Long-Time Direction of Herbicide Use in Paddy Fields in Korea

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Abstract

Due to rapid industrialization since the 1970s, farm labour has decreased and the amount of herbicide use has drastically increased. In the 1970s as the annual herbicides consisting of diphenylethers and acid amides were widely used, in the 1980s perennial weeds dominated in paddy fields. "One-shot herbicides", i.e. combinations of two or three herbicides including sulfonylureas, were used to control annual and perennial weeds at the same time by application during the growing season. Ideally, these combination products should maximize the synergistic effect of each herbicide so that the amount applied to a given area can be decreased. However, since weed species in a rice field may not need such broad coverage, the combination products are not always ideal in it. Thus, intensive use of these herbicides can actually enhance soil contamination in the long-term. Especially in Korea, the sudden change in the cultural system from transplanting to direct seeding has resulted in a longer rice growing season in fields and generated weed species which became tolerant to combinations of herbicides. Under such conditions, control of weeds can not be achieved with the existing combination products. To improve the efficiency of rice herbicide use the following should be considered ; ① reestablishment of crop-weed competitive relationship in different cultural systems (in relation to sequential application) ; ② avoidance of indiscriminate use of one-shot herbicides and sequential application of herbicides ; ③ development of reduced use technology to minimize environmental contamination ; ④ rotation of herbicides with different modes of action ; ⑤ development of specific herbicides for certain weeds ; ⑥ development of foliar-applied herbicides ; and ⑦ development of herbicide use technology toward integrated weed management.

Key words: direct seeding rice, weed problem, one-shot herbicide, sequential application, tank-mix, IWMS, rotation application

Introduction

Rice in Korea is grown on 1.2 M ha or 52% of total cropping acreage. Thus, rice is the single most important crop accounting for 43% of agricultural gross income of farmers with more than 115 kg of annual per capita consumption.

Rice production in Korea is presently confronted with very critical socio-economic conditions due to the rapid decrease in rural population, low labour quality, high wages in rural society and rejection of 3-D (difficult, dangerous, and dirty) agricultural work.

Self-sufficiency in rice had been one of the nation's goals for decades until 1977 when it was achieved through breeding of high-yielding varieties and improved cultural practices. As a result of continuous national research for technical innovations, the production of rice has been maintained above the level of self-sufficiency resulting in surplus availability, particularly, during the last few years.

On the other hand, rice production in Korea today is faced with critical challenges due to ① oversupply of rice, ② changes of farm demography to smaller and older farm population, and ③ weakness in competing with international rice market. In order to overcome these internal as well as external chal-

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lenges, rice production in Korea will have to undergo significant changes in cultural practices in the next few years. Accordingly, it is essential to reduce the production cost by improving labour productivity in rice cultivation.

Until recent years, the most important target of rice culture was maximum yield, whereas presently achieving economic yield that minimizes the production cost, is the major objective.

Since 1990, Rural Development Administration (RDA) has introduced so-called "machine-transplanting of infant seedlings (8 to 10 days old)". More recently, direct seeding and minimum tillage/no-till rice cultivation is being developed to improve the competitiveness of Korean rice in the open market. It will be an interesting task to identify key issues related to rice production in Korea in the future.

In comparing the productivity of labour and land, the land productivity of Korea is not significantly lower than that of California but the labour productivity of Korea is far below that of California. This is probably due to the small-scale farming in which large machinery is not practicable and land is not adjusted for. Therefore, the conditions should be improved and the cultural system should also switch to direct seeding culture.

Review of the changes in rice culture systems

Machine transplanting was introduced in the late 1970s using 30–35 days old seedlings. Before, conventional hand transplanting was used with 40–45 days old seedlings. From the viewpoint of weed control, there were 2 major problems ① herbicidal phytotoxicity increased as the seedlings were younger and transplanting depth was shallower, and ② the infestation area with perennial weeds, typically *Sagittaria pygmaea*, *Cyperus serotinus*, *Eleocharis kuroguwai*, etc. significantly increased.

New herbicides were screened for the younger rice seedlings and one-shot herbicides with SU have been successfully introduced since 1983.

