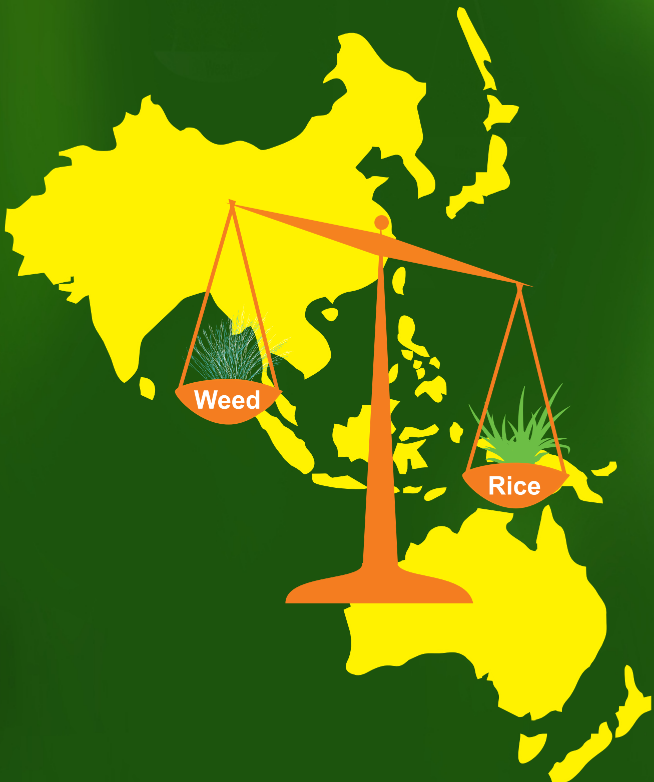
WEED MANAGEMENT IN RICE
IN THE ASIAN-PACIFIC REGION



Editors

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1

Rice Weed Management in the Asian-Pacific Region: An Overview

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@ APWSS 2017. Weed Management in Rice in the Asian-Pacific Region (Eds. A.N. Rao and H. Matsumoto)

Abstract

Rice yields increased several folds in many areas of the Asian-Pacific region, **s**ince the mid-1960s, due to introduction and adoption of new rice cultivars and associated improved production methods including weed management. The most commonly used weed control methods in rice include manual weeding, land preparation, cultural methods, such as manipulating the cultivar grown and planting density, water level management, herbicide application, crop rotations, crop residues use and management. Over the years, these methods have been integrated with preventative weed control (such as clean seeds and clean equipment) and where possible, biological control. Herbicide resistance in rice weeds, shifts in weed floras and climate change pose new and major challenges in the Asian-Pacific region for increasing rice productivity further in a sustainable manner. Despite the research, allelopathic rice accessions or cultivars are yet to make a major impact in rice weed management in on-farm situations. Over the past 50-60 years, a large corpus of knowledge has been developed in Asian-Pacific region on both constraints and opportunities in rice cultivation, including those posed by weeds. Direct-seeding of rice is now favoured over transplanting by farmers in many countries. To sustain productivity and increase rice yields, weed scientists in the region must build on the existing knowledge of ecological and biological attributes of rice weeds and apply well established principles of weed management. Whilst herbicides may continue to play an important role, particularly, in managing specific and serious problems, such as 'weedy rice', over-reliance on herbicides is not likely to be beneficial to the Asian-Pacific region in the long run. Instead, attention should be on developing holistic, country-specific, or region-specific rice weed management packages, integrated with cultivar-specific recommendations. The success of better management of weeds in rice-field will depend on recognizing that weeds are but only one major constraint to increasing rice yields and on applying natural resource management principles, with appreciation of the broader socio-economic factors that influence farmers decision making.

Keywords: Asian-Pacific region, rice cultivation, herbicides, herbicide resistance, integrated weed management, rice-field biodiversity.

1. Introduction

The majority of countries in the Asian-Pacific Region are largely agrarian societies with a high proportion of the population engaged in agriculture and related activities. The Asian-Pacific Region, with over 4.5 billion people, is home to nearly 60% per cent of the world's population. It is a geographically diverse region, with seven of the world's ten most populous countries (UN, 2015). Agricultural growth is critical for sustainable and inclusive economic growth in the region, as the vast majority of the population depends on the agricultural sector for their livelihood. Since the

'Green Revolution' era, the Asian-Pacific region has achieved impressive growth in agricultural production, boosting food security and reducing poverty. However, the growth in agricultural production continues to lag behind the current and future needs, and poverty and malnutrition remain widespread. There are 490 million people still suffering chronic hunger in the region, and Asian-Pacific Region is home to almost 62% of the world's under nourished (FAO, 2014a; 2015b). The major challenge for the region in the coming decades is to manage natural resources sustainably, conserve the environment, while raising the productivity of major crops, including rice, to meet the growing food demand of an increasing population.

Rice (*Oryza sativa* L.) is the staple grain of the majority (56% of world) of the people (4 billion). Rice is cultivated by 144 million farm families (25% of world farmers) (Morell, 2017). However, most of them have less than two hectares (GRiSP, 2013a). Rice is the major cereal crop of the Asian-Pacific region, where around 90% of the world's rice is produced (Table 1). In the region, India, China and Australia, have the highest cultivated area, total production and productivity (tons ha^{-1}), respectively, of rice in the world. All the five major exporters of rice (India, Pakistan, Thailand, Vietnam and USA) are also from this region (FAO, 2015a). Achieving rice self-sufficiency, is a major national priority and policy platform of governments in the region (GRiSP, 2013a; b; FAO, 2015b), as the region's food security and people's livelihoods are very much dependent on rice. An additional one billion people (half of the predicted global increase), by 2050, is expected to occur in the Asian-Pacific region.

Rice will be the single most important source of calories in the region for many more decades, and rice demand will also grow rapidly in other parts of the world, including the sub-Saharan Africa and the Middle East. The developing countries in the Asian-Pacific region will need to increase their food production by up to 77% (from the 2005/07 level) to feed their people by 2050 (FAO, 2015a), when the world's population is expected to top nine billion (Alexandratos and Bruinsma, 2012). Rice will continue to play a major role in meeting the challenge of ensuring food security to the populations of the region, with other flow-on effects. Rice productivity growth is central to economic growth, poverty reduction and food security in the region. Increased rice production, if achieved in a sustainable manner, will also have other positive effects, such as contributing to environmental protection and even to geo-political stability in the Asian-Pacific countries.

There is limited scope for expansion of arable land in the Asian-Pacific region and the quality of available land is also rapidly declining. Hence, increased rice productivity will have to mostly come from existing areas, and the general, prediction is a need for an increase of nearly 90% of current production by 2050. Such an increase in rice productivity, to be achieved in a sustainable manner, is only possible by understanding on-going constraints (which include weeds), and other agronomic and socio-economic factors influencing on-farm production. Managing these constraints, whilst protecting the agro-ecosystem health of rice-field environments, is quite challenging. The future of rice productivity will depend on achieving this effectively, in an economical and ecologically sustainable way.

Table: 1. Total Area Production and Productivity of Rice in Asian-Pacific Region Countries, 2014*

Country	Production (000 tonnes)	Area (000 ha)	Productivity (t ha^{-1})
Australia	819	76	10.776
Bangladesh	52,325	11,319	4.622
Bhutan	76	20	3.763
Cambodia	9,324	2,856	3.264
China	206,507	30,300	6.815
China, Taiwan (ROC)	1,732	271	6.391
South Korea	2,626	525	5.002
Fiji	5	2	2.533
India	157,200	43,855	3.584
Indonesia	70,846	13,797	5.134
Iran	2,300	529	4.347
Japan	10,549	1575	6.697
Laos	4,002	957	4.178
Malaysia	2,645	689	3.835
Myanmar	26,423	6,790	3.891
Nepal	5,047	1,486	3.394
Pakistan	7,002	2,890	2.423
Papua New Guinea	0.843	0.422	1.997
Philippines	18,967	4,739	4.002
Rep. of Korea	5,637	815	6.913
Sri Lanka	3,381	881	3.838
Thailand	32,620	10,664	3.059
Vietnam	44,974	7,816	5.754
Total – Asian-Pacific Region	**663,980(89.5%)**	**142,852 (87.8%)**	**4.648**
Rest of World	77497(10.5%)	19,864 (12.2%)	3.901
World	**741,477**	**162,716**	**4.556**

*FAO, 2014b (http://www.fao.org/faostat/en/#data/QC) (accessed on-line 1-7-2017)

Since the 1950s, and particularly after the establishment of the International Rice Research Institute (IRRI) in the Philippines, substantial research has been conducted globally, as well as in the Asian-Pacific region, on rice cultivation methods, rice breeding, crop protection, including weed management. This research, and its adoption, has led to significant improvements in‘on-farm’ rice productivity across the region, providing both increased profits for farmers and food security to the large populations of Asian-Pacific countries (De Datta, 1989; GRiSP, 2013a).

As a prelude to the other following Chapters, which follow in this Volume, in this Chapter1, we provide an overview and synthesis of rice weeds and their management in the Asian-Pacific countries, are discussed briefly. The constraints and challenges rice farmers and weed scientists would face. In so doing, we direct attention to the principal factors, which influence the changes in the weed flora, and sustainable weed management, within the rice production systems of our region. Drawing on our own experiences, with in the above context, we provide some perspectives on how countries of the region may increase rice yields, whilst protecting vulnerable rice agroecosystems.

