pyrazosulfuronethyl (PSE),	*PSE • mefenacet*	
		PSE • pretilachlor	
		Pyributicarb • bromobutide • benzofenap	
		BSM • thiobencarb • mefenacet	
		BSM • mefenacet • daimuron	

weeds simultaneously. Phenoxys such as 2,4-D and MCPA were registered about 40 years ago. If these are included there are quite a large number of registered herbicides, available either as single chemicals or combination products, most of which are still being used.

There are several kinds of herbicidal formulations, but granules are generally used, applied as combination products of two or three chemicals to transplanted rice at the early growing stages.

MAIN RECOMMENDED HERBICIDES USED FOR RICE

Of the many chemical herbicides used for paddy rice in Japan, there have been changes in popularity from year to year. Recently, the so-called "one-shot herbicides" have become very popular in weed control for transplanted rice, being applied to 84% of paddy fields in 1991. There was a corresponding decrease in the use of herbicides applied to soil and foliage (Fig. 2).

The main herbicides currently recommended are shown in Table 2. In terms of applied area, the most popular herbicide in 1991 was a combination of bensulfuron-methyl (BSM) and mefenacet. The second most important was a mixture of BSM, thiobencarb and mefenacet. Both BSM and mefenacet were applied to more than half of Japanese paddy fields in 1991. In addition to these one-shot herbicides, pre-emergence ones were still widely used as a supplementary treatment.

SERIOUS PADDY WEEDS IN JAPAN

The most serious weeds found in paddy fields in Japan are shown in Table 3. An increase in annual broadleaf weeds and some perennial species has recently been reported in a number of regions.

Changes in Major Paddy Weeds

There have been changes in the dominant weeds in paddy fields since the introduction of herbicides (Table 4). Before the widespread use of herbicides, when hand weeding and rotary weeders were the most important control measures, barnyard grass (*Echinochloa oryzicola*), and annual broadleaf weeds such as monochoria (*Monochoria vaginalis*) were dominant. After the introduction of 2,4-D and MCPA for the control of broadleaf weeds in the 1950s, barnyard grass became dominant and caused serious problems. Pentachlorophenol (PCP), nitrofen and chlornitrofen (CNP) were introduced

