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PJBS

ISSN 1028-8880

Pakistan Journal of Biological Sciences

ANSInet
Asian Network for Scientific Information
308 Lasani Town, Sargodha Road, Faisalabad - Pakistan

Pakistan Journal of Biological Sciences 5 (12): 1352-1362, 2002

Are Herbicides Essential for Paddy Weed-control in East Asia?

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Abstract: Until the introduction of herbicides, weed control was one of the most difficult and labor-intensive cultural practices in rice cultivation. Herbicides have dramatically reduced the time spent on weed control and chemical weed control is presently the method of choice for eliminating weeds. However, herbicide application brings about water soil and atmospheric pollution: the most harmful by-products of commercial rice cultivation. New farming systems aimed at the reduction of herbicide dependence are being developed and tried in Korea and Japan. They include prescriptive pesticide usage, changes in soil management practices and water management, the introduction of natural enemies and integrated weed management. These new low-input cultivation methods require further study and offer unlimited challenges to researchers.

Key words: Herbicides, paddy weed-control, rice cultivation, pollution

Introduction

Located in the Asian monsoon zone, Korea and Japan have an annual precipitation of 1,200-1,800 mm, almost twice as high as the world average. However, about 2/3rds of the rain falls mostly between June and August. Thus, the countries are confronted with substantial flood and water-shortage risks mainly because of the mountainous terrain and seasonal torrential rainfall on the one hand and strong water demand required to satisfy the 46.14 and 124 million people living in South Korea and Japan respectively, on the other. Against such a background, paddy fields have played a major role not only in food production but also in mitigating the severe geographical and climatic conditions throughout the country's history of more than 2,000 years. The estimated value of the paddy fields in South Korea and Japan based on the substitutive cost method is given in Table 1. It is been widely recognized by the public that without making major changes on natural environment, paddy fields are highly effective in preventing floods and fostering water resources and that the terraced paddy fields are highly effective against soil erosion on the steep hillsides. Farm areas which are composed of paddy fields provide landscape, sightseeing and recreational sites. Furthermore, paddy fields form soil-based circulating systems that purify NOx and SOx in the air. Calculations made using the substitutive cost method estimate the total value of environmental externalities provided by paddy fields to reach 25,834 and 34,278 million $ in South Korea and Japan, respectively. Herbicide application diminishes the capacity of paddy fields for soil purification and underground water storage.

Although weed management in many parts of the world is still dominated by herbicide usage, there are strong indications that in the near future this will change. The development of herbicide resistance by noxious weeds remains a persistent problem that has rendered herbicide-dependent cropping systems increasingly vulnerable. Widespread concern about the environmental side effects of herbicides combined with increasing public awareness have resulted in the banning of several herbicides in some countries and an increasing pressure on farmers to reduce the use of herbicides (Matteson, 1995).

Both the purification of irrigation water by soil filtration and the extraction of water-borne nutrients by rice plants are benefits derived from flooding in paddy. However, in commercial production, the fertilizer and pesticide quantities used often exceed the crop and soil capacities for uptake and purification. As a consequence, agro-chemical residues in surface runoff and below ground leachate account for most of surface and ground water pollution. The perception that many developed countries have of agriculture as being a primary industry geared towards the production of raw materials explains the excessive use of pesticides. Low input sustainable agriculture involving integrated pest management and some aspects of organic farming will increase flora and fauna biodiversity and contribute to a healthier living environment (Itoh, 2000).

The average labour h ha^{-1} of cropland under rice in Korea and Japan has decreased from 2200 to 30 h ha^{-1} during the last 50 years. The potential reduction in rice yield caused by uncontrolled weed growth throughout a cropping season has been estimated to range between 45 and 96%, depending on the cropping system (Nyarko and de Datta, 1991).

The time saving was achieved through mechanized transplanting, the mechanization of other production steps and chemical weed control. Even though, there has been such significant labour saving, rice grain yield has increased by effective fertilization and weed control from 3 to over 5 tons only of un-hulled rice ha^{-1}.

This paper reviews the historical and practical aspects of paddy weed control and the possibilities of integrated control in East Asia, especially Korea and Japan.

Rice cultivation in Korea and Japan: For thousands of years in Korea, rice was cultivated by direct seeding and it was only in the 1600s that a shift to the higher yielding transplanting method started. It is believed that between 40,000-50,000 ha were maintained as direct-seeded dry paddy from 1900 to 1967 (Chae, 1983), though by the beginning of 1977, direct-seeded rice cultivation was completely substituted with machine transplanting in Korea. However, transplanting consumes lots of mechanical and manual labour (Table 2), a fact that prompted the return to direct seeding around 1991 with the area under direct seeding increasing remarkably to 117,500 ha in 1995 (Chae, 1999). The area under direct seeding in Japan is much smaller at around 8,800 ha because rice seedlings are more susceptible to lodging in the soft volcanic ash soils common in Japan. In 1998, paddy fields covered 1.18 and 2.66 million ha in Korea and Japan and paddy rice was cultivated in 1.01 and 1.79 million ha, respectively (Kim, 1998; Shibayama, 2001). Although rice cropping patterns have been classified into four categories: I) machine transplanting; ii) hand transplanting; iii) dry-direct and iv) wet (flooded) direct seeding, practically all farmers in Korea and Japan presently use machine transplanting. This change from hand to machine transplanting has decreased the height of seedlings from taller (ca 20 cm) to shorter (ca 5 cm) ones. Direct seeding is now rare and is estimated to account for less than 0.5% of the total land area under rice in Japan (Matsunaka, 2001).

The field operations carried out prior to transplanting render the paddy fields perfectly uniform and under these conditions, the use of granular herbicides is practical. Up to 1949, all weeding in rice fields had to be done manually and was one of the most labor-intensive cultural practices. Modern weed control via herbicide sprays has dramatically cut down on the man-hours devoted to rice cultivation. Relative to non-flooded fields, the flooded conditions also limit weed establishment and rice plants benefit from the reduced competition with C4-weeds (Matsunaka, 1983).

Table 1: Estimated value of paddy fields according to substitutive cost method Research on the Environmental Externalities of Paddy Fields, Korea Rural Development of Agriculture in 2000; Mitsubishi Research Institute, March, 1991, and estimated again with a consideration to changes of the unit cost and the other data after the publication of above-mentioned research

Functions	Benefits	Korea (Million $; 1300 Won base)	Japan (Million $; 135 Yen base)
Function of Preventing Flood	Mitigating the damages caused by floods	1222.3	14464.4
Function of Fostering Water Resources	Supporting steady water flow and inexpensive ground water supply	5.2	5480.0
Function of Preventing Soil Erosion and Landslide	Mitigating the damages caused by soil erosion and/or landslides	21.0	349.6
Function of Soil Purification	Reducing the cost of waste treatment such as food leftovers	4585.8	33.3
Function of Preserving Rural Landscape and Recreational Amenities	Value of visits by urban inhabitants	Unevaluated	12678.5
Function of Air Purification and Cooling	Absorbing contaminants and purifying air	19207.4	1271.9
Total Environmental Externalities		25834.1	34277.8

Table 2: Changes in planted area of rice in accordance with cultural practices in Korea (National Crop Experiment Station, 1999) (Unit: 1,000ha)

Years	Planted area	Hand trans-planting	Machine transplanting 30-day-old seedling	Direct-seeding 10-day-old seedling	Total	On dry paddy	On flooded paddy
1915	-	-	-	-	42,512	42,512	-
1926	-	-	-	-	50,000	50,000	-
1937	-	-	-	-	22,522	22,522	-
1955-60	-	-	-	-	3,000	3,000	-
1967	-	-	-	-	40,000	40,000	-
1977	1,208	1,207.8	0.2	-	-	-	-
1978	1,219	1,216.8	2.2	-	-	-	-
1979	1,224	1,208.2	15.8	-	-	-	-
1980	1,220	1,153.7	66.3	-	-	-	-
1981	1,212	1,108.3	103.7	-	-	-	-
1982	1,176	1,042.3	133.7	-	-	-	-
1983	1,220	1,049.0	171.0	-	-	-	-
1984	1,225	995.7	229.3	-	-	-	-
1985	1,233	963.0	270.0	-	-	-	-
1986	1,233	868.0	365.0	-	-	-	-
1987	1,259	699.0	560.0	-	-	-	-
1988	1,257	579.0	678.0	-	-	-	-
1989	1,254	426.0	828.0	-	-	-	-
1990	1,242	201.0	1024.0	17.0	0.1	-	-
1991	1,207	139.0	833.0	234.0	0.9	0.3	0.6
1992	1,156	83.0	674.0	396.0	2.7	1.7	1.0
1993	1,135	50.0	504.0	573.0	7.6	3.6	4.0
1994	1,102	30.0	476.0	523.0	72.7	35.2	37.5
1995	1,056	20.0	518.0	401.0	117.5	67.7	49.8
1996	1,050	17.3	620.3	301.6	110.4	65.2	45.2
1997	1,052	12.7	705.9	223.3	110.6	57.2	53.4
1998	1,059	10.0	785.4	199.7	63.9	16.3	47.9
1999	-	-	-	-	71.7	-	-
(Ratio, %)	(100)	(0.9)	(74.2)	(18.9)	(6.0)	(1.5)	(4.5)