2. Rice Production Systems in the Asian-Pacific Region

The rice production systems in the Asian-Pacific region countries have been classified in different ways depending on the context (Rao et al., 2017a). The classifications of rice environments are based on altitude (upland, lowland, deep water) and water source (irrigated, or rainfed). Lowland rice production systems (continuously grown under flooding) are largely, irrigated lowland rice cultivation, or rainfed systems. In recent times, irrigated upland, or aerobic rice production systems are gaining interest among farmers of the Asian-Pacific region (Seck et al., 2012). Weeds are a common factor associated with rice, irrespective of the type of rice production system, prevalent in different countries of the region. For the present chapter, the classification of rice production systems, based on the method of rice establishment (Rao et al., 2017a) is used.

The major methods of rice establishment of rice in the Asian-Pacific region are: (i) Transplanting, and (ii) Direct-seeding. Based on these two methods of rice establishment, the production systems can be categorized as: (i) Transplanted rice (TPR) [in this method, rice seedlings are transplanted into puddled soil (wet tillage); transplanting can be done manually, e.g. in India, or by machine e.g. in Korea, Japan]; and (ii) Direct-Seeded rice (DSR). Direct-seeding of rice involves machine drilling, or broadcasting rice into dry beds (dry-seeded rice); or broadcast seeding or drum-seeding pregerminated rice seed on to puddled and levelled soil (wet-seeded rice) or into standing water (water-seeded rice). Details of these rice production systems are provided in GRiSP (2013a,b); Kumar and Ladha (2011); Matloob et al. (2015); Pandey et al. (2002); Rao et al. (2017a) and Singh et al. (2008). The puddled soil in TPR ensures good crop establishment, and weed control with standing water, whilst reducing deep-percolation water losses. In TPR, weeds are suppressed by the standing water, and the aged, transplanted rice seedlings have a ‘head start’ over germinating weed seedlings, leading to competitive control of weeds (Moody, 1983). However, conventional TPR requires a large amount of water, labour, and energy, which are becoming scarce, and more expensive, leading to reduced profitability and sustainability of this cultivation method. DSR was proved to saves irrigation water by 11-18% and reduces the total labour requirement by 11-66%, compared to TPR. DSR also makes planting faster and easier; the crop matures 7-10 days earlier than in TPR; improves soil health; increases tolerance to water deficits; emits less methane from cropping fields,and generally increases net income for farmers (Rao et al, 2007; Kumar and Ladha, 2011).

After its re-introduction in the late-1970s, farmers in the Asian-Pacific region have preferred DSR to TPR. Labor scarcity has been the key factor in the rapid adoption of mechanized, direct-seeding. Among the primary disadvantageous of DSR is the rich diversity of the weed flora and the difficulties in managing weeds, compared with TPR. In DSR, weeds emerge simultaneously with crop seedlings, grow more quickly in moist soil than in TPR and expose rice to much higher risks of yield losses due to weeds, which could be as high as 50-90% losses of yield and quality (Chauhan and Johnson, 2011; Pandey et al., 2002; Rao et al., 2007; Singh et al., 2008).

3. Major Rice Weeds in the Asian-Pacific Region

In the Asian-Pacific region, rice is grown in a wide range of climatic conditions and the weeds associated with rice are well adapted to those conditions. In most tropical Asian countries, year-round warm temperatures and high humidity encourage a diversity of weeds to grow, competing with rice for space, sunlight, water and other resources. Important factors that influence the abundance of weed species in rice fields include latitude, altitude, rice culture method, soil moisture regime, crop rotation, soil and air temperatures, land preparation, fertilization, rice cultivar, weed control technology, and the interactions of those factors (Noda, 1977; Smith, 1983; 1989; Soerjani et al., 1987; Moody, 1989; Chandrasena, 1990; Pandey et al., 2002; Rao et al., 2007).

According to Moody (1989), over 1800 plant species have been reported as weeds in rice from 15 different countries in South and Southeast Asia. Weed species exhibit considerable plasticity, or ecological amplitude, in their adaptations to wet environments and aquatic habitat. Both moisture-loving and upland weed species could invade a rice field, depending on the soil moisture saturation level or standing water depth.

The following can be highlighted from a review of data and information on rice weeds:

- It is common to find about 300-350 species occurring in the rice-field environments in any country of the region (IRRI, 1983).
- Holm et al. (1977) reported that barnyard grass (*Echinochloa crus-galli)* as the most serious weed of rice, because it is found almost everywhere the rice is grown. While, *E. crus-galli* has a greater distribution range from north to south across the globe, *E. colona* tends to clustered along the equatorial (tropical) regions. Ranked No. 3 and 4 were globe fringe-rush (*Fimbristylis miliacea*) - a very serious weed in southern and eastern Asia and in the Caribbean region; and umbrella sedge (*Cyperus difformis*) – a major rice weed in Africa, Asia, Australia and Europe.
- Among the other major weeds of rice listed by Holm et al. (1977) were six additional taxa: purple nutsedge (*Cyperus rotundus*); *Ischaemum rugosum*; goose grass (*Eleusine indica*); goose weed (*Sphenoclea zeylanica*); flat sedge (*Cyperus iria*) and pickerel weed (*Monochoria vaginalis*). Despite its seriousness, *Monochoria vaginalis* was noted to be restrictedin regional

distribution (i.e. eastern Asia, and Indonesia, Japan, Korea, Philippines, Sarawak and Taiwan).

- Holm et al. (1977) also distinguished that weeds of upland rice were different from those of lowland rice. *Echinochloa colona* was ranked the worst weed of upland rice, followed by *Eleusine indica* and *Echinochloa crus-galli*. Other important upland rice weeds were: Bermuda grass (*Cynodon dactylon*); purslane (*Portulaca oleracea*); purple crabgrass (*Digitaria sanguinalis*); goat weed (*Ageratum conyzoides*); spiny amaranth (*Amaranthus spinosus*) and crabgrass (*Digitaria ciliaris*; syn. *D. adscendens*).
- Rao et al. (2007) compiled a list of 140 monocotyledonous and dicotyledonous species, in 27 families, that have been reported as important, globally, in DSR. Moisture-loving grasses (Family Poaceae) are the most common weeds in rice-fields, and sedges and rushes (Cyperaceae) come next, as the second most abundant.

Table 2 provides a list of the main species that have been reported as the most important rice weeds in the majority of the Asian-Pacific countries in recent decades. This list is by no means comprehensive, given the variability in the way data has been gathered and reported, in various sources. However, it does show the dominance of some species in the common rice culture systems (i.e. dry-seeded rice - DSR; wet-seeded rice -WSR; or transplanted rice -TPR). Weeds also vary with the type of rice establishment. A much diverse weed flora is characteristic of DSR (Tomita et al., 2003).

Based on our review of data and information, which may vary widely in terms of reliability, across the Asian-Pacific region countries, we have compiled the top twelve weed species that have been reported as the most troublesome from the region (Table 3).

4. Rice Yield Losses due to Weeds

The yield losses caused by weeds in rice depend upon various associated factors, such as the constituent weeds in the weed flora associated with a specific site; density of specific species; time of emergence of weeds relative to rice; the duration of weed competition and other cultural factors, such as standing water (Zoschke, 1990; Rao and Chauhan, 2015; Rao and Ladha, 2011; 2013). The yield losses reported are much less under continuous flooding than under saturated soil conditions. The following key factors are involved in rice yield losses due to weeds (Chisaka, 1977; Smith, 1989): (a) weed species; (b) density of weeds; (c) duration of interference; (d) distance of interference (due to the patchy distribution of weeds in a rice-field) and (e) rice cultivar.

The exact length of the ‘critical period’ for rice and weed interactions varies in different countries and rice culture conditions. However, research results concur that failure to control weeds during early stages of the growing season could reduce yields significantly. Studies in Japan (Chisaka, 1977) identified two critical

Table 2. List of Principle Rice Weeds in the Asian-Pacific Region*

Family	Taxon	Common Name**	Habit***	Rice Culture [a]	Impact Level [b]
Aizoaceae	*Trianthema portulacastrum* L.	giant pigweed	Annual, UPL	DSR>WSR	C
Alismataceae	*Alisma lanceolatum* With.	water plantain	Annual; OH	WSR	B
	*Alisma plantago-aquatica*L.	water plantain	Annual; OH	WSR	B
	Damasonium minus (R. Br.) Buchen.	starfruit	Annual; OH	WSR	B
	Limnocharis flava (L.) Buchen.	Yellow velvetleaf	Annual; OH	WSR	B
	Sagittaria graminea Michx.	arrowhead	Annual; OH	WSR	B
	Sagittaria montevidensis Cham. & Schltdl.	arrowhead	Annual; OH	WSR	B
	Sagittaria platyphylla (Engelm.) J.G. Sm	arrowhead	Annual; OH	WSR	B
Amaranthaceae	*Alternanthera sessilis* (L.) R. Br.	sessile joyweed	Perennial, FH	DSR > WSR	B
	Amaranthus spinosus L.	prickly amaranths	Annual, FH	DSR	C
Araceae	*Pistia stratiotes* L.	water lettuce	Perrenial, OH	TPR>DSR	C
Asteraceae	*Ageratum conyzoides* L.	goat weed	Annual, FH	DSR	C
	Eclipta prostata (L.) L.	false daisy	Annual, FH	DSR > TPR	C
Azollaceae	*Azolla filiculoides* Lam.	azolla (Fern)	Annual; OH	TPR	B
Commelinaceae	*Commelina benghalensisi* L.	tropical spiderwort	Perennial	DSR >> TPR	B
	Commelina diffusa Burm.f.	spreading dayflower	Perennial, FH	DSR > TPR	C