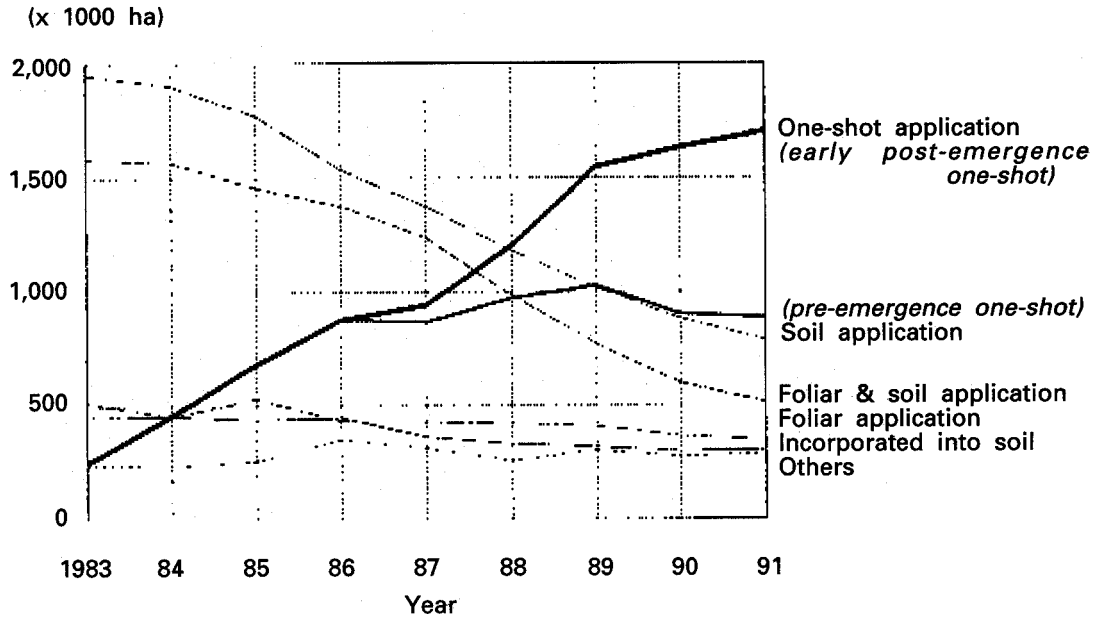

Fig. 2. Area of paddy fields in Japan to which are applied various herbicides (JAPR 1991)

Table 2. Main herbicides applied to paddy rice fields in Japan (1991)

Herbicide	Area applied (x1000 ha)
Soil incorporation (pre-emergence)	
Oxadiazon (EC)	78
Oxadiazon + butachlor (EC)	221
Soil application (pre-emergence)	
Butachlor (G)	85
Chlomethoxyfen(G)	107
Chlornitrofen (G)	266
Chlornitrofen + diamuron (G)	122
Pretilachlor (G)	112
Thiobencarb + chlornitrofen (G)	42
Foliar and soil application (early post-emergence)	
Bentazone (AS, G)	33
MCPA-thioethyl (phenothiol) + simetryn + dimethametryn (G)	21
Molinate + simetryn + MCPB (G)	223
Piperophos + dimethametryn (G)	26
Thiobencarb + simetryn (G)	51
Thiobencarb + simetryn + MCPB	94
Foliar application (post-emergence)	
ACN (G)	23
2,4-D (EC, G, SP, AS)	124
MCPA (EC, G, SP, AS)	171
After harvesting rice or on levee (post-emergence)	
Diquat + paraquat (AS)	90
Glufosinate (AS)	38
Glyphosate (AS)	143
Pre-emergence one-shot application	
Bensulfuron-methyl (BSM) + dimepiperate (G)	83
BSM + pretilachlor (G)	80
BSM + thiobencarb (G)	47
BSM + thiobencarb + mefenacet (G)	415
Pyrazolate + butachlor (G)	143
Pyrazolate + pretilachlor + dimethametryn (G)	47
Pyrazosulfuron-ethyl (PSE) + pretilachlor (G)	11
Pyrazoxyfen + pretilachlor (G)	32
Pyributicarb + bromobutide + benzofenap (FL)	17
Early post-emergence one-shot application	
BSM + esprocarb (G)	193
BSM + mefenacet (G)	434
Naproanilide + bromobutide + mefenacet (G)	34
PSE + mefenacet (G)	147

Note) AS: Aqueous solution; EC: Emulsifiable concentrate; FL: Flowable; G: Granules; SP: Water soluble powder
Total rice planted areas in 1991: 2.03 million ha
Source: JAPR