Table 3: Distribution of soil conditions and life cycles of total weeds occurring in agricultural land in Korea (Kang, 1999)

Life cycle / Soil condition	Total weeds	Paddy field weeds and hydrophyte	Halophyte	Upland field weeds and xerophyte
Total weeds	1,448 (100)	223(100)	74(100)	1,151(100)
	(100)	(15.4)	(5.1)	(79.5)
Annual weeds	366(25.3)	81(36.3)	20(27.0)	265(23.0)
	(100)	(22.1)	(5.5)	(72.4)
Winter annual or Biannual weeds	210(14.5)	10(4.5)	13(17.6)	187(16.2)
	(100)	(4.8)	(6.2)	(89.0)
Perennial weeds	814(56.2)	132(59.2)	37(50.0)	645(56.0)
	(100)	(16.2)	(4.5)	(79.2)
Woody	58(4.0)	0(0.0)	4(5.4)	54(4.7)
Weeds	(100)	(0)	(6.9)	(93.1)

Dominant weeds in Korean and Japanese paddy fields: The distribution of soil conditions and life cycles of total weeds and weed occurrence (dominance, %) in rice fields in Korea (Tables 3, 5). The current major weed species in paddy fields are shown in Tables 4.1 and 4.2 for Korea and in Table 6 for Japan. Dominant annual species are barnyard grass (*Echinochloa crusgalli*), small flower umbrella sedge (*Cyperus difformis* L.), Cmonochoria (*Monochoria vaginalis*), toothcup (*Rotala indica*), false pimpernel (*Lindernia* spp.), ammannia (*Ammannia multiflora*) and others, while common perennials are knotgrass (*Paspalum distichum*), "mizugayatsuri" (*Cyperus serotinus*), spikerush (*Eleocharis acicularis*), bulrush (*Scirpus juncoides*), sagittaria (*Sagittaria pygmaea*) and others (Shibayama, 2001). Bog pondweed (*Potamogeton distinctus*) is more common in Korea than in Japan (Huh, 1985).

An increase in annual broad-leaf weeds and some perennial species

Table 4.1: Changes in weed occurrence and dominant weed species 30 days after sowing in accordance with cultural practices and seedling date in rice field of Youngnam, Korea ('96, '97, Kyoung-buk Provincial Agri. Tech. Administration; Kim *et al.*, 1997)

Cultural practice	Seeding date	Weed occurrence (g m^{-2})	Dominant weed species (Dominance value, %)			
Direct-seeding on dry paddy	May 10	757	E.c. (47)	D.s. (27)	C.b. (16)	S.v. (5)
	May 25	698	E.c. (41)	D.s. (22)	C.b. (17)	C.d. (13)
	June 10	552	C.d. (43)	E.c. (29)	C.b. (16)	F.m. (9)
Direct-seeding on flooded paddy	May 10	508	P.h. (37)	M.v. (32)	E.c. (20)	C.d. (7)
	May 25	462	M.v. (35)	C.d. (29)	P.h. (26)	E.c. (5)
	June 10	412	M.v. (32)	C.d. (27)	P.h. (25)	E.c. (11)
Machine transplanting (10-day-old seedling)	May 10	266	M.v. (57)	P.h. (21)	E.p. (14)	E.c. (6)
	May 25	247	M.v. (51)	C.d. (27)	P.h. (13)	E.c. (6)
	June 10	227	M.v. (47)	E.c. (23)	A.j. (18)	E.p. (8)

Table 4.2: Importance value of several weed species at various growth stages by seeding time as affected by seedling methods (Choi *et al.*, 1997)

Sowing dates	Checking time	Direct-seeding on dry paddy			Direct-seeding on flooded paddy		
April 30	20	E.c. (26)	C.b. (19)	S.v. (19)	E.c. (31)	M.v. (25)	C.s. (19)
	40	E.c. (51)	E.k. (10)	C.a. (10)	E.c. (36)	M.v. (17)	A.j. (14)
	60	E.c. (53)	E.k. (16)	C.s. (10)	E.c. (43)	A.j. (25)	M.v. (8)
	Heading stage	E.c. (68)	E.k. (12)	A.j. (10)	E.c. (43)	A.j. (32)	E.k. (5)
May 15	20	E.c. (52)	C.a. (11)	S.v. (10)	E.c. (24)	M.v. (17)	A.j. (16)
	40	E.c. (53)	C.s. (14)	C.b. (8)	E.c. (32)	A.j. (23)	C.d. (13)
	60	E.c. (60)	E.k. (16)	A.j. (9)	E.c. (37)	A.j. (23)	M.v. (13)
	Heading stage	E.c. (66)	E.k. (16)	A.j. (9)	E.c. (40)	A.j. (25)	M.v. (9)
May 30	20	E.c. (42)	C.s. (13)	D.s. (9)	E.c. (36)	A.j. (15)	C.s. (12)
	40	E.c. (45)	C.s. (25)	C.b. (7)	E.c. (38)	A.j. (15)	C.s. (10)
	60	E.c. (48)	E.k. (16)	C.s. (15)	E.c. (39)	A.j. (26)	C.s. (8)
	Heading stage	E.c. (53)	E.k. (15)	C.s. (14)	E.c. (43)	A.j. (29)	C.s. (9)
June 15	20	E.c. (35)	D.s. (17)	S.v. (16)	E.c. (27)	M.v. (23)	C.s. (12)
	40	E.c. (42)	C.s. (20)	D.s. (12)	E.c. (35)	A.j. (19)	M.v. (11)
	60	E.c. (42)	C.s. (14)	E.k. (13)	E.c. (38)	A.j. (19)	C.s. (6)
	Heading stage	E.c. (45)	C.s. (14)	E.k. (12)	E.c. (39)	A.j. (20)	C.s. (6)

A.j.: *Aneilema japonica*; C.a.: *Chenopodium album*; C.b.: *Capsella bursa-pastoris*; C.d.: *Cyperus difformis*; C.s.: *Cyperus serotinus*; D.s.: *Digitaria sanguinalis*; E.c.: *Echinochloa crus-galli*; E.k.: *Eleocharis kuroguwai*; M.v.: *Monochoria vaginalis*; S.v.: *Setaria viridis*

Table 5: Weed occurrence (dominance, %) in rice fields. (Kim, 1983; Kim *et al.*, 1992)

1971		1981		1991	
Rotala indica	34.5	Monochoria vaginalis	22.2	Eleocharis kuroguwai*	19.6
Eleocharis acicularis	11.9	Sagittaria pygmaea*	17.5	Sagittaria pygmaea	15.6
Monochoria vaginalis	11.1	Sagittaria trifolia*	9.0	Sagittaria trifolia	13.2
Cyperus difformis	8.7	Potamogeton distinctus*	9.0	Echinochloa crus-galli	12.2
Echinochloa crus-galli	6.9	Cyperus serotinus*	8.5	Monochoria vaginalis	11.2
Lindernia procumbens	3.3	Rotala indica	6.0	Cyperus serotinus*	4.6
Potamogeton distinctus*	3.1	Aneilema japonica	4.4	Potamogeton distinctus*	3.3
Aneilema japonica	2.4	Lindernia procumbens	3.9	Ludwigia prostrata	2.6
Eleocharis kuroguwai*	1.8	Eleocharis kuroguwai*	3.4	Aneilema japonica	2.5
Polygonum hydropiper	1.8	Ludwigia prostrata	3.0	Cyperus difformis	2.3
		Polygonum hydropiper	2.7	Rotala indica	2.2
		Echinochloa crus-galli	2.3	Leersia japonica	1.3
		Leersia japonica*	2.1	Polygonum hydropiper	1.1
		Eleocharis acicularis*	1.6	Lindernia procumbens	0.7
		Scirpus hotarui	1.3	Fimbristylis miliacea	0.6

* Indicated weeds are perennials.

has been reported in a number of regions. In particular, broad-leaf species such as *Lindernia* sp. are a serious problem in northern regions because of the increase in herbicide-resistant, intra-specific variations. Itoh *et al.* (1999) and Uchino *et al.* (1999) reported that paddy weeds such as "mizuaoi" (*Monochoria procumbens*), common false pimpernel (*Lindernia procumbens*), low false pimpernel (*Lindernia dubia*), "azetogarashi" (*Lindernia micrantha*), several other broad-leafs and bulrush had developed resistance to sulfonylurea herbicides in Japan. The problematic weeds in Korea and Japanese paddy fields have changed since the introduction of herbicides (Shibayama, 1994; 1996; 2000) (Table 7).