Table 2. Continued

Family	Taxon	Common Name**	Habit***	Rice Culture [a]	Impact Level [b]
Convolvulaceae	*Ipomoea aquatic* Forssk.	water Spinach	Perennial, OH	TPR >DS	C
Cyperaceae	*Bolboschoenus maritimus* (L.) L. Palla	saltmarsh bulrush	Perennial, OH	WSR, TPR >DS	C
	Cyperus difformis L.	umbrella sedge, Dirty Dora	Annual; OH	WSR > TPR >DS	A
	Cyperus iria L.	Flatsedge	Annual; OH	DSR, WSR >> TPR	A
	Cyperus rotundus L.	purple nutsedge	Perennial, UPL	DSR	A
	Cyperus serotinus Rottb.	tidal marsh flatsedge	Perennial, OH	WSR, TPR >DS	C
	Eleocharis acuta R. Br.	spike rush	Perennial, OH	DSR, WSR	B
	Fimbristylis dichotoma (L.) Vahl	forked fringe-rush	Perennial; OH	DSR > WSR > TPR	B
	Fimbristylis miliaceae (L.) Vahl	globe fringe-rush	Perennial; OH	DSR > WSR > TPR	B
	Schoenoplectiella juncoides (Roxb.) Lye	rock bulrush	Annual, OH	WS, TPR	C
	Scirpus grossus L.f.	giant bur rush	Perennial, OH	DSR, TPR	B
Elatinaceae	*Elatine gratioloides* A. Cunn.	waterwort	Perennial, OH	DSR, TPR	C
Fabaceae	*Aeschynomene aspera* L.	sola pith plant	Perennial, OH	DSR > TPR	C
	Aeschynomene indica L.	Indian joint-vetch	Perennial, OH	DSR > TPR	C
	Mimosa diplotricha C. Wright ex Sauvalle	giant sensitive plant	Perennial,	DSR > TPR	C

Table 2. Continued

Family	Taxon	Common Name**	Habit***	Rice Culture [a]	Impact Level [b]
			FH		
Lythraceae	*Ammannia baccifera* L.	red stem	Annual; OH	WSR	C
	Ammania multiflora Roxb.	jerry-jerry	Annual; OH	WSR	C
	Lythrum hyssopifolia L	loosestrife	Annual; OH	WSR > DSR	C
	Rotala indica (Willd.) Koehne	Indian toothcup	Annual; OH	WSR > DSR	C
Marsiliaceae	*Marsilea drummondii* A. Braun	nardoo (Fern)	Perennial, OH	TPR > DSR	C
	Marsilea minuta L.	dwarf clover	Perennial, OH	TPR > DSR	C
Onagraceae	*Ludwigia adscendence* (L.) Hara	creeping water primrose	Perennial, OH	WSR > DSR	C
	Ludwigia hyssopifolia (G. Don) Exell	water primrose	Annual; OH	DSR, WSR	B
	Ludwigia octovalvis (Jacq.) Raven	long-fruited primrose willow	Perennial, FH	DSR, WSR	C
Poaceae	*Cynodon dactylon*	couch grass	Perennial, UPL	DSR	C
	Dactylocteniumaegyptium (L.) Willd,	crowfoot grass	Perennial, UPL	DSR	C
	Digitaria adscendens (L.) Scop.	purple crabgrass	Annual, UPL	DSR	C
	Digitaria ciliaris (Retz.) Koeler	crabgrass	Annual, UPL	DSR	C
	Diplachne fusca (L.) P. Beauv. ex. Roem. & Schult.	silvertop grass	Perennial	DSR	C
	Echinochloa colona (L.) Link	awnless barnyard grass	Annual, FH	DSR > WSR	A
	Echinochloa crus-galli (L.) P. Beauv	barnyard grass	Annual, FH	DSR > WSR > TPR	A

Table 2. Continued

Family	Taxon	Common Name**	Habit***	Rice Culture [a]	Impact Level [b]
	Echinochloa glabrescence Munro ex Hook. F.	barnyard grass	Annual, FH	DSR, WSR, TPR	A
	E. crus-galli (L.) Beauv. var. *oryzoides* (Ard.) Lindm.	hairy millet	Annual, FH	DSR, WSR, TPR	A
	Echinochloa oryzicola (Vasing.) Vasing	Japanese millet, barnyard grass	Annual, FH	DSR, WSR, TPR	A
	Eleusine indica (L.) Gaertn	goose grass	Annual, FH	DSR	B
	Eragrostis parviflora (R. Br.) Trin.	weeping love grass	Perennial, FH	DSR	C
	Imperata cylindrica (L.) Raeuschel	cogon grass	Perennial, FH	DSR	B
	Ischaemum rugosum Salisb.	wrinkled grass	Perennial, FH	DSR > WSR > TPR	B
	Leersia hexandra Sw.	cut grass	Perennial, FH	WSR, TPR > DSR	B
	Leptochloa chinensis (L.) Nees	red sprangletop	Annual, FH	DSR > WSR > TPR	A
	Leptochloa panicea (Retz.) Ohwl	sprangletop	Annual, FH	DSR > WSR, TPR	B
	Oryza sativa L. (f. *spontanea*)	weedy rice	Annual, FH	DSR, TPR	A
	Panicum repens L.	torpedo grass	Perennial; FH	DSR	C
	Paspalum distichum L.	water couch	Perennial, FH	DSR >WS, TPR	C
	Paspalum paspaloides (Michx.) Lams. Scribn.	water couch; paspalum	Perennial, FH	DSR > WSR, TPR	C
	Paspalum scrobiculatum L.	kodo millet	Perennial, FH	DSR > WSR	C
	Rottboellia cochinchinensis (Lour.) W.D. Clayton	itch grass	Annual, UPL	DSR	C

Table 2. Continued

Family	Taxon	Common Name**	Habit***	Rice Culture [a]	Impact Level [b]
Polygonaceae	*Polygonum hydropiper* L.	marsh pepper	Annual, OH	DSR, WSR, TPR	C
	Rumex crispus L.	curly dock	Annual, FH	DSR	C
Pontederiaceae	*Eichhornia crassipes* (Mart.) Solms	water hyacinth	Perennial, OH	TPR > DSR	C
	Monochoria vaginalis (Burm. f.) C. Presl ex Kunth	pickerel weed	Annual; OH	TPR > DSR	A
Portulacaceae	*Portulaca oleracea* L.	common purslane	Annual, UPL	DSR >> WSR	C
Sphenocleacea	*Sphenoclea zeylanica* Gaertn.	goose weed	Annual; OH	DSR, WSR > TPR	B
Typhaceae	*Typha orientalis* C. Presl	cattail	Perennial, FH	DSR, TPR	C

*This is not an exhaustive list; instead, we have highlighted the species that are most commonly reported as important in many countries of the Asian-Pacific region, and are widespread; many of the above species are likely to feature in any list of the most troublesome rice weeds, based on our experiences, and sources given in the Literature Cited.

Some of the taxa are still referred to in the region under various synonyms. However, Botanical Names and naming authorities arecontinually updated, and can be found On-line in updated Plant List of Kew Gardens, UK (see http://www.theplantlist.org/tpl1.1/record/kew-264688)

** Only the most common English name is provided, as each country has a different common name for the species.

***OH – Obligate hydrophyte; FH – Facultative hydrophyte; UPL – upland species

[a]Methods of rice establishment after which species may commonly occur; DSR = dry-seeded rice (irrigated or rainfed); WSR = wet-seeded rice; TPR = transplanted rice (irrigated or rainfed);.“>”indicatesmorethan and“>>” much more than, e.g. DS> TP means that the species is likely to occur more in direct-seeded than in transplanted rice.

[b]A = weed causes major yield or quality losses and is economically troublesome; B = weed causes moderate yield or quality losses and is economically troublesome in certain rice cultures in some countries; C = weed causes slight yield and quality losses and is only marginally, economically troublesome in some countries.