The use of machine transplanting significantly increased during the 1980s and the age of transplanted seedlings declined to 8 days. Nowadays, it is estimated that more than 95% of the area is transplanted by machines and more than 50% of the acreage is planted with 8 days old seedlings.

In order to save labour for nursery beds, the new technology of using 8 days old seedlings was introduced in 1900, instead of conventional 30 days old seedlings. In the early days, herbicide phytotoxicity was a serious problem with 8 days old seedlings.

However, the 8 days old seedlings have shown a much stronger tolerance to most herbicides than 30 days old seedlings, mainly due to the active endosperm attached to the 8-day olds seedlings at the time of transplanting.

On the other hand, direct seeding practice has been introduced since 1991. The trend of seeded acreage during the last 4 years was as follows:

The most critical factors for the success of direct seeding are: ① weed control in early growing stage and ② stable maturity as the growing period is longer than in transplanting.

In direct seeding under dry paddy conditions, effective weed control is the most serious problem. Since paddy is maintained under dry conditions up to 30 days after seeding, both lowland and upland weed species tend to coexist. Even though fields are irrigated after rice seedling establishment water can easily leach down from the soil surface. This may provide more opportunities for the weed species to germinate. Also, dry paddy conditions result in weed shift to annual grass weeds such as *Echinochloa crus-galli*, *Oryza sativa* ssp. *spontanea*, *Leptochloa chinensis*, *Setaria viridis*, *Eleusine indica*, *Digitaria sanguinalis*, etc.

Practical weeding method in direct seeding under flooded conditions is similar to that of the transplanted rice cultivation except for the seeding procedure. There are two kinds of seeding methods under flooded conditions, i.e. water soil surface broadcasting and water subsoil drill seeding. In case of water soil surface broadcasting, the rice plant during the reproductive and ripening stages may become prone to lodging by the wind or typhoon unlike in the case of water subsoil drill seeding, as shown in Table 4.

Under flooded direct seeding, effective weed control is still a challenge due to phytotoxicity of herbicides. Tank-mixes of propanil with butachlor and pendimethalin are being developed for weed control at early growth stages. In order to overcome the issue of extended growth period, direct seeding is currently

Table 1 Recent trend of direct-seeding acreage of rice in Korea

	Direct seeding (ha)	
	Dry	Flooded
1991	259	0
1992	1,710	1,010
1993	3,550	4,020
1994	35,336	37,469
(1995)	(50,000)	(70,000)

Table 2 Comparison of regional potential acreage in direct seeding rice culture RDA ('93)

Regions	Total acreage	Direct seeding potential (thousand ha)			
		Sub-total	Dry C.	Flooded C.	D+F. C
Total	1,268	703	162	169	372
Central	315	153	62	22	69
S. Western	564	361	87	96	178
S. Eastern	389	189	13	51	125

being recommended in southern areas. In the long-term, development of early maturing varieties is required.

It is considered that Korea is in a transition stage from transplanting to direct seeding. The future planting system will largely depend on the successful introduction of direct seeding under farmers' conditions. The government strongly wishes to expand the acreage of direct seeding in future as it provides an opportunity for more economical rice production in Korea. Critical factors for successful direct seeding are as follows:

- Development of efficient seeding method.
- Prevention of lodging.
- Establishment of seedling stand under flooded direct seeding.
- Development of effective weed control programs.
- Development of new rice varieties suitable for direct seeding, including lodging resistance and shorter growth period.

Actually, in Korea the acreage available should enable to increase direct seeding systems by regions as shown in Table 2.

Review of major problem weeds and weed control systems

There is a significant difference in weed occurrence among the rice-growing systems. In hand transplanting, major dominant weed species are *Echinochloa crus-galli, Scirpus juncoides, Monochoria vaginalis, Aneilema japonica*, and *Ludwigia prostrata* as annual weeds while as perennial weed species, *Eleocharis kuroguwai* and *Cyperus serotinus* are predominant. On the other hand, there are more predominant annuals including, *Scirpus juncoides, Echinochloa crus-galli, Cyperus difformis, Aneilema japonica, Monochoria vaginalis, Persicaria hydropiper, Ludwigia prostrata and Rotala indica*, and perennials such as *Eleocharis kuroguwai* and *Cyperus serotinus* are dominant in transplanted rice with semi-adult seedlings.