Weed occurrence under different cultural practices in Korea and Japan is summarized in Tables (4.1; 4.2; 7; 8; 9; 10) (Kim *et al.*, 1992; 1997; Ku *et al.*, 1993). Weed populations were lowest in transplanted paddy, doubled in flooded, direct-seeded paddy and tripled in dry, direct-seeded paddy. The dominant weed species in machine transplanted paddy occurred in the following order: *Monochoria vaginalis*, *Cyperus difformis*, *Persicaria hydropiper*, *Echinochloa crus-galli* and *Aneilema japonica*. The dominant weed species in flooded direct-seeded paddy were *Monochoria vaginalis*, *Persicaria hydropiper*, *Cyperus difformis*, *Echinochloa hydropiper*, *Echinochloa crus-galli*, *Scirpus hotarui*, *Ludwigia prostrata* and *Aneilema japonica* (Choi *et al.*, 1997; Huh *et al.*, 1995a; Huh *et al.*, 1995b; Ku *et al.*, 1993). In dry direct-seeded paddy, *Echinochloa crus-galli*, *Cyperus difformis* and the upland weed species *Digitaria sanguinalis*, *Capsella bursa-pastoris*, *Fimbristylis miliacea* and *Setaria viridis* were dominant during the early period of cultivation. Over time, *Echinochloa crus-galli* became more dominant in dry direct seeded paddy. The number of weed species since the 1990's, taking regional differences into consideration were reported to be 7 to 8 in the transplanted paddy and 15 to 16 in dry, direct-seeded paddy (Tables 8; 9) (Im *et al.*, 1993; Ku *et al.*, 1993). The highest number of weed species has been consistently reported to occur in dry, direct-seeded paddy.

Change in weed dominance as affected by continuous cultivation in dry, direct-seeded paddy is shown in Table 8 and 9. The dominant weed species changed to *Echinochloa crus-galli* from *Eleocharis kuroguwai*. The remarkable increase in *Echinochloa crus-*

Table 6: Important weed species in Japanese paddy fields (Shibayama, 2001)

Common names	Species	Family
Annual grasses		
Barnyardgrass	*Echinochloa oryzicola* Vasing	Poaceae
Barnyardgrass	*Echinochloa crus-galli* (L.) Beauv. var.*crus-galli*	Poaceae
Sprangletop	*Leptochloa chinensis* (L.) Nees	Poaceae
Annual sedges		
Smallflower umbrella sedge	*Cyperus difformis* L.	Cyperaceae
Rice flatsedge	*Cyperus iria* L.	Cyperaceae
Globe fringerrush	*Fimbristylis miliacea* (L.) Vahl.	Cyperaceae
Annual broad-leaf weeds		
Mizuaoi	*Monochoria korsakowii* Regel et Maack	Pontederiaceae
Monochoria	*Monochoria vaginalis* (Burm. F.) Kunth	Pontederiaceae
Indian toothcup	*Rotala indica* (Willd.) Koehne *var. uliginosa* (Miq.) Koehne	Lythraceae
Ammannia	*Ammonia multiflora* Roxb.	Lythraceae
Purple ammannia	*Ammannia coccinea* Rottb.	Lythraceae
Common fakse pimpernel	*Lindernia procumbens* (Krock.) Borbas	Scrophulariaceae
Low false pimpernel	*Lindernia dubia* (L.) Penn.	Scrophulariaceae
Azetogarashi	*Lindernia micrantha* D.Don	Scrophulariaceae
Eclipta	*Eclipta prostrata* (L.) L.	Compositae
Devil beggarticks	*Bidens frondosa* L.	Compositae
Bur beggarticks	*Bidens tripartita* L.	Compositae
Ludwigia	*Ludwigia epilobioides* Maxim.	Onagraceae
Indian jointvetch	*Aeschynomene indica* L.	Leguminosae
Marsh pepper smartweed	*Persicaria hydropiper* (L.) Spach	Polygonaceae
Perennial grasses		
Rice cutgrass	*Leersia oryzoides* (L.) Sw.	Poaceae
Knotgrass	*Paspalum distichum* L.	Poaceae
Perennial sedges		
Mizugayatsuri	*Cyperus serotinus* Rottb.	Cyperaceae
Needle spikerush	*Eleocharis acicularis* (L.) Roem. Et Schult. Var. *longiseta* Sven.	Cyperaceae
Kuroguwai	*Eleocharis kuroguwai* Ohwi	Cyperaceae
Bulrush	*Scirpus juncoides* Roxb. Var. *ohwianus* T. Koyama	Cyperaceae
Shizui	*Scirpus nipponicus* Makino	Cyperaceae
Koukiyagara	*Scirpus planiculmis* Fr. Schm	Cyperaceae
Perennial broad-leaf weeds		
Water plantain	*Alisma canaliculatum* A. Br. Et Bouche	Alismataceae
Sagittaria (urikawa)	*Sagittaria pygmaea* Miq.	Alismataceae
Arrowhead	*Sagittaria trifolia* L.	Alismataceae
Oenanthe	*Oenanthe javanica* (Blume) DC.	Umbelliferae
Algae		
Spirogyra	*Spirogyra arcla* Kuta.	Zygnemataceae
Pithophora	*Pithophora zelleri* (Martius) Wittrock	Cladophoraceae

Table 7: Changes in major weed species in Japanese paddy fields under herbicide applications (Shibayama, 2001)

Period	Main control measures and herbicides	Serious weeds
Before 1950	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, oxadiazon, butachlor	*Sagittaria pygmaea, Scirpus juncoides, Cyperus serotinus*
1980s	'One-shot' combinations: pyrazolate, pretilachlor, bensulfuron-methyl, pyrazosulfuron-ethyl, mefenaset	*Eleocharis kuroguwai, Sagittaria trifolia*
1990s	New laborsaving formulations	Annual broad-leaf weeds
2000s	Various herbicidal combinations (?)	Herbicide resistant weeds (?)

Table 8: Weed occurrence in directly-seeded rice paddy from 1996 to 1999 in Korea (Kim *et al.*, 1998; Park and Oh, 1995; Im *et al.*, 1999)

Directly-seeding on dry paddy (23)	Directly-seeding on flooded paddy (16)
Echinochloa crus-galli	Echinochloa crus-galli
Cyperus difformis	Monochoria vaginalis
Cyperus serotinus*	Scirpus hotarui
Aneilema japonica	Cyperus difformis
Scirpus hotarui	Cyperus serotinus*
Ludwigia prostrata	Aneilema japonica
Fimbristylis miliacea	Ludwigia prostrata
Eleocharis kuroguwai*	Eleocharis kuroguwai*
Monochoria vaginalis	Lindernia procumbens
Digitaria sanguinalis	Rotala indica
Setaria viridis	Polygonum hydropiper
Rorippa islandica	Alopecurus aesqualis
Bidens tripartite	Leersia japonica*
Eragrostis multicaulis	Sagittaria pygmaea*
Cardamine lyrata	Sagitaria trifolia*
Lindernia procumbens	Ottelia alismoides
Eclipta prostrata	
Poa sphondylodes	
Chenopodium album	
Rotala indica	
Portulaca olerace	
Cyperus orthostachyus	
Aeschynomene indica	

Asterisked weeds are perennials

Table 9: Changes of dominant weed species and their order as affected by continuous cultivation of direct-seeding on dry paddy field (Ku *et al.*, 1993)

	Dominant weed species				
Year	1st	2nd	3rd	4th	5th
1987	E.k.	E.c.	S.h.	M.v.	-
1989	E.c.	C.i.	D.s.	F.m.	C.b.
1990	E.c.	A.j.	C.i.	P.h.	D.s.
1991	E.c.	D.s.	C.i.	A.i.	E.k.
1992	E.c.	D.s.	B.t.	A.c.	A.i.

A.c.: Arthraxon cliaris; A.i.: Aeschynomene indica; A.j.: *Aneilema japonica*; B.t.: Bidens tripartite; C.b.: *Capsella bursa-pastoris*; C.i.: *Cyperus iria*; D.s.: *Digitaria sanguinalis*; E.c.: *Echinochloa crus-galli*; E.k.: Eleocharis kuroguwai; F.m.: *Fimbristylis miliacea*; M.v.: *Monochoria vaginalis*; P.h.: *Polygonum hydropiper*; S.h.: *Scirpus hotarui*

Table 10: Weed occurance and percent yield loss of rice as influenced by cultural practices ('87-'92, YCES)

Cultural practice	Weed occurrence $g\ m^{-2}$	Index	Yield loss (%)
Hand transplanting	741	100	10-20
Machine transplanting			
20-d-old seedlings	843	114	25-30
8-d-old seedlings	1,020	138	30-35
Direct-seeding			
On flooded paddy	1,643	222	40-60
On dry paddy	2,300	310	70-100

galli populations is believed to be due to changes in herbicide ingredients, inadequate management irrigation water, improper plowing, soil preparation and probably the occurrence of herbicide resistant types. Also, the occurrence of grasses and perennial weeds decreased gradually, while broad leaf and annual weeds increased.