Table 3. Top Twelve Weeds Reported as the Most Important in Rice in the Asian-Pacific Region*

Rank	Taxon	Counties reporting the species as a major weed
1	*Echinochloa crus-galli*	Australia, Bangladesh, China, India, Indonesia, Japan, Philippines, Pakistan, Malaysia, Myanmar, Nepal, Sri Lanka, Thailand, USA, Vietnam
2	*Leptochloa chinensis*	Bangladesh, China, India, Indonesia, Japan, Philippines, Pakistan, Malaysia, Myanmar, Nepal, Sri Lanka, Thailand, Vietnam
3	*Cyperus difformis*	Australia, Bangladesh, China, India, Indonesia, Japan, Philippines, Pakistan, Myanmar, Nepal, USA, Vietnam
4	*Echinochloa colona*	Australia, Bangladesh, China, India, Indonesia, Japan, Korea, Pakistan, Myanmar, Nepal, Sri Lanka, USA
5	*Oryza sativa* f. *spontanea*	Australia, Bangladesh, China, India, Indonesia, Japan, Malaysia, Pakistan, Philippines, Sri Lanka, Thailand, USA, Vietnam
6	*Monochoria vaginalis*	China, India, Indonesia, Japan, Korea, Myanmar, Nepal, Philippines, Sri Lanka, USA, Vietnam
7	*Cyperus iria*	Bangladesh, India, Indonesia, Myanmar, Nepal, Philippines, Pakistan, Sri Lanka, USA, Vietnam
8	*Fimbristylis miliacea*	Bangladesh, India, Indonesia, Myanmar, Nepal, Philippines, Pakistan, Sri Lanka, Vietnam
9	*Paspalum distichum*	China, India, Indonesia, Malaysia, Philippines, Pakistan, USA, Vietnam
10	*Cyperus rotundus*	Bangladesh, India, Indonesia, Nepal, Philippines, Pakistan, Sri Lanka
11	*Ischaemum rugosum*	India, Indonesia, Malaysia, Nepal, Philippines, Pakistan, Sri Lanka
12	*Eleusine indica*	India, Indonesia, Malaysia, Nepal, Philippines, Pakistan, Sri Lanka

* Note**:** A number of references provided in the Literature Cited are used here to compile this List and also based on our own experiences across many countries of the region. Additional information is available on http://www.knowledgebank.irri.org/training/fact-sheets/pest-management/weeds/main-weeds-of-rice-in-asia

periods in TPR, which has the initial growth advantage for rice. The first, between 4 and 6 weeks after transplanting, corresponds to the period of maximum tillering and causes the greatest reduction in the number of panicles. The second occurred during the 12^{th} week, or early ripening stage. Rice plants under severe competitive stress from weeds produce fewer tillers; fewer panicle bearing tillers; smaller panicles, and also show delayed heading (Chisaka, 1977). The critical period for DSR is typically, 3 to 8 weeks, and 4 to 6 weeks in TPR (Chauhan and Johnson, 2011, Rao and Nagamani, 2007, 2010, 2013; Rao et al., 2007;).

In estimating economic losses due to weeds, Smith (1983) pointed out that in addition to rice yield and quality losses, account must be taken of costs of weed control (herbicides, mechanical and manual weeding), which add up to approximately 15% of production losses that can be attributed to weeds. Our review finds that yield loss estimates attributable to rice are inadequate in recent times, in most Asian-Pacific countries, and this is an area that requires considerable attention from individual countries. Some updated figures are provided in Table 4, with sources of the information. The estimates vary widely and some appear unreliable as those reported losses were of unweeded situation, which practically does not exist on-farm.

At the global level, Oerke and Denhe (2004), Oerke (2006) reported potential yield losses due to weeds in rice as 35% to 37%, followed by animal pests (24% - 25%) and fungal and bacterial pathogens (13%-14%). Regional differences in the losses due to various pests resulted from the cropping intensity (diseases, weeds), climatic conditions (especially insects) and cropping systems (weeds). Actual yield increases that can be expected from the effective control of pathogens and insect pests, only reached 32% and 39%, respectively, compared to almost 75% increase for weed control (Oerke, 2006).

5. Weed Management Methods in Rice: An Overview

Brief histories and current weed management methods used in the Asian-Pacific region countries are described in individual Chapters of this Volume. Hence, only a synopsis is given here with some commentary on salient aspects of the different methods. Table 5 presents a summary of direct and indirect weed control methods used in rice in different countries of the Asian-Pacific region.

5.1. Non-Chemical Methods

In the last 50 years or so, weed management methods in rice have changed in most countries in the Asian-Pacific region. The changes have been largely driven by labour scarcity, rice cultivation methods, availability and affordability of other resources (such as water and nutrients) and changing agronomic technologies and practices, including herbicide use. The the weed community has also changed in response to changes in climate and methods used in rice cultivation and weed management.

5.1.i. Preventative measures

Although not well practiced by rice farmers in the Asian-Pacific region, preventing the initial introduction, or germination of weeds needs to be recognized as far more important than subsequent attempts to control weeds after establishment (Rao et al., 2017b).

Table 4. Yield Losses (%) Due to Weeds in Rice Established by Different Methods in South Asian Countries

Country	Transplanted rice	Direct-seeded rice	Sources
Bangladesh	15 to 40%	40 to 100%	Rao et al., 2017
Bhutan	Up to 50%	-	Rao et al. 2017
China	Up to 24%		Zhu et al., 2001, 2008, 2017
India	12 to 69%	17 to 98%	Rao et al., 2017
Indonesia	Up to 74-98%	-	Antralina et al., 2011
Korea	Machine transplanted: 25-35%; Manual transplanted: 10-20%	40 to 100%	Choi et al., 1995
Malaysia	-	10 to 35%	Kumar et al., 2017
Nepal	17-47%	14-93%	Ranjit, 2007
Pakistan	24 to 56%	80%	Rao et al., 2017
Philippines	2 to 41%	40-97%	Navarez et al., 1981
Sri Lanka	20 to 40%	20 to 40% or higher	Rao et al., 2017
Thailand	-	35 to 45%	Rao et al., 2007; Kumar et al. 2017
Vietnam	46-50%	10 to 80%	Van Chin, 2001; Van Chin and Mortimer, 2002
USA	-	53[7]	Varanasi et al., 2016

As reviewed by Rao et al. (2017b), promotion of seed predation on the soil surface by foragers can be high in rice cropping systems. However, not much research has been done on this aspect as a potential preventative measure to reduce weed seed abundance in between cropping seasons. Similarly, methods to reduce weed seeds, or the use of various plant materials as mulches and allelochemicals in decaying crop residues to prevent weed seed germination have limited value in the developing countries of the tropical Asian-Pacific region. This is because such material are of often of high economic value as feed and forage for livestock in rice-growing, rural areas and the use of residues needs specialist equipment during subsequent crop.

5.1.ii. Soil preparation

Soil and land preparation including land levelling, ploughing, disking, harrowing, soil puddling and any combination of these methods provide conditions favourable for rice growth and to achieve uniformity in crop seed germination. Levelled fields provide the most effective ecological conditions for crop growth and weed control, water use efficiencies (in terms of distribution of irrigation or rain water), nutrient distribution and the highest efficacy of herbicides. In Australia, laser-guided levelling of fields is used and was found as the most efficient method for obtaining a better crop performance through the uniform distribution of water and nutrients.

Table 5. Weed Control Methods in Rice by Countries in the Asian-Pacific Region

Country	Primary Rice Culture Method 1,2,3	Preventative methods	Soil preparation	Manual weeding	Mechanical weeding	Water management	Crop Rotation	Cultural methods	Herbicides	Biological Control	Primary Reference*
Australia	DSR	**	**			*	***		***	*	Chandrasena et al., 2017 (This Volume)
Bangladesh	TPR, DSR (19%)	*	***	***	**	**	*	**	*		Kumar and Ladha, 2011
China	TPR (66%) MTR (13%) DSR (11%)	*	***	***	**	**	*	**	**	*	Zhang et al., 2012 , Zhang et al., 2011, Feng et al., 2017
India	TPR, DSR(28%)	*	***	***	**	**	**	**	**	*	Rao et al., 2007
Indonesia	T, DSR (18%)	*	***	***	**	**	*	*	**		Pandey and Velasco, 2002; Rao et al., 2007
Japan	MTR (98%) DSR (2%)	*	*	*	*	*	*		***	*	Sakai, and Saito, 2003
Korea	MTR (90%) DSR (10%)	*	*	*	*	*	*		***		Lee et al., 2017 (This book)
Lao PDR	TPR, DSR (33%)	*	***	*	*	*	*	*	*		Pandey and Velasco, 2002; Rao et al., 2007
Malaysia	TPR,DSR (95%)	*	***	**	**	**	*	*	***		Kumar and Ladha, 2011
Myanmar	TPR, DSR (9%)	*	***	***	*	**	*	*	*		Pandey and Velasco, 2002; Rao et al., 2007
Pakistan	TPR, DSR (< 1%)	*	**	***	*	**	**	*	*		Matloob et al., 2015
Philippines	TPR, DSR (42%)	*	***	**	**	**	*	*	***		Pandey and Velasco, 2002
Sri Lanka	DSRw (>93%)	*	***	**	**	**	*		***		Marambe et al., 2015
Thailand	TPR, DSR (34%)	*	***	**	**	**	*	*	***		Pandey and Velasco, 2002; Rao et al., 2007
Vietnam	TPR,DSR (39-47%,)	*	***	***	*	**			**		Kumar and Ladha, 2011
USA	DSR (100%)	*	*	*		**	**	*	***	*	Norsworthy et al., 2013

[1]DSR – Direct-Seeded Rice; [2]DSRw – Direct Wet/Water-Seeded Rice; [3]TPR – Transplanted Rice; MTR – Machine Transplanted rice. Number of asterisks indicate importance of the method; Percentages (%) are given only for DSR, for which the information appears more reliable from the different countries of the region, as given in the quoted references.

5.1.iii. Manual weeding

Hand weeding is the oldest weed control method in rice, and has been practiced in many Asian-Pacific countries for as long as rice was grown. Hand pulling of weeds is still widely practiced in developing countries. Although labour scarcity and cost of labor have caused a decline in the practice, hand weeding is effective depending on the weed emergence and associated growing conditions.