In the rice fields transplanted with infant seedlings, dominant weed species are *Echinochloa crus-galli, Cyperus difformis, Monochoria vaginalis, Aneilema japonica, Persicaria hydropiper, Lindernia procumbens* as annual weeds, and also *Eleocharis kuroguwai* and *Cyperus serotinus* as perennial weeds are predominant as in the case of fields transplanted with semi-adult seedlings.

Unlike in transplanted rice, dominant weed species in direct seeding would be different in lowland rice field.

In general, *Alopecurus aequalis, Echinochloa crus-galli, Cyperus difformis, Monochoria vaginalis, Aneilema japonica, Persicaria hydropiper, Lindernia procumbens, Rotala indica, Ludwigia prostrata, Aeschynomene indica, Eragrostis multicaulis, and Centipeda minima* as annuals, and *Eleocharis kuroguwai* and *Cyperus serotinus* as perennial weeds were dominant in water-seeded rice.

In particular, dominant weed species are quite different in direct seeding under dry conditions. There are predominant weed species such as *Alopecurus aequalis, Cardamine flexuosa, Stellaria alsine, Mazus miquelii, Echinochloa crus-galli, Scirpus juncoides, Cyperus difformis, Lindernia procumbens, Aneilema japonica, Rotala indica, Persicaria hydropiper, Ludwigia prostrata, Lindernia angustifolia, Centipeda minima, Aeschynomene indica, Eragrostis multicaulis,* and *Digitaria sanguinalis* as annual weeds, and also perennial weed species like *Eleocharis kuroguwai* and *Cyperus serotinus* are dominant.

Evaluation of weed control systems based on herbicide use

1. Reestablishment of critical period of competition according to change in rice culture systems

Direct seeding method will undoubtedly result in drastic increment of weed growth compared with transplanting method, and also will lead to a shift to the troublesome weed flora. The important troublesome weeds in direct-seeded rice will be *Echinochloa* spp., *Digitaria* spp., annual *Cyperus* spp., *Leptochloa* spp. and *Setaria* spp., etc. In addition, some annual broadleaved weeds such as *Aeschynomene* spp. which is not an important weed in transplanted rice may become important and flooded direct-seeded rice will be suppressed by the occurrence of algae. Therefore, new integrated weed management concept including reestablishment of critical period concept in weed competition due to shifting of cultural methods might be needed to achieve an effective weed control in direct-seeded rice fields.

Figure 1 shows the critical period of competition under different cultural systems of rice in Honam district.

The critical period of competition in conventional hand-transplanting is not well determined. In this system critical competition with weeds can be avoided either by herbicide application at 4 weeks or 8 weeks after transplanting. Thus, satisfactory control of weeds can be achieved by treatment as soil application or foliar application. A similar trend was observed in transplanting with infant seedlings (8 days old), in which weed control can be satisfactorily achieved by a treatment at either 5 or 7 weeks after transplanting.

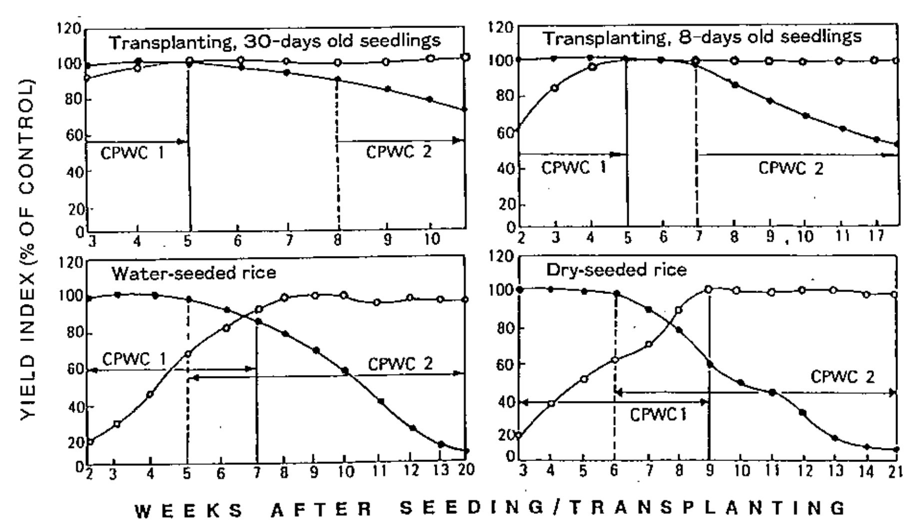

Fig. 1 Critical period of weed competition (CPWC).
○—○ : weed-free, ●—● : weed competition