Table 3. Major weeds in Japanese paddy fields

Common name	Species	Family
Annual grasses		
Barnyard grass	*Echinochloa oryzicola Vasing.*	Poaceae
Barnyard grass	*E. crus-galli* (L.) Beauv. var. *crus-galli*	Poaceae
** Sprangletop	*Leptochloa chinensis* (L.) Nees	Poaceae
Annual sedges		
Smallflower umbrella sedge	*Cyperus difformis* L.	Cyperaceae
Annual broadleafs		
* Mizuaoi	*Monochoria korsakowii* Regel et Maack	Pontederiaceae
Monochoria	*M. vaginalis* (Burm. f.) Presl var. *plantaginea* (Roxb.) Solms-Laub.	Pontederiaceae
Toothcup	*Rotala indica* (Willd.) Koehne var. *uliginosa* (Miq.) Koehne	Lythraceae
** Ammannia	*Ammannia multiflora* Roxb.	Lythraceae
** Purple ammannia	*A. coccinea* Rottb.	Lythraceae
False pimpernel	*Lindernia procumbens* (Krock.) Borbas	Scrophulariaceae
* Oabunome	*Gratiola japonica* Miq.	Scrophulariaceae
** Eclipta	*Eclipta prostrata* (L.) L.	Compositae
Bidens	*Bidens frondosa* L.	Compositae
Bidens	*B. tripartita* L.	Compositae
* Jointvetch	*Aeschynomene indica* L.	Leguminosae
Perennial grasses		
* Rice cutgrass	*Leersia oryzoides* (L.) Sw.	Poaceae
** Knotgrass	*Paspalum distichum* L.	Poaceae
Perennial sedges		
Mizugayatsuri	*Cyperus serotinus* Rottb.	Cyperaceae
Spikerush	*Eleocharis acicularis* (L.) Roem. et Schult. var. *longiseta* Sven.	Cyperaceae
Kuroguwai	*E. kuroguwai* Ohwi	Cyperaceae
Bulrush	*Scirpus juncoides* Roxb. var. *ohwianus* T. Koyama	Cyperaceae
* Shizui	*S. nipponicus* Makino	Cyperaceae
Koukiyagara	*S. planiculmis* Fr. Schm.	Cyperaceae
Perennial broadleafs		
* Water plantain	*Alisma canaliculatum* A. Br. et Bouche	Alismataceae
Urikawa	*Sagittaria pygmaea* Miq.	Alismataceae
Arrowhead	*S. trifolia* L.	Alismataceae
Potamogeton	*Potamogeton distinctus* A. Benn.	Potamogetonaceae
Oenanthe	*Oenanthe javanica* (Blume) DC.	Umbelliferae
Algae		
* Spirogyra	*Spirogyra arcla* Kutz.	Zygnemataceae
** Pithophora	*Pithophora zelleri* (Martius) Wittrock	Cladophoraceae

* Serious mainly in northern Japan; ** Serious mainly in southwestern Japan

in the 1960s, and were effective in killing barnyard grass and other annual weeds at germination. Spikerush (*Eleocharis acicularis*) then became very serious in paddy fields, and was regarded as the most powerful competitor of rice because dense populations caused a marked decrease in yield as a result of their allelopathic effect.

Thiobencarb was extremely popular in the 1970s because it gave good control of annual weeds and also spikerush, but perennial weeds such as sagittaria (*Sagittaria pygmaea*) and bulrush (*Scirpus juncoides*) soon became dominant. In the 1980s,

Table 4. Changes in major weed species in Japanese paddy fields under herbicide applications

Period	Main control measures	Serious weed species
Before 1950s	Rotary and hand weeding	Annual and some perennial weeds
1950s	Foliar application: 2,4-D, MCPA	*Echinochloa oryzicola*
1960s	Soil application: pentachlorophenol, chlornitrofen, nitrofen	*Eleocharis acicularis*
1970s	Foliar and soil application: thiobencarb, simetryn, molinate	*Sagittaria pygmaea* *Scirpus juncoides* *Cyperus serotinus*
1980s	One-shot application: pyrazolate, bensulfuron-methyl, pyrazo-sulfuron-ethyl, mefenacet	*Eleocharis kuroguwai* *Sagittaria trifolia*
1990s	New labor-saving formulations	Annual broadleafs

one-shot herbicides were introduced. These were chemical compounds which could control annuals and the widely distributed perennials listed above. Since they have come into use, the perennial sedge kuroguwai (*Eleocharis kuroguwai*), and the perennial broadleaf weed Sa*gittaria trifolia*, together with some other species, have become the most difficult to control.

METHODS OF INTEGRATED WEED MANAGEMENT (IWM) IN PADDY RICE

Prevention

Removal of Weed Seeds

To prevent weed infestation, weeds should be eradicated during preceeding years from paddy fields and irrigation ditches before their seeds can ripen and fall to the ground. Clean soil, and rice free of weed seeds, are used in nursery boxes for mechanized transplanting. The compost applied to paddy fields should also be free of weed propagules.

Soil Preparation

Thorough land preparation, including puddling after irrigation water has been introduced into the field, are effective in killing emerging weed plants.