Weed occurrence and rice yield: Yamasue *et al.* (1997) reported that grain yield decreased by up to 60% in the presence of *Echinochloa oryzicola* mostly due to a reduction in panicle number per plant. Yield loss (%) caused by competition from weeds relative to cultural practices in Korea (Table 10). Yield loss without weed control was 10-20% in hand transplanted paddy, 25-30% in machine transplanting, 40-60% in flooded and direct-seeding 70-100% in dry and direct-seeded paddy. Therefore, the competition between rice and weeds is stronger in direct-seeded rice cultivation, especially in dry paddy because of the concurrent germination of rice and weeds.

History of chemical weed control in paddy: Conventionally, Korean and Japanese rice farmers have been controlling paddy weeds mainly by chemical methods, whereby herbicides are commonly applied an average of 1.8 times in one growing season. However, the kinds of herbicides applied have been changing drastically, year by year, from old, high-content products to very low-content 'one-shot' herbicides. The recommended herbicide spray regime in both dry, direct seeded and flooded paddy in Korea is a systematic application at two time points: before and after water logging, in case of medium weed occurrence and an additional application in areas with a heavy weed presence (RDA, 1999). The commercially recommended herbicides that can be used before water logging in dry direct seeded paddy are shown in Fig. 1. Herbicides to be applied after water logging are imazosulfuron/thiobencarb, thiobencarb, butachlor, bensulfuron-methyl/thiobencarb, bensulfuron-methyl/pretilchlor/dymron within 5 days after irrigation (DAI) and azimsulfuron/cyhalofop-butyl/molinate, imazosulfuron/mefenacet/dymron, cyhalfopbutyl/ imazosulfuron/pretilachlor, molinate/imazosulfuron, cyhalofopbutyl/ pretilachlor/ bensulfuron-methyl, cyhalfopbutyl/pretilachlor/pyrazosulfuron-ethyl, bensulfuronmethyl/ molinate at 10 DAI. An application of bentazone before the panicle initiation stage is recommended if heavy weed infestation is expected.

However, chemical weed control has not been successful in controlling all weeds uniformly. The constant shift in weed population dynamics with the introduction of new herbicides has always been a precursor to the development of new and more potent herbicides. When a particular herbicide is applied, susceptible weeds are controlled and their populations will decrease, but the number of tolerant weeds will increase. Also, even in one species, intraspecific variations in ecological

Table 10.1: Labor hours per 10a for rice cultivation in Korea in 1996. Parentheses are percent (Park *et al.*, 1997)

Stage	Machine transplanting: 30-d-old seedlings	10-d-old seedlings	Direct-seeding: On dry paddy	On flooded paddy	On flooded paddy by hand	Mean
Raising seedling, transplanting	14.7 (100)	10.9 (74.1)	4.4 (29.9)	5.7 (38.8)	4.9 (33.3)	5.0(34.0)
Main field	16.4	15.8	17.7	17.7	18.2	17.9
Total labor hours	31.1 (100)	26.7 (85.9)	22. (71.1)	23.4 (75.2)	23.1 (74.3)	22.9(73.6)

* Total labor hours includes family, employed and custom operation labor hours

Table 11: Difference of dry weight of weeds and weed species at ripening stage of rice in several rice based cultivation systems in first year (Cho *et al.*, 2002 Accepted)

	Control(no-tillage)	White clover-Rice (Direct-seeding)	White clover-Rice (Direct-seeding-herbicide)	Conventional (tillage, transplanting)
--------------------- First year --------------------				
Total DW (g/m²)	482.4	333.4	125.8	198.8
Echinochloa crus-galli	206.4± 28.4	127.4± 56.5	54.4± 22.2	150.2± 6.1
Paspalum distichum	-*	-	-	7.0± 3.7
Monochoria vaginalis var. *plantaginea*	-	-	0.1± 0.1	-
Murdannia keisak	7.0± 5.0	2.6± 23.5	2.3± 1.5	0± 0.2
Scirpus juncoides var. *ohwianus*	22.0± 17.7	74.9± 7.9	14.0± 6.3	37.3± 1.2
Scirpus juncoides Roxb. var. ohwianus T. Koyama	47.0± 21.8	-	-	0.0± 0.5
Cyperus brevifolius var. *leiolepis*	0.6± 0.6	0.0± 0.2	-	-
Cyperus difformis	2.1± 1.9	0.3± 0.6	-	0.6± 0.0
Polygonum hydropiper	169.4± 50.9	125.8± 31.9	54.8± 27.6	9± 4.5
Ludwigia epilobioides	1.6± 1.4	-	0.2± 0.4	0.2± 0.1
Ammannia coccinea	-	-	-	0.5± 0.0
Aeschynomene indica	24.3± 12.5	2.2± 2.2	-	2.1± 0.5
Eclipta prostrata	2.0± 1.6	0.0± 0.6	-	0.0± 0.2
Control(no-tillage)	White clover-rice (no-tillage, transplanting)		White clover-rice (no-tillage, direct-seeding)	
--------------------- Second year --------------------				
Total DW (g/m²)	318.3	19.0	32.0	
Echinochloa crus-galli	232.4± 32.6	15.2± 13.1	22.3± 13.7	
Murdannia keisak	8.2± 4.7	3.8± 2.7	5.1± 4.2	
Scirpus juncoides var. *ohwianus*	24.3± 13.5	-	-	
Scirpus juncoides Roxb. var. ohwianus T. Koyama	49.2± 15.7	-	-	
Cyperus brevifolius var. *leiolepis*	1.6± 0.7	-	-	
Cyperus difformis	3.1± 1.2	-	-	

-* means not observed in that treatment

Table 12.1: Global acreage of transgenic crops (excluding China) in 1997 and 1998: by crop (millions of acres)

Crop	1997 Acres	%	1998 Acres	%
Soybean	12.8	46	36.6	52
Corn	8.0	30	20.8	30
Cotton	3.5	13	6.3	9
Canola	3.0	11	6.0	9
Potato	< 0.3	< 1	< 0.3	< 1
Total	27.5	100	69.5	100

Table 12.2: Global acreage of transgenic crops (excluding China) in 1997 and 1998: by trait (millions of acres)

Trait	1997 Acres	%	1998 Acres	%
Herbicide resistance	17.3	63	49.5	71
Insect resistance (Bt)	10.0	36	19.3	28
Insect/herbicide resist.	< 0.3	< 1	0.8	1
Quality traits	< 0.3	< 1	< 0.3	< 1
Total	27.5	100	69.5	100

Table 12.3: Globally dominant transgenic crops in 1998 (excluding China)

Rank	Crop	% Global Transgenic Acres
1	Herbicide-resistant soyben	52
2	Insect-resistant (Bt) corn	24
3	Herbicide-resistant canola	9
3	Insect (Bt)/herbicide-resistant cotton	9
4	Herbicide-resistant corn	6

characteristics or in herbicide susceptibility often appear in rice fields leading to a decrease in herbicide efficacy. Naturalized species that have been introduced within the last 40-50 years by importation of cereals, hay and other crops are causing new weed problems (Shibayama, 2001). A short history on the response of weed species to chemical control will sufficiently illustrate this predicament.

Prior to the introduction of herbicides, a mixed weed community including barnyard grass, annual broad-leaf species such as monochoria and some perennial species were controlled by hand weeding and the use of rotary weeders. After 2,4-D and MCPA were introduced for broad-leaf weed control in the 1950s, barnyard grass became the most dominant weed and proved practically impossible to eradicate by hand or rotary weeding. Pentachlorophenol (PCP), nitrophen and chloronitrophen (CNP) were introduced in the 1960s to control barnyard grass and other annual weeds at germination. However, spikerush emerged as a new problem, inhibiting rice through allelopathy and nutritional competition.