Table 3 Changes in dominant weed species in lowland rice field

Year	Order of dominance				
	1 st	2 nd	3 rd	4 th	5 th
1971	*Rotala indica*	*Eleocharis acicularis*	*Monochoria vaginalis*	*Cyperus difformis*	*Echinochloa crus-galli*
1981	*Monochoria vaginalis*	*Sagittaria pygmaea*	*Sagittaria trifolia*	*Potamogeton distinctus*	*Cyperus serotinus*
1992	*Eleocharis kuroguwai*	*Sagittaria trifolia*	*Echinochloa crus-galli*	*Cyperus serotinus*	*Monochoria vaginalis*

Table 4 Comparison of major weed emergence by rice planting systems

Planting systems	Individuals (No./m^2)	Dry Wt. (g/m^2)	No. species	Diversity	Yield reduction (%)
Adult seedling 1 Hand T.	269	15.7	7	0.631	15
30 days old seedling 1 Machin T.	295	58.8	10	0.687	27
10 days old seedling 1 Machin T.	625	164.8	10	0.657	33
Direct seeding/flooded	840	751.6	15	0.793	50
Direct seeding/dry	1,090	776.1	20	0.865	85

Table 5 Survey of weed occurrence from farmers' fields (Chonnam, random 111 fields, 1994)

Weed occurrence (coverage %)	Field (%)	Sub-total
Less (<5%)	26(23.4)	26(23.4)
Annuals mostly (5~10%)	37(33.3)	
Annuals mostly (10~30%)	11(9.9)	50(45.0)
Annuals mostly (>30%)	2(1.8)	
Annuals and perennials mixed (5~10%)	23(20.7)	
Annuals and perennials mixed (10~30%)	7(6.3)	31(27.9)
Annuals and perennials mixed (>30%)	1(0.9)	
Perennials mostly (5~10%)	3(2.8)	
Perennials mostly (10~30%)	1(0.9)	4(3.7)
Perennials mostly (>30%)	−(−)	
Total	111(100)	111(100)

However, in water-seeded rice weed control must be implemented from 5 weeks after seeding and the required critical weed-free period is about 7 weeks from seeding, indicating that the period of weed control is longer. Therefore, one-shot application of herbicide or foliar application is not sufficient to control weeds satisfactorily, and sequential application is needed to control weeds in water-seeded rice.

In dry-seeded rice weed occurence including upland weeds is much more severe. Therefore, it is necessary to apply herbicides one time during the first dry period and two times after flooding.

2. Appraisal of one-shot herbicides

One-shot herbicides are premixtures with more than two herbicides with different target weeds. They are designed to obtain satisfactory control of weeds by one application during the whole season. However, there are two purposes for the use of one-shot herbicides. First, they should be designed to control a broad spectrum of weeds by the application of a smaller amount of each compound because they must have synergistic or additive effects. The second point is to save labour by reducing the number of applications in the season, though no additive or synergistic effects are expected. Most of the one-shot herbicides or premixtures in Korea are designed to save labour.

In Korea the herbicides registered in rice in 1994 included 54 products, of which 12 products were single and 42 products consisted of double or triple combinations. During the past 10 years the combination products were registered as one product.

The products registered for dry-seeded use were butachlor, Giljabi (propanil + pendimethalin), Satanil (propanil + thiobencarb), Momanna (propanil + molinate), and those for water-seded rice Dubaenon (dithiopyr + bensulfuron), Ddaji (pretilachlor + fenclorim).

Most of the one-shot herbicides are used for direct-seeded rice because of the time of weed emergence, difference in weed spectrum, and crop growth stages. But in the near future herbicides for sequential application may be developed for direct-seeded rice. In general most of the one-shot herbicides display a weed spectrum with overlapping by each herbicide, except for barnyardgrass (*Echinochloa crus-galli.*). In addition, one-shot herbicides are convenient for farmers in terms of application time for most annual and perennial weeds expected from the overall situation.