Water Management

Flooding paddy fields with water to a depth of 10-15 cm has been found to be effective in the control of barnyard grass and other hygrophytic weed species after the rice has been planted.

Mechanical Methods

Manual Weeding

Hand weeding is still widely practiced by small-scale farmers, who pull out barnyard grass and other large weeds by hand when they look over their land holdings every two or three days during the rice growing season. Older farmers are particularly likely to do this kind of work.

Mechanized Weeding

Rotary weeders, with or without an engine, are useful in weed control, and some Japanese farmers still like to use them. Rotary weeders are often used to control perennial weeds which emerge late from deep underground tubers after annual weeds have been controlled by herbicides. However, this method is suitable only for small-scale farmers who do not suffer from a labor shortage, as it involves a great deal of heavy work.

Cultural Methods

Competition

Transplanted rice seedlings, especially larger ones, are much more competitive with weeds than direct seeded plants. Closely planted rice seedlings are also better able to compete with weed infestation than those planted at a normal density, although the

yield is not necessarily any higher. There are some rice varieties which are relatively tolerant of weed competition, probably because their plant types are competitive in shading newly emerging weeds beneath their leaves. Their allelopathic activity may also have some effect in controlling weeds (see Fujii, this volume).

Cropping Systems

Farmers are recommended to plow their paddy fields in late autumn, since this is effective in killing the underground propagules of perennial weeds by bringing them to the soil surface, where they die in the cold, dry winter air. Japanese farmers usually use rotary tillers for paddy soil cultivation, but plowing has been found to be a more effective way of digging up propagules. Double cropping and crop rotation in paddy fields are recommended, to make more efficient use of available land and reduce the rice surplus. These cropping systems are also very effective in controlling paddy weeds, particularly a paddy-upland rotation such as rice and soybean. After two or three years of crop rotation, there is a striking reduction in paddy weeds under upland conditions, and in upland weeds under paddy conditions.

Chemical Methods

Chemical methods of paddy weed control are currently the most popular in Japan, because they have the lowest labor input. The cost of weed control has fallen with the application of herbicides because of the sharp decrease in the hours of labor involved. Herbicides will certainly be a key technology in weed management in future, even in an IWM system, but chemical treatments should be developed which are safer to human beings and the environment.

Biological Control

Some organisms, including insects and tadpole shrimps (see Goto, Takahashi this volume), fungal pathogens, snails, carp and a breed of duck have been studied as a potential method of controlling paddy weeds. Some of these have proved to be very useful control agents in local fields under traditional practices of rice cultivation.

Carp, and a duck breed Aigamo (a cross between wild and domesticated ducks), are good 'weed-sweepers' under flooded conditions, as they dig out and eat the submerged young seedlings of paddy weeds. They are favored by farmers who are interested in organic farming, although their cost, in terms of the labor they require and the enclosure of fields, is fairly high. In addition, farmers have to guard their paddy fields from homeless dogs and other wild hunters. This method was successful only in local situations, and when carried out by small-scale farmers.

The control of paddy weeds by fungal diseases has also been studied in Japan. We hope that these bioherbicides can be developed into a practical weed control measure in future, as an important component of IWM systems for Asian paddy fields which are safe to people, crops and the environment generally.

CURRENT PROBLEMS IN THE MANAGEMENT OF PADDY WEEDS IN JAPAN

Development of Integrated Technology with Low Chemical Inputs

To protect the environment from the over-application of chemicals to rice fields, farmers are asked to use the minimum quantity of herbicides for appropriate weed management. However, they sometimes prefer to apply very large quantities of herbicide to save time in the daily management of their fields.

Farmers are also recommended to follow a paddy-upland rotation, partly because of the surplus in rice production in Japan, but also because crop rotation is very effective in decreasing the number of weeds in paddy fields. To our regret, however, many farmers are not willing to plant crops such as wheat, barley or soybean in their paddy fields, as the prices they receive are unsatisfactory. Mechanical weed control is common in upland crops instead of heavy chemical applications, but it is not popular for paddy rice as mechanical operations are more difficult under flooded conditions. Deep flooding is effective in the management of weeds such as barnyard grass, but levees in paddy fields in Japan are usually only high enough to flood soil to a depth of 3-5 cm. Shallow flooding has been recommended to farmers for many years in order to maximize the

number of tillers and increase rice yields.