In the 1970s, thiobencarb became popular because it effectively controlled annual weeds and spikerush, but after a few years, perennial weeds such as *Cardmine lyrata*, sagittaria and bulrush became the dominant species. In the 1980s, one-shot herbicides were introduced as compound herbicides that could control the annual and widely distributed perennial weeds listed above by a single application. Since they have come into use, the perennial sedge (*Eleocharis kuroguwai*) and the perennial broad-leaf, arrowhead (*Sagittaria trifolia*), together with some other species have become the new problem as a result of the reduced

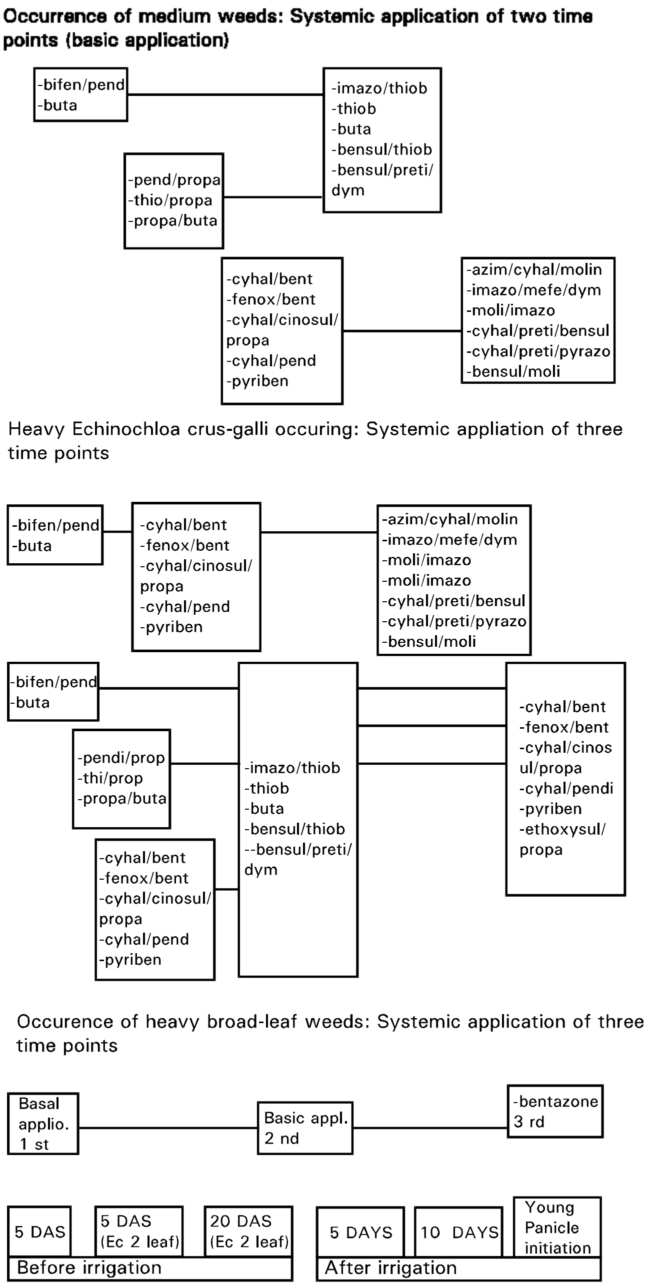

Fig. 1: Recommendations of herbicide application for direct-seeding on dry rice paddy in Korea

competition from other weeds. In 1992, some one-shot herbicides were found to be effective at decreasing or preventing the spread of water chestnut and arrowhead but annual broad-leaf weeds such as monochoria, false pimpernel and others were often observed to grow abundantly in many farmer's fields, mainly because of inadequate water management and partly because of herbicide resistance and movement of escaped seeds (Kang, 1999).

Many scientists insist that herbicides should be recommended as one of the key technologies in future weed management, even in integrated weed management (IWM) systems by use of genetically modified plants. The cultivation area under such plants, traits and crop types are currently increasing rapidly (Tables 12-1, 2, 3). Herbicides application before rice germination can be done over large areas in a short time making them suitable for large farms. They also provide good weed control during the early stages of growth when rice is most susceptible to weed competition and herbicides. In this regard, Shibayama (2001) mentioned that effort should be made to develop safer herbicides that will exert less pressure on the environment. However, safer herbicides are not as good for weed control. It is our opinion that non-herbicide weed control methods should be considered before anything else.

Non-herbicide weed control methods

Manual and mechanical methods: Manual weed control includes burning, hand pulling and mechanical hand weeding. These labour-intensive methods are the oldest methods of weed control and several hand tools are still the principal means of rice weed control in many developing countries. However, manual methods are slow, unattractive and tedious. In Korea and Japan, hand weeding is still widely practiced by small-scale farmers, who pull out barnyard grass and other large weeds every 2 or 3 days during the growing season. Older farmers are particular likely to do this kind of laborious work. Small-scale farmers and some religious organizations in Korea still carry out manual weeding, mostly to eradicate barnyard grass after controlling other weed species by chemical methods. Rotary weeding with or without engines is still used by some farmers practicing low input agriculture in Korea and Japan. This mechanical method is applicable only to small-scale farmers who can do a great deal of heavy work. Other powered weeding methods are not yet widely applied to practical paddy weed control (Shibayama, 2001).

Biological methods: Several biological agents, such as insects, mites and fungi have been used successfully to control rice weeds. Biological agents are selective in their control action and their activity may be restricted to a single weed. Biological control programmes may be applicable to an introduced perennial weed growing in areas that are seldom disturbed, such as pastures and forests. Some organisms including insects, tadpole shrimps, fungal pathogens, golden snails, carp, small ducks and others have been studied or utilized by researchers or by diligent farmers who are practicing organic or low-input farming. Other alternatives include commensal plants like Azolla (*Azolla imbrica*); *Azolla japonica*, Algae, greater duckweed (*Spirodela polyrhiza*), and minute duckweed (*Lemna paucicostata*). Vromant *et al.* (2001) studied the effect of rice seeding rate and fish stocking on the direct-sown paddy. He evaluated the effects of: (1) absence or presence of such a polyculture, and (2) different rice-seeding rates (100 and 300 kg pre-germinated rice ha^{-1}) on field floodwater ecology. Silver carb, common carp and Nile tilapia were stocked in polyculture at densities of 3150, 310 and 550 fish ha^{-1}, respectively. About 50% of the observed variation in the floodwater could be attributed to the stocked fish and to rice seeding rate. The above ground dry weight of rice plants increased in the presence of fish and with an increase in rice seeding rate. The lower more than the higher rice seeding rate seemed better for fish production: at the lower rate, dissolved oxygen concentrations were higher throughout the rice cycle. In Korea and Japan, carp and "aigamo" ducks (a cross between wild and domesticated ducks) are used. The ducks are particularly good weed sweepers under flooded conditions, as they dig out and eat submerged young seedlings of paddy weeds. Some of these have proved to be useful weed control agents in fields under traditional rice cultivation. These methods are not yet widely applied as there are no official recommendations and are successful only in local situations when carried out by small-scale farmers with the necessary skills. Generally, they have often been found unsatisfactory as practical weed control agents in paddy (Shibayama, 2001).

The potential advantages and disadvantages of rice-fish culture are listed in the book by Alex Bocek.

Potential advantages of fish-rice culture

1. Additional food and income in the form of fish.
2. Control of mollusks and insects which are harmful to rice.
3. Reduced risk of crop failure resulting from integration of rice and fish.
4. Continued flooding of the paddy and rooting activity of fish help control weeds.
5. Fish stir up soil nutrients making them more available for rice. This increases rice production.

Potential disadvantages of rice-fish culture

1. Pesticide use must be restricted.
2. Rice-fish culture may require more water than rice culture alone.
3. Trenches must be dug about 40 to 50 cm below the paddy bottom. In many places, this makes drainage difficult. Rice yield area^{-1} is usually reduced because paddy area used for trenches is not planted with rice.
4. Fish produced with the system are often small and total production is lower than what could be produced in a pond of equal size.
5. Because rice production is seasonal, fish are harvested at the same time by every farmer and marketing may be a problem. Consequently, rice-fish culture may be more appropriate for small-scale paddies where fish are consumed by the producing family.
6. Because rice paddies may be irrigated from a common water supply, it is difficult to ensure that water used to supply the paddy will be pesticide-free. This may make rice-fish culture impractical.
7. Substantial investment in fish and rice paddy modification increases risk to farmers.
8. Requires more labour than rice culture alone.

The book lists more disadvantages than advantages but it is clear that this is one of the production methods with the greatest potential for herbicide-free sustainable rice cultivation.

Preventive, ecological and cultural methods

Prevention: To prevent weed infestation in paddy, weeds should be eradicated during the preceding years from fields and irrigation ditches before they can set and shed seeds in the soil. Clean soil and rice seeds free of weeds should be used in nursery boxes. All farm machinery should be washed well to remove weed seeds and propagules of perennial species in attached soils from neighboring weed-infested fields before being moved into clean paddy fields (Shibayama, 2001).

Soil preparation: It is recommended that farmers plough paddy fields in late autumn to winter, since this is effective in killing underground propagules of perennial weeds by digging them up to the soil surface while burying weed seeds deep within the soil layers. Japanese farmers usually utilize rotary tillers for paddy soil cultivation, but plowing has been found to be a more effective way of digging up underground weed propagules. Therefore, frequent cultivations (although consuming much power), double cropping with winter crops and upland-paddy rotation with other summer and winter crops have been recommended for decreasing weed infestation in paddy fields. After 2 or 3 years of crop rotation, there is a striking reduction in paddy weeds under upland conditions and in upland weeds under paddy conditions (Shibayama, 2001).

Cultural methods: A basic principle of cultural control is to increase the competitive ability of rice and enable it to suppress weed growth. A vigorous rice crop competes more effectively against weeds than a less vigorous crop. Cultural control methods include prevention of weed introduction, land preparation, crop rotation, cultivar selection, timed seeding, planting methods, plant population, fertilization and water management. Cover crops like winter wheat and Chinese milk vetch (*Astragalus sinicus*) when introduced prior to rice cultivation in no-till, direct-sown, rotation systems are capable of significantly reducing weed density and biomass (Cho *et al.*, 2001a, b). Cover-crop weed control has a lot of potential though hand weeding or herbicide application is essential for sustaining grain yield during initial cropping years.