5.1.iv. Mechanical weeding

Removing or killing weeds with hand-pushed rotary weeders, or other weeders that can operate between rows of transplanted rice is a common practice. Rotary weeders were developed in Japan in 1892, and mechanical weeding, either by hand tools, or mechanical weeders, have long been used effectively in rice grown under both dryland and wetland conditions. Most upland and aerobic rice growers in Asia mechanically weed their crops two or three times per season, even now.

5.1.v. Water management

Water management has always been an important, traditional method of controlling weeds in rice, particularly in countries that receive high annual rainfall through monsoonal rains. Many weeds do not germinate well under flooded conditions and even flooding up to 2-3 cm reduce weed densities significantly. Flooding is effective only when the area is submerged from the time of planting until the crop forms a continuous canopy (Rao et al., 2007). If the water level drops within this period, then conditions become favourable for seed germination or regrowth of moisture-loving weed species. Thus, the availability of water for flooding and timing are critically important in both irrigated and rainfed rice. Proper levelling of rice fields is important, not just for the even distribution of water during early flooding, but also for the even distribution of pre- and post-emergent herbicides, when they are used.

5.1.vi. Crop rotation

Crop rotation has two primary purposes- promoting the build-up of soil nutrients, and weed control by changing the ecological conditions in the fields. A common practice in the USA is to rotate rice with soybean (*Glycine max* (L.) Merr.) and oat (*Avena sativa* L.), or rice, and pasture grasses. In Japan, double cropping of rice is common, rotated with a winter crop of wheat (*Triticum aestivum* L.) and/or rape (*Brassica napus* L.). Rotations are known to seriously reduce moisture-loving, common rice weeds, because of the altered conditions and moisture regimes in the fields. Although the value of disrupting the weed growth of monoculture rice cropping, through crop rotation is well understood, farmers in the tropical Asian-Pacific countries rarely have the opportunity to convert rice paddies to other profitable crops.

5.1.vii. Cultural methods

Increasing the rice density tends to modify the crop-weed interactions in favour of the crop. Use of higher seed rates as a means of controlling weeds is a common practice in most Asian and South-Asian countries, particularly with traditional, taller cultivars. Among other cultural control methods, as previously stated, transplanting of aged, rice seedlings has long been known to offer a competitive advantage to rice over weeds, compared with the direct-seeding of rice. The reduction in weed emergence achieved by the standing water, transplanting provides a greater scope for using selective herbicides, because the aged seedlings are less prone to injury.

Choice of cultivar grown is a well-established method to reduce weed competition (Ramesh et al., 2017). The increasing prices of fuel and chemical inputs have implications for the rice cultivars that may be favoured by farmers in the future. The cultivars that give higher yields with lower inputs and also compete better with weeds should be developed.

5.1.viii. Biological methods

Biological control approaches, apart from allelopathy, have been considered promising for weed management in rice, although the progress in developing practical applications has been slow and inadequate. The rice-duck-fish farming system has long been touted as a promising option, as ducks provide some degree of biological control of weeds through direct foraging, and also reduce insect pests; they also add their waste materials, which fertilize the field and possibly increase the margin of profit for the farmer through savings of fertilizer. However, such systems are complex and are limited in implementation to specific areas or regions with high water availability, or seasons. They are also limited by cultural and socio-economic factors.

Research on bio-herbicides, particularly from pathogenic fungal isolates (mycoherbicides), has been actively undertaken in the Asian-Pacific region, targeting the major weeds, such as barnyardgrass. However, success has been limited and there are no commercialized products that can be used directly in rice cultivation (Watson, 2017).

Two mycoherbicides that have been commercially released in USA with possible implications for rice environments include Collego® (based on *Colletotrichum gloeosporioides* f. sp. *aeschynomene*) to control Northern Jointvetch [*Aeschynomene virginica* (L.) Britton, Stearns &Poggenb]; and ABG5003 (*Cercospora rodmani*) against water hyacinth (see review by Boyette, 2000). Although the principles of developing such products are well established, and have direct relevance in the Asian-Pacific region, there are no registered mycoherbicides, relevant to rice cultivation, up to now in the region.

With regard to insect biocontrol agents, the success of agents that have been released in the region for aquatic weeds, such as water hyacinth (*Eichhornia crassipes* [Mart.] Solms), salvinia (*Salvinia molesta* D. S. Mitchell) and other weeds, is well known. These weeds do occur in rice fields in problematic proportions (see Table 2) and the bio-control insects released for these weeds are known to be active in most tropical, Asian-Pacific countries.

5.1.ix. Allelopathy

Rice has been extensively studied for its allelopathic potential, as part of a strategy for sustainable weed management, and to reduce the reliance on herbicides. Rice screening for allelopathy started in the early 1970s and has been widely studied in the USA, Europe, Japan, Korea, India and China (see Khanh *et al*., 2007). In early studies, conducted in the USA, more than 10,000 rice accessions were screened for allelopathic potential using ducksalad (*Heteranthera limosa* (Sw.) Willd.) as the test organism. About 3.5% of accessions from 30 countries showed some degree of allelopathic activity against the weed. The rice collections of China and Pakistan constituted a promising genetic base for rice allelopathy (Dilday *et al.*, 1994).

Subsequent research by other groups also confirmed the capacity of various rice varieties to inhibit the growth of weeds, under both field and laboratory conditions (Berendji et al., 2008; Gealy et al., 2014; Kim et al., 1999; Kim et al., 2005; Olofsdotter et al., 1995; 1999).

Numerous phytotoxins, such as cytokinins, diterpenoids, fatty acids, flavones, glucopyranosides, indoles, momilactones (A and B), oryzalexins, phenolic acids, including p-hydroxybenzoic, vanillic, p-coumaric and ferulic acids and various other bioactive compounds occur in the exudates of rice plants (Lee et al., 1999; Kim et al., 1999; Khanh et al., 2007; Kato-Noguchi et al., 2010; Mattice et al., 1998; Rimando et al., 2001). However, the fate and actual modes of action of these compounds in relation to allelopathy associated with rice are not well understood. Although a range of well-known allelochemicals are known to be exuded by rice plants, soil concentrations of these compounds do not reach phytotoxic levels in the field (Olofsdotter et al. 2002). Kim et al. (2005) concluded that the allelopathic suppression of weeds by rice was very much species-specific and dependent on the source and concentration. Research has also shown that rice allelopathy is variety dependent, and origin dependent, where Japonica rice shows greater allelopathic activity than Indica and Japonica-Indica hybrids. The question of which compounds play a major role in rice allelopathy has therefore remained obscure, and it is probable that rice allelopathy is attributable to the interaction of several allelochemicals, which are released into the plant's immediate environment, either as root exudates, or as compounds released during the decay of plant parts.

Despite the demonstration of rice allelochemicals and allelopathic interactions, research has been slow to establish how the phenomenon could be useful in commercial rice production. Kong et al. (2008; 2011) demonstrated this potential by developing commercially accepted allelopathic rice in China, via crosses between an allelopathic rice cultivar Pl12777 and commercial cultivars (Kong et al., 2011). The new cultivar, Huagan-3 achieved 80% control of barnyardgrass, whilst reducing the total weed population by up to 50%. The allelopathic potential of Super Basmati, a popular rice cultivar in Pakistan, was also reported by Farooq et al., (2008).

The adoption of allelopathic cultivars, if successful, would reduce the load of herbicides in rice agroecosystems, particularly, by eliminating the need for pre-emergence herbicides.

5.2. Chemical Weed Control

Commencing with the post-emergence applications of selective, auxin-like herbicides (2, 4-D and MCP), chemical control was introduced into rice production in the USA in the late-1940s to control broad-leaf weeds. These and other herbicides were also evaluated in other Asian-Pacific region countries in the 1950s and 1960s, but herbicides were not widely used in commercial rice production until around the 1970s. The 'Green Revolution' introduced short-statured, high yielding varieties (HYVs) of rice in the Asian-Pacific region during 1960s. These required optimal levels of weed management during the early, critical periods of the crop growth to achieve higher rice yields. Along with the Green Revolution, the irrigated rice area increased dramatically in the Asian-Pacific region, which also necessitated much more effective weed management than it was up to that time (see De Datta, 1980; Smith, 1983; IRRI, 1983; GRiSP, 2013a).

Herbicide use became very popular in countries, such as USA, Australia, Korea, Japan and Taiwan initially. In Japan, herbicides were used on 100% of the total rice acreage, twice a year, in 1974 (Noda, 1977). In the USA, 80-90% of commercially grown rice was treated with one or more herbicides each year (Smith, 1983). South Korea, Taiwan and Philippines also began to rely largely on herbicides for rice weed control by the late-1970s, although adoption of chemicals was much slower in other Asian-Pacific countries. The slower adoption of herbicides in other countries of the region was possibly due to the availability of relatively cheap labour until around mid-to-late-1980s, smaller-sized farm holdings and generally, poorly developed productive agriculture sector in those economies. Exposed to the aggressive marketing by the global agrochemical companies, countries like Sri Lanka, Thailand, Indonesia and Malaysia embraced herbicide use by early-1980s (De Datta, 1989), followed by India and Vietnam. Herbicides are now commonly used in almost all Asian-Pacific countries.