On the other hand, in a survey on weed occurrence in 111 farmers' fields, perennial weeds were found to be problems in only 35 fields (31%). In other words, the fields with problems of annual weeds accounted for 69%, suggesting that one-shot herbicides may not be necessary in some fields and that the application of one-shot herbicides resulted in the increase of herbicide residues in soil and possibility of contamination, thereby causing economic loss to farmers. In the United States, tank-mix treatments are widely used to broaden the spectrum of weed control, but in Asia (Korea), one-shot herbicides cause the same problems because they were used for convenience and labour-saving. Thus, tank-mix treatments should be recommended for farmers.

Long-term requirements for sequential application systems of herbicides for large-scale farming with direct seeding

The advantages of the use of herbicides are as follows (Table 6):

In order to optimize the advantages of herbicide use, the herbicides to be developed should meet the

Table 6 Advantages of herbicide use among other weeding methods

- Selective application on a specific crop
- Control of weeding time
- Energy saving → increase of cropping and frequency density
- Decrease of physical damage to crops → application possibility
- Weeding possibility in any sites (forest, waterway, etc.)
- Decrease with soil interference → rapid and whenever application
- Somewhat additionally, growth-regulating effects on crops

Table 7 Prerequisites of herbicides

- Low toxicity (safe to environment, humans and animals)
- High selectivity (crop damage ↓, weeding efficacy ↑)
- High environmental stability
- Low price (otherwise low cost)
- Easy handling in storage, transport, application and production
- Others

Table 8 Effect of labour-saving depending on formulation types of rice herbicides

	SC (5 ℓ /ha)	GR (30kg/ha)
Application method	Irrigation channel	Hand spread
Application hour/ha	50min	300min
Bioactivity (%)	92	95
Labour-saving (%)	83	0

Table 9 Characteristics of existing soil-applied herbicides (necessity of developing foliar-applied hebicides)

1. Inconsistent and incomplete efficacy of soil-applied herbicides
   ← considerable effect of soil and water management
   → increased competition with regrown weeds
2. Low possibility of application at proper time
   ← large-scale timing, difficulty in mechanization, uniqueness of crop growth stage
3. Difficulty in consistent prescription (in case of direct seeding)
   → changing pattern of weed emegerence time, year by year, and region by region
4. Difficulty in minimizing labour power, herbicide cost, and herbicide selection
   → selective application of optimum rates and selective herbicides (in case of foliar-applied herbicides)
5. Usage in sequential application
   → most soil application, pre-and early postemergence pre-mixed herbicides
6. Difficulty in controlling weeds in water channels and levees
   → minimizing contamination of water and soil by use of foliar-applied herbicides.

following conditions (Table 7).

Therefore, the requirement for large-scale farming in Korea are as follows :

1. Development of herbicides for control of resistant weeds

As the rice culture system switches from hand and machine transplanting to direct seeding, the distribution ratio of annual grass and broadleaved weeds has increased. Especially, the dominant weeds in water-seeded rice are *Alopecurus aequalis*, *Aneilema japonica*, *Aeschynomene indica*, *Leptochloa* spp., *Lindernia procumbens*, *Centipeda minima* and *Eragrostis multicaulis*, and those in dry-seeded rice are *Alopecurus aequalis*, *Cardamine flexuosa*, *Mazus miquelii*, as winter annual weeds, and most noxious weeds as in water-seeded rice.

Most of the weeds that predominate in direct seeding are tolerant to the existing rice herbicides.

2. Development of special formulations

Most of the rice herbicides are formulated in granular types, because of the small rice acreage/household and lack of application equipment. However, development of effective spreader or new formulation types will be necessary for large-scale farming in the future.