Ecological or cultural methods, such as winter cultivation, ploughing of drained paddy fields after harvesting, double cropping with winter cereals and vegetables, upland-paddy rotation involving the growing of alternate crops like soybean and vegetables among others, have been recommended, because they eliminate perennial weed propagules in winter due to their exposure to cold, dry air on the soil surface after digging. Farmers in the southwestern and some other parts of Japan have tried these methods, although they still applied herbicides at the prevailing rates (Shibayama, 2001).

Crop residue mulch especially residual straw from winter cereals such as wheat and barley is useful for decreasing weed emergence before flooding in dry-seeded paddy fields. This is practical in no-till, dry-seeded rice farming in relay cropping with winter cereals (Cho *et al.*, 2001a, b). Mulching or covering with corrugated paper is sometimes done using a specific transplanter in low input production to retard weed emergence from the soil surface (Shibayama, 2001). Other possible mulches include rice hulls, beer dregs, rice bran, charcoal, and others. Additional cropping systems related that contribute to weed control are introduced by Cho *et al.* (2002). White clover effectively reduced weed populations when planted as a pre-crop in a no-till, direct-sown white clover–rice relay cropping system (Table 11). The weed control effect was a little low in first year but improved in the second year after establishment of higher white clover densities, better management of irrigation water and improved rice seeding tools. The improved management resulted in a higher seedling establishment ratio which was associated with a greater weed control effect.

Duck introduction into rice production is popular in Korea and Japan, even though attack by crows is a problem in Japan. In Korea and Japan similarly, the focus is on improving rice quality. Asano *et al.* (1999, 2000) evaluated the effect of duck introduction on grain quality by measuring total protein content. The total protein content in brown and milled rice tended to decrease with delayed harvesting irrespective of the cultivar (Koshihikari or Kinuhikari) in the presence of standard and Agigamo ducks. Late harvesting in the Agigamo duck farming system improved rice taste by decreasing the number of green-kerneled rice and protein and amylose content. The decrease in protein content also improved the palatability of brown rice.

Competition and weed tolerant rice varieties: Breeding competitive crops to increase yield and reduce weed stands is a major objective in several parts of the world (Callaway and Forcella, 1993; Kropff and van Laar, 1993). Dingkuhn (1998) introduced a new fertile progeny from *Oryza sativa* × *O. glaberrima* crosses, which gives rice breeders access to a broader range of germplasm. A recent breakthrough in generating fertile progeny from interspecific crosses might provide new solutions to the low productivity of upland rice production systems prone to weed competition. In both field and pot environments, CG14 (*O. glaberrima*) produced two to three times the LAI and tiller numbers as WAB56-104 (*O. sativa*). This was associated with a high specific leaf area (SLA) and low leaf chlorophyll content.

Johnson (1998) reported results from an experiment where the rice cultivars - IG10, an *O. glaberrima* Steudel; Moroberekan, a traditional *O. sativa* L. and IDSA6, an improved *O. sativa* L. where grown in conditions with and without competition from weeds. IG10 suffered less from competition with weeds and suppressed weeds better than the *O. sativa* cultivars. IG10 accumulated more biomass, produced more tillers, established a higher leaf area index, had higher specific leaf area and in the earlier stages of growth, partitioned more of its biomass to leaves than the *O. sativa* cultivars.

Transplanted rice seedlings, especially large ones, are much more effective competitors against weeds as compared to direct-seeded plants. Closely spaced rice seedlings are also better able to limit weed infestation than those planted at a normal density, although the yield is not necessarily higher. There are some rice varieties i.e.

relatively tolerant to weed competition, probably because owing to their growth patterns and more capable of shading newly emerging weeds beneath their leaves (Shibayama, 2001).

Water management: Flooding paddy fields with water to a depth of 10-15 cm after the rice has been planted has been found to be effective in the control of barnyard grass and other hygrophyte weed species. This is practiced also in the USA and other countries. In an experiment where the growth of weeds from the soil seedbank and sown *Echinochloa colona* and *E. crus-pavonis* was studied in relation to different water depths (0, 2, 4 and 8 cm) and flood durations (2, 4 and 7 days in 7), deeper flooding increased plant numbers in *Ammannia prieriana*, *Sphenoclea zeylanica* and *Heteranthera callifolia*, decreased plant numbers in *E. colona* and *E. crus-pavonis* and had no effect on *Fimbristylis littoralis*. Increased flood duration increased plant numbers in *H. callifolia* had no effect on *S. zeylanica* or *A. prieriana*, but decreased plant numbers in *S. filicaulis*, *E. colona* and *E. crus-pavonis*. Weed biomass at 28 days followed a similar pattern, with increased depth resulting in higher biomass of *H. callifolia* and *A. prieriana*, but lower biomass of *S. filicaulis*, *E. colona* and *E. crus-pavonis*. Deeper but intermittent flooding stimulated growth of *A. prieriana* and *F. littoralis* (Kent and Johnson, 2001). Shallow flooding is also recommended to induce an increase in tillering and heading in order to improve grain yield in machine-transplanted paddy (Shibayama, 2001). Bhagat *et al.* (1996) discuss the interactions between water, tillage and weed management practices. These are complex interactions that are further complicated by soil and climatic variabilities and heterogeneities. Studies from the tropical regions on possible effects of tillage and water control on weed emergence and growth in the presence and absence of herbicides have yielded conflicting results due to site specificity. Surface water in rice (*Oryza sativa* L.) reduces weed emergence and growth with variable degrees of success depending upon water depth, nature of weed species and time of flooding. Most studies, however, indicate that shallow flooding for the first few weeks after planting can effectively suppress weeds. Herbicide integration into a weed control programme makes proper water management more critical. However, water control is still unsatisfactory in most parts of tropical Asia. Investigations on various tillage intensities have revealed that invariably zero tilled soils have more weed populations compared with conventionally tilled soils in the absence of herbicides. Tillage may bury some weed seeds and expose others that were once deeply buried. Also, repeated tillage will uproot and bury the already germinated weeds. In a diverse weed community situation, effective control can be achieved if tillage is combined with herbicide application, because tillage is known to enhance herbicide effectiveness. There are reports of identical rice yields being obtained from flooded, zero and conventionally tilled soils.

Allelopathy as an important factor of sustainable weed management: Allelopathy is the direct influence from a chemical released from one plant on the development and growth of another. This could be an alternative or supplementary weed management technique. Rice allelopathy has been intensively studied in recent years. Dilday *et al.* (1991) identified rice cultivars exhibiting allelopathic potential against duck salad (*Heteranthera limosa*). Rice allelochemical(s) will soon be identified and the gene(s) involved in allelopathy will be ultimately incorporated into crops to breed allelopathic crops (Olofsdotter *et al.*, 2000). In other words, allelopathic genes can be possibly incorporated into hybrid rice, thus guaranteeing an increase in yield by 20 to 30% (Lin *et al.*, 2000). Thus, allelopathic crop varieties can be used as a means of sustainable weed management, which can in turn reduce herbicidal use (Chou, 1999). The control of paddy weeds by bio-herbicides or myco-herbicides, which are bacterial and fungal pathogens that naturally infest weeds, has been studied and some have been developed as registered products in the USA, Australia, Canada, the International Rice Research Institute (IRRI), Japan, parts of Europe and other countries (Shibayama, 2001).
Another allelopathic strategy involving the use of weed smothering crops has been proposed by Narwal (2000). It is conceptualized that the inclusion of summer fodder crops before the rice crop in a rice-wheat rotation may provide satisfactory weed control in the succeeding rice crop and may minimize the use of herbicides. Likewise, the replacement of wheat by winter fodder crops such as oat and berseem (*Trifolium alexandrinum*) may also help in the control of winter weeds. It is a rather long way to go, but the future of allelopathic crop breeding looks bright.

Integrated weed management: Integrated weed management is the rational use of direct and indirect control methods to provide cost effective weed control. Among the commonly suggested indirect methods in rice cultivation are: land preparation, water management, plant spacing, seed rate, cultivar selection and fertilizer application. Direct methods include hand weeding and use of herbicides. The essential factor in any integrated weed management programme is the number of indirect and direct methods that can be combined economically in a given situation. Sustainable agriculture has been a popular agricultural topic of various symposia during the last 10 to 15 years in Japan. Many discussions have already been conducted in presentations and in publications on the details of IWM technologies and on the possible or current successful examples of particular eco-friendly technologies and whether they will be useful or promising in paddy weed management in Japan. Conversely, it has also been suggested that while most of these IWM technologies are difficult to apply widely to Japanese paddy production, agro-chemical companies are more likely to improve herbicides so that they are safer to humans and impose less pressure on crops and the environment. To the Japanese small-scale farmers, mechanical, cultural or ecological weed control methods usually present practical difficulties because their rice farming takes place on holdings that are generally less than 1 ha. This means high costs, intensive labour and low income under the current IWM technologies. However, we should not lose sight of the ecological benefits from these useful measures. It is hoped that the economic benefits occruing from the introduction of alternate crops could in future act as an incentive for the adoption of IWM methods in both small and large-scale rice cultivation in Japan. Continuous use of the same control measures in some areas may contribute to a buildup in some tolerant weed species. Therefore, for effective and sustained weed control, integrated weed management with proper tillage and water control is needed.
Weed scientists should study target technologies further in order to develop them into practical and economically viable tools for the management of paddy weeds.