With the increasing adoption of herbicide-based weed control, Smith (1989) cautioned that the use of herbicides requires considerations on environmental impacts. Readers are referred to various Chapters of this Volume for information on the main selective herbicides used in rice cultivation in individual countries. There is a large array of herbicides and sequential combinations that are being used in the region. The main ones are: MCPA, propanil, butachlor, molinate, thiobencarb, quinclorac, oxadiazon, oxyfluorfen, oxydiargyl, pretilachlor, piperophos, bentazon, pendimethalin, mefenacet, various sulfonyl ureas (i.e. bensulfuron; cinosulfuron; azimsulfuron, halosulfuron), clomazone and bispyribac-sodium. Their use is dependent on the rice culture (DSR or TPR), and are influenced by other factors, such as time of irrigation and water availability.

Although herbicide use contributed to increased yields and profitability from rice cultivation, the continuous use of some herbicides quickly led to the development of herbicide resistance in major rice weeds in East Asia, Southeast Asia and Australasia by the mid-1980s.

In India and Thailand, herbicide use in rice has been steadily increasing, year after year. Herbicides in rice accounted for 17% of total herbicides used in India in 2010. In India, increasing labor costs and labor shortage have led to increasing herbicide sales, which now have 16% of the market share of pesticides used. Herbicides are predicted as the fastest growing segment in agrochemicals sales in India (FICCI, 2015). Herbicides are now used in 96-98%of Philippines rice farmers and continue to be used in 100% of rice acreages in Korea and Japan. In China, herbicides are used in 70 million ha of rice.

The use of herbicides is increasing in worldwide crop production and the value of the global herbicide market grew by 39% between 2002 and 2011 and was projected to grow by another 11% by 2016 (Philips McDougall, 2013[1]). The herbicide market was worth US $ 22.3 billion in 2014. Growing at a compound annual growth rate of about 6.25%, the herbicide market is expected to be US $ 31.5 billion in 2020 and $ 38.3 billion by end of 2023[2]. This market research indicates that the Asian-Pacific region as the largest market for herbicides (40% of market share) over the

1 Quoted by Gianessi (2013) from Phillips McDougall Data [Online], Available: http://phillipsmcdougall.com

2 As given [Online], Available: http://www.marketsandmarkets.com/PressReleases/herbicides.asp

next five years, dominated by China, likely to use more than 50% of herbicides sold in the region. The adoption of DSR has resulted in extensive reliance on herbicides for weed control (Gianessi, 2013).

5.3. Integrated Weed Management in Rice

Integrated Weed Management (IWM) attempts to incorporate all of the available weed control methods, based on ecological principles, weed thresholds, as well as economic goals of weed control, into an integrated approach (Thill et al., 1991; Wyse, 1992; Zimdahl, 2012). Instead of focusing on increasing the efficacy of an individual weed control method, IWM shifted the emphasis from ‘weed control’ to ‘weed management’, with the incorporation of knowledge of population biology (e.g., weed seed population dynamics; soil seedbank; species shifts over time) into control programmes. Other vital elements in IWM include weed hygiene (preventative weed control); cultural practices (i.e. crop rotations, multiple cropping, and minimum tillage); and biological control. Vital elements in IWM include weed hygiene (preventative weed control); cultural practices (i.e. crop rotations, minimum tillage, and uses of crop residues as mulches; water and nutrient management and manipulations) and biological control.

The primary intentions of IWM are sustainable weed management, and large-scale reductions in herbicides used for weed control. For this, it is important to understand the nature of competition between rice and its major weeds through eco-physiological studies. Much is known about the interactions between rice and the major weeds and how each component responds to cultural practice, such as water and nutrient regime, application times and manipulations that can be done, as well as various weed control practices (Ampong-Nyarko and De Datta, 1989; Bhagat et al., 1999; De Datta and Barker, 1977; Juraimi et al., 2009; Kim, 1989; Kim and Moody, 1989; Moody and Drost, 1983; Noda, 1977; Smith, 1989). Despite this knowledge, the applications of IWM in rice are limited to the few methods that most farmers can afford (such as cultivar selection, clean seeds, hand weeding, often involving family members to reduce labour costs, preventing weeds on bunds, fences and adjacent areas from ‘going to seed’). Knowing that some weed problems are ‘site-specific’, in most cases, the rice farmer in developing countries learns to live with his weed problems, accept some losses, but keep losses and costs at tolerable levels.

Inadequate ‘system thinking’, farmer education, support and extension services continue to be major constraints to the wide-scale adoption and on-ground implementation of IWM practices in most countries.

6. Weed Flora Shifts

Weed species shifts (species composition and abundance) occur largely as response to both method of crop establishment and herbicide use in rice (Mortimer and Hill, 1999). The adoption of DSR has resulted in extensive reliance on herbicides for weed control (Gianessi, 2013).The adoption of DSR has resulted in extensive reliance on herbicides for weed control (Gianessi, 2013). r In tropical Asia, the widespread replacement of tall, tropical rice cultivars by modern, semi-dwarf cultivars created a major shift in the late-1960s towards annual grass weeds, such as *Echinochloa* spp.; *Leptochloa* spp. and *Ischaemum rugosum*. The transformation from transplanted to DSR culture, in the 1980s, then aggravated the annual grass weed problems across many countries. Along with an array of annual grasses, various sedges (mainly, *Cyperus iria*; other *Cyperus* species and *Fimbristylis* spp.) and a few broad-leaf weeds also became dominant competitors in rice-fields under DSR.

Traditionally, farmers practiced hand weeding, which resulted in the dominance of moisture-loving grasses, particularly, *Echinochloa* species. The habit of grasses, such as *Echinochloa* spp. is similar to rice, which makes it difficult to recognize until much later in the growth cycle of both species (Rao and Moody, 1987; 1988). The introduction of selective, auxin herbicides (2,4-D and MCPA) also contributed to an increase in the dominance of *Echinochloa* species, as they controlled broad-leaf weeds well without injury to grasses (Azmi and Baki,1995).

A notable shift in the weed flora from broad-leaf weeds toward competitive annual grasses and sedges was recorded due to the change in the rice establishment method from transplanting (TPR) to direct-seeding (DSR) in most irrigated rice regions of the Asian-Pacific region (Rao et al., 2007). In addition, there is evidence that among the annual grasses and sedges themselves, there are notable shifts occurring, due to the heavy use of herbicides, (Azmi, 2002, Azmi et al., 2005; Azmi and Mortimer, 2002; Marambe, 2002; Qiang, 2006; Singh et al., 2008, 2013; Yadav et al., 2015).

It is also important to note that the shift in the method of rice establishment to DSR has led to the emergence of 'weedy rice' (or red rice) as a new threat in several countries in the Asian-Pacific region. Weedy rice has weedy characteristics, such as a short life span, tall plant, weak culms, small seeds, easy shattering and a red pericarp. It is currently recognized as a major pest that threatens rice production in several countries, including Vietnam, Malaysia, Philippines, India and Sri Lanka (Chauhan, 2013).

7. Herbicide Resistance in Rice Weeds

The evolution of herbicide-resistant weeds is one of the most serious problems associated with herbicide use in rice production in the Asian-Pacific region. According to the *International Survey of Herbicide Resistant Weeds*, weeds have evolved resistance to 23 of the 26 known herbicide sites of action and to 163 different herbicides. Herbicide resistant weeds have been reported in 91 crops in 69 countries. North America remains the ‘hotspot’, followed by Europe, Australia, Asia, and South America. Not surprisingly, regions that do not use herbicides intensively, such as Africa, have few problems of herbicide resistance (Heap, 2015). An important quest that can not be ignored: *Is there too much emphasis on herbicides*?

According to Heap (2015, 2017), there are now a total of 95 reports of herbicide resistance in 43 weed species, reported from 11countries of the Asian-Pacific region. Whilst the incidences of resistant weeds are high in countries that have been using herbicides for long (e.g. USA - 30 species; Japan – 22 species; Korea– 13 species; China - 10 species), other countries, in which herbicide usage is increasing, such as Malaysia and Thailand have also reported increased numbers of resistant species. Of the 16 sites of action, so far determined, resistance to ACCase (acetyl co-enzyme A carboxylase), ALS (acetolactate synthase), and EPSP (5-enol-pyruvyl-shikimate-3-phosphate) synthase inhibitors are among the most common resistance mechanisms (Heap, 2015).

Details of herbicide resistance development (weed taxon, herbicide and year reported) in different countries of the Asian-Pacific region, up to 2007 are given in Rao et al (2007). Since then, this list has grown considerably. Herbicide resistant weeds are discussed in relevant chapter of this volume. Hence the repetition regarding herbicide resistant weeds is avoided in this chapter.

Farmers in many of the developing countries apply the same herbicide year after year in the same fields, and also mix herbicides with sand or fertilizer to make the application operations easy. Such practices, perhaps combined with less than ideal levelling of the field paddocks lead to uneven distribution of herbicides in rice fields, which is a factor in poor weed control and a high survival rate of targeted weed populations. Evolution of resistance development has been rapid, due to both the excessive use of herbicides, and sub-lethal applications, which provide the selection pressure operating in the fields for weeds to evolve. Resistance management includes changing the selection pressure, disturbing the trajectory of evolution, by integration cultural control methods and rotating herbicides across several years (Heap, 2015; Norsworthy et al., 2012; 2013).