Table 10 Model 1: Rotation of different herbicides in the same crop

Year	Crop sequence	Chemical weed control treatments		
		Pre-planting	Preemergence	Postemergence
First	Corn	EPTC	Atrazine	2,4-D
Second	Corn	Atrazine+alachlor	Atrazine+propachlor	Linuron
Third	Corn	Cyanazine+butylate	Propachlor	Dicamba
Fourth	Soybeans	Trifluralin	Metribuzine	Bentazon+2,4-DB

Table 11 Model 2: Rotation of different herbicides in all crops

Year	Crop sequence	Chemical weed control treatment		
		Pre-planting	Preemergence	Postemergence
First	Corn	Atrazine+alachlor	Atrazine+propachlor	2,4-D
Second	Peanuts	Vernolate	Alachlor+dimoseb	2,4-DB
Third	Cotton	Trifluralin	Fluometuron	MSMA+methazole
Fourth	Soybeans	Fluchloralin	Metribuzin+alachlor	Bentazon+2,4-DB

Table 12 Advantages of herbicides when used in IWMS (1, 3)

- A wide array of herbicides is available to control most weeds at moderate cost
- Herbicides act quickly; and are effective against dense weed populations
- Reliable equipment is widely available to apply herbicides
- Herbicides permit the individual grower to protect his crops irrespective of any action taken by his neighbours
- Most herbicides are used selectively
- Herbicides are dependable and essential to the effective use of IWMS

3. Development of herbicides for foliar application

Most of the rice herbicides are applied to soil before or right after weed emergence. They are not adequate for use in large-scale farming in terms of application time and application quantity.

Due to the shortage of labour, and lack of application equipment and machines, herbicides for foliar application with a wide window should be developed under conditions prevailing in Korea where the application time is concentrated in a short period of time after transplanting or seeding.

4. Stability of herbicide activity and selectivity to rice crop and weeds

In large-scale farming, it is not easy to consistently control cultural operations such as irrigation, drainage, and cultivation. Therefore, emergence and growth characteristics of weed species are different, resulting in differences in activity and selectivity of herbicides applied.

5. Necessity to develop a technology of sequential treatment with single product and of tank-mix treatment

As the critical period of weed competition in large-scale direct seeding is longer, sequential treatment is required. However, as the dominance of a certain weed species increases with the succession of weeds, the system of sequential treatment should include a herbicide with a broad spectrum of control and a spe-

Table 13 Necessity of IWMS

– New species (resistant and new species) to be managed in order to reduce requirement for development of new herbicides
– Use of ecological and physical methods for the control of perennial weeds in order to solve the problems of one-shot herbicides
– Introduction of rotation systems of crops and herbicides in order to avoid the problems of consecutive application
– Maximum efficiency of herbicide efficacy by gradually reducing weed emergence and number

cial herbicide controlling new weeds.

When various species emerge at the same time, as satisfactory efficacy can not be achieved by the application of a single product, a small number of products and low rate will be effective.

6. Technology to avoid consecutive use of a certain herbicide

Farmers tend to select and apply a certain herbicide continuously because they do not know about herbicides and weed species well.

Continuous use of one herbicide enhances soil residues, decreases the occurrence of certain groups of microorganisms in soil, and increases the dominance of resistant weed species. Show (1982) proposed a rotation model for herbicides and crops, though not in the case of rice.

7. Development of Integrated Weed Management Systems (IWMS) technology

Chemical weed control has significantly contributed to the increase of yields, reduction of weed seeds in soil, reduction of tillage, improvement of harvesting efficiency, reduction of labour requirements, and dramatic increase of net farm profits without damaging the biological, chemical, or physical properties of soil, without reducing the productivity of soil and without causing undesirable shifts in weed populations (Shaw, 1982).

For these technologies, basic cultural practices should be maintained under optimum conditions. Advances in and cost of weed control technology must be assessed as a part of total farm-management production and protection technology, which includes the following.

These production and protection practices have been integrated into high-yielding agroecosystems that are compatible with the quality of the environment and they have had far-reaching benefits (Ennis *et al*., 1963; Shaw, 1974).

In conclusion, use of herbicides should be minimized for stability and safety of ecosystems, although herbicides must be used for farmers' benefit.

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Discussion

Mukhopadhyay, S. (India): If direct seeding is applied instead of transplanting, the use of radio control helicopter for the application of herbicides is probably the best method as it enables to save time, labour and does not cause appreciable damage to the rice crop. This method of application was illustrated during our visit of Ibaraki Experimental Station.