Trends of weed science in the 21st century: Asia is undergoing a process of change in its cropping systems due to a shortage of labour. Increased labour costs have caused a shift from transplanting to direct seeding in a few South-East Asian countries where population densities are low and the labour costs are escalating. This shift in crop establishment exacerbates the problems of grass weeds and weedy rice (Gressel, 1999).
Barnyard grass, weedy rice and sedges are listed as millennial weeds in rice that are not being adequately controlled worldwide (Gressel, 1999). *Echinochloa* species have always been problem weeds in paddy, but they are now developing resistance to the herbicides used for their control. Weedy rice will cause more problems in direct-seeded rice due to its genetic and morphological similarities to domestic rice and also due to the easy shattering nature and prolonged dormancy of its seed. There is a great potential for direct seeding in paddy, but for the time being, it will be limited to South-East Asian countries where population densities are low and farm wages are rapidly increasing (Kim, 2000).

Increased use of herbicide and need of new novel herbicides: Although hand weeding is the most common method of weed control in this region, herbicides have become one of the most important components for weed control. The use of herbicides to control rice weeds has increased over time in Asia. Two reasons were given to explain the increased use of herbicides: i) widespread adoption of high yielding varieties which created economic incentives for farmers to reduce weed infestation and ii) availability of cheap herbicides, e.g. the cost of weed control by herbicides in wet-seeded rice is less than one-fifth of the cost of a single-hand weeding in Illoilo, Philippines. Similar situations exist in West Java, Indonesia and the Mekong Delta, Vietnam (Pandey and Pingali, 1996).

Due to the availability of cheaper herbicides, the use of herbicides will continuously increase in countries where herbicides are currently used sparingly. However, the repeated and intensive use of herbicides on rice has resulted in about 20 weed species worldwide that are resistant to sulphonylurea herbicides (Valverde *et al.*, 2000). More herbicide-resistant biotypes will evolve if the present control systems are continuously used. There are already biotypes of some species that are resistant to propanil, 2,4-D and butachlor as well.

Herbicides possessing novel methods of action are needed to combat the evolution of resistance to currently available herbicides. New herbicides target sites such as geranylgeranyl diphosphate synthase, glutamate dehydrogenase, auxin transport, glutathione transferases (GTS) and cytochrome P450 monooxygenases (P450s) should be further studied as a new chemistry of herbicides to counteract the current problems caused by the use of herbicides.

Need for countermeasures against invasive weeds: Invasion by plants or animals is not a serious problem if control measures are put in place before full-scale invasion occurs in the main production areas. The large-scale movement of species around the world is now considered a clear and present danger to biodiversity and sustainability of agricultural production. The ability of a species to invade a habitat has been intensively studied, but no consensus on the biological attributes of weeds has emerged. There is not a single set of characteristics that leads to invasiveness. Rather certain combinations of species' characteristics such as life history and genetics interact with the biological and ecological components of specific environments, which then result in invasion (Schaal, 2000).

Prevention is the first step of defense against invasive species. Early detection, containment and eradication of incipient infestations of invasive species are the second most important form of defense (Epilee and Westbrooks, 2000). A worldwide effort is essential to prevent the international spread of invasive weeds.

The role of research and technology in weed control part: All the aforementioned research problems can be solved with weed scientists' patient, endeavor and enthusiasm. Many researchers insist on the following five scenarios in dealing with the weed control problem: I) it is expected that new herbicide groups satisfying all the currently desired requirements will be available. ii) application of biotechnology will yield the development of acceptable GM crops and highly competitive crop varieties having C4 photosynthetic ability and allelopathic crops. iii) many weeds and weed relatives will be identified as being sources of nutraceuticals, pharmaceuticals and drugs (Hatzios, 2000) and some of the weeds and their relatives will be identified as bio-energy sources. In addition, some of them will be utilized as ornamental and edible plants. Finally, a new paradigm of weed science acceptable to all parties will be set, leading to the recognition of the importance of weed science in 21st century agriculture. However, the acreage under GM crops continues to increase rapidly along with available traits and variants (Tables 12-1, 2, 3).

Need for international collaboration: Harada and Labrada (1999) insist on the need to establish a Weed Inventory Center in the Asia-Pacific region was proposed attached to FAO proposed the establishment of a Farmer Participatory Training Center for Asia (Personal communication, 2000). To establish the two centers mentioned above will require international collaboration among individual weed scientists, institutes and organizations. The Asia-Pacific Weed Science Society, the steering committee of Asia and the Pacific Working Group for Improved Weed Management (organized in 1992 with help of the FAO) will play some role in this regard.

The preceding contents show clearly that herbicides remain an integral part of weed control in Asia, despite the recent development of new production technologies based on Integrated Weed Management (IWM). One of the biggest impediments to the adoption of these new technologies is the inevitable reduction in yield with the adoption of IWM. This is particularly serious in the Korea and Japan where individual holdings are economically viable only under high input intensive cultivation.

However, the chemical-free methods already being tested in the two countries are likely to contribute to future weed control methods. Integrated weed management combining cultural, ecological, manual, mechanical and biological methods, prescriptive chemical control and contributions from plant breeding is the weed control tool of the future. With IWM, herbicides may not be absolutely necessary but will still be needed to supplement other more environmentally friendly methods of weed control.

References

Alex Bocek. Water Harvesting and aquaculture for Rural Development - Introduction to Fish Culture in Rice Paddy.

Asano, H., F. Hirano, K. Isobe and H. Sakurai, 2000, Effect of harvest time on the protein composition (glutelin, prolamin, albumin) and amylose content in paddy rice cultivated by duck farming system. Japanese J. Crop Sci., 69: 320-323.

Asano, H., K. Isobe and Y. Tsuboki, 1999. Effect of harvest time on the quality and palatability of paddy rice cultivated by Agigamo Duck Farming System, 68: 375-378.

Bhagat, R.M. and S.I. Bhuiyan, K. Moody, 1996. Water, tillage and weed interaction in lowland tropical rice. Agricultural Water Management, 31: 165-184.

Callaway, M.B., F. Forcella, 1993. Crop tolerance to weeds. In. Callaway, M.B., Forcella, C.A. (Eds.), Crop Improvement for Sustainable Agriculture. University of Nebraska Press, Lincoln, NE, pp: 100-131.

Chae, J.C., 1983. Direct seeding techniques of rice cultivation. In history of agricultural technology in Korea. Chongminsa, pp: 226-230.

Chae, J.C. and H.O. Guh, 1999. Occurrence and control of weeds in direct-seeded rice paddy in Korea. Jpn. Weed Sci. Tech., 44: 391-404.

Cho, Y.S., Z.R. Choe and S.E. Ockerby, 2001a. Managing tillage, sowing rate and nitrogen top-dressing level to sustain rice yield in a low-input, direct-sown, rice-vetch cropping system. Australian J. Exp. Agric., 41: 61-69.

Cho, Y.S., K. Hidaka and T. Mineta, 2002. Evaluation of White Clover and Rye as fallow crops in no-tilled Rice (*Oryza sativa* L.) production. Field Crops Research. Accepted.

Cho, Y.S., B.Z. Lee, Z.R. Choe and S.E. Ockerby, 2001b. An evaluation of a no-till, direct-sown, wheat-rice cropping system in Korea. Australian J. Exp. Agric., 44: 53-60.

Choi, C.D., J.G. Won, W.H. Lee and B.S. Choi, 1997. Shift in weed occurrence accompanying type of direct-seeded rice fields. Korean J. Weed Sci., 17: 139-146.

Chou, C.H., 1999. Frontiers of allelopathy in sustainable agriculture: experiences from Taiwan. In: Biodiversity and Allelopathy from Organisms to Ecosystems (Ed. Chou C.H., Waller G.R. and Reinhardt C.). Academia Sinica, Taipei, pp: 247-261.

Dilday, R.H., P. Nastasi, J. Lin and R.J.Jr. Smith, 1991. Allelopathic activity in rice (*Oryza sativa* L.) against duck salad (*Heteranthera Limosa* (Sw.) Wild.). Proceedings on Sustainable Agriculture for the Great Plain (Ed. Hensen J.D., Schaffer M.T., Ball D.A. and Vern Cole C.). USDA. ARS. Beltsville, MD, pp: 193-201.

Dingkuhn, M., M.P. Jones, D.E. Johnson and A. Sow, 1998. Growth and yield potential of *Oryza sativa* and *O. glaberrima* upland rice cultivars and their interspecific progenies, 57: 57-59.