8. Climate Change as a Factor Influencing Rice and Weed Interactions

Human activities, including expanded fossil fuel use and deforestation, have caused atmospheric CO_2 to increase significantly from a pre-industrial concentration of about 280 $\mu L\ L^{-1}$ to a current estimate of about 370 $\mu L\ L^{-1}$. Even if CO_2 emissions are immediately scaled back, levels are expected to double sometime during the 21st Century (Bunce, 2001, IPCC, 2014; Stern, 2006). An increase in CO_2 and other greenhouse gases is likely to cause an increase in global surface temperature. Rainfall patters are likely to change across many areas of the globe and extreme events, like drought and cyclones, are predicted to be more prevalent and intense. The resultant major climate changes will affect the growth of plants, through modification of their photosynthetic performance and other physiological changes.

As CO_2 rises, plants with C_3 photosynthesis are likely to benefit more, and respond with increased net photosynthesis, growth, and yield, compared to those with the C_4 photosynthetic mechanism (Patterson, 1995; Patterson et al., 1999, Ziska and Bunce, 1997). Therefore, higher atmospheric CO_2 is predicted to stimulate the yields of most of the world's major crops, including rice, which are C_3 plants. There are a large number of C_3 weeds in the world, which may become more aggressive in many situations, under elevated CO_2 and warmer conditions. Under such changed climatic conditions, the likely scenario is that both C_3 and C_4 weeds will become more competitive, with potentially negative consequences for the environment, as well as agricultural productivity across different regions of the globe. This will have the effect of negating some of the otherwise beneficial effects of CO_2 'fertilization' of the C_3 world crops. It is also probable that many colonising plants will extend their bio-geographical ranges as global environmental changes occur, and weed management in the field will become more costly and difficult (see review by Chandrasena, 2009).

The predictions, based on climate modelling, indicates temperature increases in the Asian-Pacific region in the order of 0.5-2°C by 2030 and 1-7°C by 2070 (Preston et al., 2006). Studies indicate a high degree of spatial variability in the vulnerability of Asian-Pacific agriculture to climate change. For instance, temperatures are likely to warm more quickly in the arid areas of northern Pakistan and India and western China. The predicted increases in the summer rainfall may benefit crop production in South Asia; however, stresses from rising temperatures felt by the crop may offset such benefits, particularly for rice yields.

Most studies of cereal and rice production in South Asia indicate declining yields ha^{-1}, while the crop quantities produced may increase in Southeast Asia and East Asia. For a rise in temperature greater than 4°C, studies suggest declining rice yields in Bangladesh, India, the Philippines and Thailand, but increases in Indonesia and Malaysia. Overall, as given in Table 6, the changes in rice yields in Asia have been predicted as likely to be declining (-31%) to increasing (+7%) (Winters et al., 1999) and for the world, as declining (-9.5% to -12%).

Alberto et al. (1996), studied competition outcomes between rice and *Echinochloa glabrescens* L., a C_4 weed, using replacement series mixtures at two different CO concentrations (393 and 594 $\mu L\ L^{-1}$) under day/night temperatures of 27/21°C and 37/29°C. Increasing the CO_2 concentration, at 27/21°C, resulted in a significant increase in above ground biomass (+47%) and seed yield (+55%) of rice, averaged over all mixtures. For the C_4 weed, higher CO concentration did not produce a significant effect on biomass or yield. When grown in mixture, the proportion of rice biomass increased significantly relative to that of the C_4 weed in all mixtures at elevated CO_2 indicating increased'competitiveness' of rice. However, under the elevated CO_2 level and the higher temperature regime, competitiveness and reproductive stimulation of rice was reduced compared to the lower growth temperature, suggesting that while a C_3 crop like rice may compete better against a

Table 6. Projected Impacts of Climate Change for Rice in Asian-Pacific Regions and Sub-Regions Under Future Scenarios*

(Source: Porter et al., 2014)

Region	Sub region	Yield impact (%)	Scenario	Reference (cited in Porter et al., 2014)
East Asia	China	• –18.6 to –6.1 (–10.1 to +3.3) • –31.9 to –13.5 (–16.1 to +2.5) • –40.2 to –23.6 (–19.3 to +0.18)	+1ºC, +2ºC, +3ºC –CO2 (+CO2)	Tao et al., 2011
	Eastern China	• −10 to +3 (+7.5 to +17.5) • −26.7 to +2 (0 to +25) • −39 to −6 (−10 to + 25)	2030, 2050, 2080 –CO2 (+CO2)	Tao and Zhang, 2013
	Yangtze River, China	• (Irrigated) Rice: –14.8 (–3.3) • (Rainfed) Rice: –15.2 (–4.1)	B2 2021–2050 –CO2 (+CO2)	Shen et al., 2011
South Asia	South Asia	Net cereal production –4 to –10	+3ºC	Lal, 2011
	India	• (I) Rice: –4, –7, –10 • (R) Rice: –6, –2.5, –2.5	A1B; A2; B1; B2 2020, 2050, 2080 +CO2 MIROC; PRECIS/HadCM3	Kumar et al., 2013
	Northeast India	• (Irrigated) Rice: –10 to +5 • (Rainfed) Rice: –35 to +5	A1B 2030 +CO2 PRECIS/HadCM3	Kumar et al., 2011
	Coastal India	• (Irrigated) Rice: –10 to +5 • (Rainfed) Rice: –20 to +15		
	Western Ghats, India	• (I) Rice: –11 to +5 • (R) Rice: –35 to +35		
	Pakistan	–16, –19	B2, A2 2080	Iqbal et al., 2009

*Crop yield impacts in parentheses correspond to parentheticals in the scenario column; - CO_2 = without CO_2 effects; + CO_2 = with CO_2 effects; CSIRO = Commonwealth Scientific and Industrial Research Organisation, Australia; HadCM3 = Met Office Hadley Centre Climate Prediction Model 3; MIROC = Model for Interdisciplinary Research On Climate; PRECIS = Providing Regional Climates for Impact Studies; **cited in Porter et al., 2014.
1. Tao et al., 2011; 2. Tao and Zhang, 2013; 3. Shen et al., 2011; 4. Lal, 2011; 5. Kumar et al., 2013; 6. Kumar et al., 2011'; 7. Iqbal et al., 2009

C_4 weed at elevated CO_2 alone, simultaneous increases in CO_2 and temperature could still favour C_4 species.

As a C_3 crop, rice is expected to have competitive advantage over C_4 weeds under elevated CO_2 concentrations. However, rice yield losses may be higher, particularly in the presence of weeds that share the same physiological, morphological, or phenological traits with the crop, including those weeds that are wild relatives of the domesticated crop species (e.g., rice and wild/weedy/red rice) under elevated CO_2 (Ziska and McClung, 2008; Ziska et al., 1999). A greater physiological plasticity and genetic diversity is likely to be present among weedy rice relatives, compared to cultivated rice varieties, and this may increase the threat from weedy rice under elevated CO_2 (Ziska et al., 2015). Elevated levels of CO_2 may also increase below ground growth, relative to above ground growth, in some perennial C_3 species, making mechanical control less effective. Bir et al. (2014) suggested that C_3 weed species in rice, particularly, rhizomatous perennials, such as salt-marsh bulrush (*Bolboschoenus maritimus*), *Cyperus halpan* L., *Leersia hexandra,* long-stamen rice (*Oryza longistaminata* A. Chev. & Roehrich); and purple swamp grass (*Sacciolepis africana* C.E. Hubb. & Snowden) may become more competitive against both the crop and C_4 weeds under an elevated CO_2 regime.

Climate change is likely to further alter the availability of water resources, driven by seasonal reductions in rainfall and runoff in South and Southeast Asia, and increases in runoff in other areas, particularly the Pacific Islands. Water may become scarce in future. Thus, aerobic rice and alternate wetting and drying culture will replace the season-long flooding of lowland rice fields. Both conditions may become conducive for increased weed growth. Hand-weeding requirements may increase by up to 35% under such situations (Latif et al., 2005). The growth of other perennial C_4 weeds, such as purple nutsedge (*Cyperus rotundus*) is commonly suppressed by prolonged flooding. The use of a flood water layer to manage weeds is likely to become quite difficult in many countries, as water becomes scarcer; consequently, farmers lacking the means for effective weeding are likely to suffer severe yield losses (Barrett et al., 2004), if alternative strategies are not adopted. In the Philippines, Peña-Fronteraset al. (2009) reported vigorous growth of purple nutsedge in both flooded and upland conditions, indicating the occurrence of purple nutsedge ecotypes, which may become severe problems under both upland and low land rice.

Nutrient and CO_2 interactions were reported to be influence competition between rice (C_3 plant) and the barnyard grass (*Echinochloa crus-galli*), which is a C_4 plant (Zhu et al. 2008). Rice is a poor competitor under drought conditions and the expected prolonged drought spells may benefit C_4 weeds over C_3 rice. Thus, higher drought and heat tolerant species, such as cogon grass (*Imperata cylindrica*), *Paspalum scrobiculatum*, Bermuda grass (*Cynodon dactylon*), itch grass (*Rottboellia cochinchinensis*), goose grass (*Eleusine indica*), crowfoot grass (*Dactyloctenium aegyptium*) are likely to become more competitive in rainfed rice (Bir et al., 2014). To counter such developments in weeds, adaptation strategies for both DSR and upland rice, require the development of drought and heat-tolerant rice cultivars with some degree of competitiveness.