Biological management of paddy weeds using insects, fungi, and other organisms as agents has also been studied in Japan, but these methods are still far from practical application in farmers' fields.

Development of Labor-Saving, Low-Cost Technology

Decreasing the amount of labor required for weed control will be the most effective way of reducing the cost of weed management in Japan. It is necessary to develop labor-saving methods of spraying herbicides in the paddy fields of both large- and small-scale farmers. More effective one-shot herbicides may help to decrease the number of herbicide applications needed, from the two applications used at present to a single operation. To decrease the cost of herbicides, it is necessary for farmers to choose the chemical appropriate to their own particular paddy fields. It is a waste of chemicals to use expensive one-shot herbicides for annuals and perennials repeatedly each year, after the perennial weeds have been controlled.

Weed Management and Changes in Weed Populations

When a particular herbicide is applied, susceptible weeds are controlled and their populations will decrease, but numbers of tolerant weeds will increase. Also, even in the same species, intra-specific variation in ecological preferences or in herbicide susceptibility often appear in paddy fields, and decrease the efficacy of weed management practices. Newly introduced species which entered Japan within the last 40 to 50 years in imported cereals, hay etc. infest some crops, including rice, causing new weed problems.

PROSPECTS FOR IMPROVING THE INTEGRATED MANAGEMENT OF PADDY WEEDS IN JAPAN

As mentioned above, Japanese paddy farmers depend mainly on herbicides for their weed management, and are using large amounts of chemicals each growing season. Sometimes they also spray herbicides after the harvest to control the regrowth of weeds, and before transplanting rice to control the growth of emerging weeds in spring. To prevent the overuse of chemicals, we should develop other effective weed control measures which can substitute for at least one of the chemical applications.

For Japanese small-scale farmers, physical, mechanical or ecological methods such as deep flooding, mechanical weeding, paddy-upland rotation and double cropping present practical difficulties, because their rice farming takes place on land holdings which are generally less than one hectare in size. This means high costs, intensive labor and low incomes. Of course, we should inform farmers repeatedly about these useful measures.

However, the number of small-scale farmers is decreasing year by year, although they will still be in the majority for many years. They are nearly all "weekend farmers", who get most of their income from their city jobs, and like to manage their own land themselves, not so much for the cash income as for their own food. There are still not many farmers who operate on a larger scale, but their number is increasing. These farmers may find it possible in future to improve their weed management techniques as much as leading farmers in other advanced countries, including water management, cropping systems and other practices.

Therefore, biological methods, especially bioherbicides, can be seen as a promising new technology which is likely to become available in the near future, to improve integrated paddy weed management for both small- and large-scale farmers practicing Japanese intensive rice culture. It is likely that other biological agents as well may be put to practical use in the years to come.

DISCUSSION

The question was raised of the effectiveness of herbicide granules. One participant mentioned that some farmers in his country had noticed a reduction in effectiveness over time if the granules are used for a number of years. Dr. Shibayama answered that the granules are very effective in Japan under flooded conditions, although work is in progress to improve the formulation, and pointed out that one advantage of the granules is that they are easy to apply. Whereas liquid formulations might need a team of three or four persons for each application, which also involves transporting a large water tank to the paddy field plus a long hose with which to spray the field, granules can be spread easily by individual farmers working alone. It is hoped that improved formulations will make it possible to reduce the weight of granules applied in Japan from the present level of 30 kg/ha to around 10 kg/ha. Dr. Kim described the recent development of jumbo-sized granules about the size of a golf ball, which release herbicides gradually. In reply to a question of toxicity to fish, Dr. Shibayama thought that granules would be likely to present less of a toxicity problem than liquid formulations.