Epilee, R.E. and R.G. Westbrooks, 2000. The Great Global Exchange. A Prospective on the Global Movement of Invasive Species. Abstracts of the Third International Weed Science Congress (Foz Do Iguassu. Brazil, 6-11 June 2000). International Weed Science Society, Corvallis. 2.

Gressel, J., 1999. Fulfilling needs for transgenic herbicide-resistance rice while preventing and mitigating introgression into weedy rice. Proceeding of the 17th Asian Pacific Weed Science Society Conference (Bangkok, Thailand, 22-27 November 1999). Asian-Pacific Weed Science Society, Bangkok, pp: 21-38.

Harada J., 1999. Weed science in year 2000s in Asian-Pacific region. Proceedings of the 17th Asian Pacific Weed Science Society Conference (Bangkok, Thailand, 22-27 November 1999). Asian-Pacific Weed Science Society, Bangkok, 9-12.

Hatzios, K.K., 2000. My view, weed science as an academic discipline in the era of biotechnology. Weed Sci., 48: 403-404.

Huh, S.M., L.G. Cho and S.L. Kwon, 1995b. Emergence of weed species and their competitive characteristics in direct-seeded rice (*Oryza sativa*). 2. Duration of weed competition with dry-seeded rice. Korean J. Weed Sci., 15: 289-297.

Huh, S.M., 1985. Weed emergence and its composition in the differently cropped paddy fields in southern districts. Theses of Suncheon National University, 4: 39-49.

Huh, S.M., L.G. Cho and S.L. Kwon, 1995a. Emergence of weed species and their competitive characteristics in direct-seeded rice (*Oryza sativa*). 1. Distribution and growth of weeds in direct-seeded rice. Korean J. of Weed Sci., 15: 278-288.

Im I.B., C.K. Kang, S.S. Han and S.Y. Choi, 1999. Weed control by weed emergence types in dry-seeded rice fields. Korean J. Weed Sci., 19: 7-14.

Im, I.B., J.O. Kuh and K.Y. Park, 1993. Weed occurrence and competitive characteristics under different cultivation types of rice (*Oryza sativa*). Korean J. Weed Sci., 13: 26-35.

Itoh, K., 2000. Importance of biodiversity of aquatic plants in agro-ecosystem for rice production. Abstracts of the International Symposium on Weed Biodiversity (National Sun Yat-sen University, Kaohsiung, Taiwan, 28-30 November 2000). Weed Science Society of the Republic of China and National Sun Yat-sen University. Kaoshing, 10.

Itoh, K., G.L. Wang and S. Ohba, 1999. Sulfanylurea resistance in *Lindernia micrantha*, an annual paddy weed in Japan. Weed Res., 39: 413-423.

Johnson, D.E., M. Dingkuhn, M.P. Jones and M.C. Mahamane, 1998. The influence of rice plant type on the effect of weed competition on *Oryza sativa* and *Oryza glaberrima*, 38: 207-216.

Kent, R.J. and D.E. Johnson, 2001. Influence of flood depth and duration on growth of lowland rice weeds, Cote d'Ivoire. Crop Protection, 20: 691-694

Kang, B.H., 1999. Weeds and Exotic Weeds Occurred in Rural and Urban Regions. Korean J. Weed Sci., 19: 34-70.

Kim, H.H., S.G. Lee, J.C. Lee, I.M. Song, C.W. Shin , C.S. Moon and J.Y. Pyon, 1998. Weed infestation and effective weed control in direct-seeded rice. Korean J. Weed Sci., 18: 1-11.

Kim, K.H., 1998. World food perspective and food security in Korea. Proceedings KSCS (Korean Society of Crop Science) and KBS (Korean Breeding Society) Symposium for 50th anniversary GSNU: 189-209.

Kim, K.U., 2000. Weed management implications and trends of direct seeding in Asia. Abstracts of the Third International Weed science Congress (Foz do Iguassu, Brazil, 6-11 June 2000). International Weed Science Society, Corvallis, 245.

Kim, S.J., Y.H. Kim, W.H. Lee, C.D. Choi, C.Y. Kim and B.S. Choi, 1997. Weed occurrence in lowand rice fields in Gyeongbuk Province. Korean J. Weed Sci., 17: 262-268.

Kim, S.C., Y.J. Oh and Y.W. Kwon, 1992. Weed flora of agricultural areas in Korea. Korean J. Weed Sci., 12: 317-334.

Kim, S.C., 1983. Status of paddy weed flora and community dynamics in Korea. Korean J. of Weed Sci., 3: 223-245.

Kropff, M.J. and H.H. van Laar, 1993. Modeling crop-weed interactions. CAB International, Wallingford, UK.

Ku, Y.C., K.H. Park and Y.J. Oh, 1993. Changes of weed flora under direct seeded rice cultivation in dry paddy field. Korean J. Weed Sci., 13: 159-163.

Lin, W., K.U. Kim, K. Lang and Y. Guo, 2000. Hybrid rice with allelopathy. Proceedings of the International Workshop in Rice Allelopathy (Kyungpook National University, Taegu, Korea 17-19 August 2000). Institute of Agricultural Science and Technology, Kyungpook National University, Taegu, pp: 41-47.

Matsunaka, S., 1983. Evolution of rice weed control practices and research: world perspective. In: Weed Control in Rice (ed. By International Rice Research Institute and International Weed Science Society). I.R.R.I., Manila, pp: 5-17.

Matsunaka, S., 2001. Historical review of rice herbicides in Japan. Weed Biology and Management, 1: 10-14.

Matteson, P.C., 1995. The 50% pesticide cuts in Europe: a glimpse of our future? Am. Entomol., 41: 210-220.

Narwal, S.S., 2000. Weed management in rice: Wheat rotation by Allelopathy. Critical Rev. Pl. Sci., 19: 249-266.

Nyarko, K.A and S.K. de Datta, 1991. Significance of Weeds in Rice Farming. In: A Handbook of Weed Control in Rice, Nyarko, K.A. and S.K. de Datta (Ed.). IRRI, Manila, pp: 1-5.

Olofsdotter, M., L.B. Jensen, D. Navarez, R.R. Pamplona and A. Rimando, 2000. Progress in rice allelopathy research. Proceedings the Third International Weed Science Congress (Foz do Iguassu, Brazil, 6-11 June 2000). International Weed Science Society, Corvallis, pp: 33.

Park, K.H and Y.J. Oh, 1995. Changes of weed community in lowland rice field in Korea. Korean J. Weed Sci., 15: 254-261.

Pandey, S. and P.L. Pingali, 1996. Economic aspects of weed management in rice. In: Weed Management in Rice. FAO plant Production and Protection Paper 139. Food and Agricultural Organization of the United States, Rome, pp: 55-73.

RDA, (Rural Development Administration, Korea), 1999. New technology for rice culture, pp: 107-128.

Schaal, B.A., 2000. The ecology and genetic of weeds: Theoretical issues and practical studies. Abstracts of the International Symposium on Weed Biodiversity (National Sun Yat-Sen University, Kaoshiung, Taiwan 28-30 November, 2000). Weed Science Society of the Republic of China and National Sun Yat-sen University, Kaoshing. 1.

Shibayama, H., 1994. Integrated management of paddy weeds in Japan: current status and prospects for improvement. In: Integrated Management of Paddy and Aquatic Weeds in Asia (Ed. Shibayama H. and Kiritani K.). FFTC Books Ser., No. 45. FFTC. Taipei, pp: 78-87.

Shibayama, H., 1996. Experience with rice herbicides in Japan. In: Herbicides in Asian rice: transitions in weed management (Ed. Naylor R.). Stanford University and IRRI, Stanford, pp: 243-254.

Shibayama, H., 2000. Weed management in sustainable rice production in Japan. Proceedings of the international Workshop on Biology and Management of Noxious Weeds for Sustainable and Labor Saving Rice Production. National Agricultural Research Center, MAFF, Tsukuba, pp: 16-21.

Shibayama, H., 2001. Weeds and weed management in rice production in Japan. Weed Biology and Management, 1: 53-60.

Uchino, A., H. Watanabe, G.X. Wang and K. Itoh, 1999. Light requirement in rapid diagnosis of sulfonylurea-resistant weeds of *Lindernia* spp. (Scrophulariaceae). Weed Tech., 13: 680-684.

Vromant, N., N.T.H. Chau and F. Ollevier, 2001. The effect of rice seeding rate and fish stocking on the floodwater ecology of the rice field in direct-seeded, concurrent rice-fish systems. Hydrobiologia, 445: 151-164.

Valverde, B.E., C.R. Riches and J.C. Caseley, 2000. Prevention and management of herbicide resistant weeds in rice. Crafos, S.A., Cartago, pp: 25-30.

Yamasue, Y., H. Murayama, H. Inoue, T. Matsui and T. Kusanagi, 1997. Productive structures of rice and *Echinochloa oryzicola* Vasing in mixed stands. J. Weed Sci. Tech., 42: 357-365.