Several studies have indicated the decreased herbicide efficacy in response to elevated CO_2 and/or temperature for some weed species, both C_3 and C_4 (Archambault, 2007; Manea et al., 2011). *Cyperus rotundus* and *Cynodon dactylon* are difficult to control by majority of the herbicides available for the control of weeds in rice. Glyphosate efficacy was observed to get decreased at elevated CO_2 (Ziska et al. 1999) and thus, control of these weeds may become more difficult in future. The herbicide tolerant weeds may also become predominant. The development of a glyphosate-resistant mechanism would be easier under elevated CO_2 in C_3 weeds which have a simpler photosynthetic pathway than for C_4 weeds (Fernando et al., 2016). At elevated CO_2, weeds may get protected from post emergence herbicides as the amount of foliar-applied herbicide taken up by the targeted weeds could be reduced, due to increase in leaf thickness (Varanasi et al., 2016). There is also concern that upland weeds, such as *Parthenium hysterophorus*, may become more predominant in DSR due to changed cultural conditions.

To effectively predict which weeds may become dominant in the next decade or so, and evaluate the vulnerability of rice production in various countries of Asian-Pacific region, the interactions between plant responses to CO_2, high temperature, and drought need to be better understood. This may lead to better planning for climate change adaptations and for changes in the cropping systems, along with weed management practices to minimize vulnerability of rice production exposed to climate change.

9. Challenges and Future Outlook

The problem of food allocation can be alleviated to some extent by intensifying rice productivity, particularly in the developing countries of the region, where the demand is high and continues to increase. In many regions rice crop productivity may be increased by high-yielding varieties, improved water and soil management and other cultivation techniques, combined with improved management of weeds. New challenges have arisen and weeds are but one major constraint to increase rice yields. Uncritical analysis of the productivity constraints, lack of consideration of agroecosystem health in farming landscapes and the non-availability of fine-tuned, needs-based technologies, prescribed to suit different rice ecosystems, across large, rice-growing regions, is a severe limitation.

To meet the challenges of building more productive and resilient rice production systems in order to achieve food security for the Asian-Pacific region, it is essential to renew our focus on IWM strategies and knowledge-based, decision support weed management approaches that integrate well with best management practices of rice cultivation. Instead of focusing on herbicides alone, we recommend research effort to focus on integrating it with the development and use of weed-competitive rice cultivars, and cultural practices (such as optimal sowing time, seeding rate, crop row spacing, fertilizer and water inputs and their application method and timing, and manual and mechanical hoeing) for sustainable outcomes.

We present below a brief outlook and our own perspectives on important focus areas for increasing rice productivity in the future, whilst protecting the rice-field environments for future generations. Our observations are particularly directed at the Asian-Pacific region, although they may have validity in applications elsewhere.

i. Monitoring of changes in the weed flora and economic losses due to weeds in farmers' fields: As highly successful organisms, weeds, as a group, respond to selection pressure. The introduction of new cropping practices (e.g., reduced or no-tillage and HT rice) may result in shifts in weed species or populations within a species to individuals more able to survive the new practice.

Given the evidence of significant changes in weed composition in the rice-field environments across large areas, regions, or countries, systematic monitoring is a priority. Systematic sampling, with valid statistically-based sample sizes and surveys of rice-fields should be regular activities, conducted each season, to estimate rice productivity. These surveys, or others, selected to represent particular rice-growing systems, districts, or regions, will allow not just yield losses due to weeds to be better estimated, but also any shifts in the weed floras. They will also provide the opportunities to detect any new weed introductions through contaminated seed (Rao and Moody, 1990) or irrigation water. After decades of research, it must be said that data and information on yield losses attributable to rice weeds are still unreliable from many countries. Countries would benefit from stablising research programs that place weed management more holistically among crop protection packages.

ii. Climate change related changes and management: Evidence of changes in the rice-field weed flora that can be undisputedly attributed to actual climate change are yet to be established. There is a need for continuous monitoring of the changing weed flora, to enable better predictions to be made under changing environmental conditions.

iii. Integration of the Catchment Management approaches to management of rice-weeds: Weed problems in rice, as in other agricultural systems, are mostly region-specific or district-specific, although, sometimes, it could be 'site-specific' down to much smaller land units (as a single farmer's field). The rice-field environments are highly conducive to weed growth (as they are human-disturbed), and weeds thrive naturally in such landscapes. In addition, new entrants may arrive through established pathways and vehicles of weed spread (such as water, wind, animals and humans). Such factors, coupled with the patchiness of weed occurrence, dictate that rice weed management needs to be based on broader catchment management principles. This would involve establishing preventative weed management more rigorously and holistically, taking into account the pathways of potential introductions (contaminated seeds; poorly made compost; poor quality fertilizer; weed infested drainage canals). Upstream catchment management, regular vegetation surveys to detect any new weeds, and rapid control responses to new threats must be part of the solutions considered to improve weed management. Crucial in this approach would be to ensure that all farmers of a region or district, equally receive education and support for managing weeds, through extension and awareness campaigns.

iv. Integration of ecological and biological knowledge into management of rice-weeds: Knowledge of ecology and biology of the weeds inadequate and patchy in most countries. This includes data on life histories of major species, weed seedbanks under different production systems, weed seed germination profiles, and understanding of the nature of the inter-specific interactions, including population biology, as weeds grow in competition with an aggressive neighbour (i.e. rice). The targeted research is needed on the interactions between new and improved rice cultivars and weeds, under prevailing conditions in a rice field, and also on temporal and spatial scales. Agronomic and cultural practices have a pronounced impact on weed populations and provide opportunities for manipulating weed communities towards less competitive taxa, while reducing the dominance of the most competitive species. To maintain adequate weed control with reduced herbicide inputs, it is necessary to utilize the full gamut of available technology and practices, generated on preventative, cultural, mechanical and chemical methods.

Integration of preventive methods, and time-tested, cultural weed management techniques, based on the knowledge of important weeds, would allow the worst weed problems from arising. Preventing weed problems from arising must be the highest priority for rice weed scientists, as they embark on solving weed problems in rice.

v. Improved Rice cultivars to compete against weeds: The question that arises – *can we develop a suite of rice cultivars that can primarily compete against weeds successfully without significantly losing yields*? Preliminary accounts from USA (Gealy et al., 2014), combined with those on allelopathic cultivars (Kong et al., 2011) appears to indicate that this is achievable, although it would take more research effort to develop varieties that would compete with weeds and be stress tolerant at the same time, across a wider range of rice culture conditions. Developing cultivars to tolerate climate changes such as drought, temperature increases,or nutrient shortages, can reduce fertilizer and irrigation inputs considerably. The incorporation of cultivars with enhanced weed suppression ability into any rice production system can reduce herbicide inputs substantially (Korres et al., 2016). The cultivars that exhibit allelopathic attributes should be prioritized in breeding programs, and the genes responsible for competitive traits in rice should be fully discerned, as the basis for improving those varieties.

vi. Management of Herbicide Resistant rice weeds: Management methods to prevent or delay the evolution and spread of herbicide resistant weeds in the Asian-Pacific region has now become a top priority, as herbicides use has been predicted to increase in the years to come. A greater focus on non-herbicidal rice weed control methods is needed, particularly, in countries where the herbicide resistant weed problem is only at initial stages. In some situations, where some herbicide use may be beneficial, chemicals with different modes of action need to be combined, sequentially. In other situations, solutions may be found by combining lower rates of proven herbicides with cultural methods. The overall evidence of more than 50 years of research in the region is that herbicides rates required may also be reduced, and not increased, if they are effectively integrated, where necessary, with other weed control methods.

vii. Herbicide tolerant (HT) rice: Herbicide-tolerant (HT) rice varieties have been developed mainly to manage the 'weedy rice' problem in DSR. Infestation of herbicide resistant weedy rice, due to gene flow has already been reported in countries like Malaysia, when rice is not rotated with other crops (Ziska et al., 2015). Herbicide-resistant volunteer rice could be a new problem that may have to be managed in future rice farming.

The HT solutions are promoted as 'broad-based' with potentiality for management of diverse weed flora that normally occurs with rice, established by different methods. Wide choices in selecting herbicides and varieties must be made available to farmers to enable farmers to use those herbicides, in sequential combinations in a single season, and then rotate the herbicides, across the seasons. Herbicides with newer modes of action may have to be developed, in implementing this solution. The stewardship guidelines provide evidence of strict regimes, which have to be followed to guarantee success in using the HT technology without any deleterious effects (BASF, 2011).

Genetically modified HT rice may improve weed management, eliminate trouble some weeds at an early stage of the crop and improve crop yields, but there is concern about the environmental impact of herbicide-resistant rice, in particular about the possibility of transfer of the resistance trait to red/weedy rice. Such a situation could prove more problematic than the current one in direct-seeded rice areas.

viii. Beneficial weeds in rice production systems: There is vast potential for using weeds as resources, such as food for humans and animals, raw materials for a range of products, phyto-remediation and for further exploitation of plant residues as sources of allelopathic compounds that may reduce certain weeds in rice. The bio-diversity values of weeds within the rice production systems of the Asian-Pacific region have not been examined to any significant degree. Learning from other regions, particularly, Europe, research in the region needs to focus on the bio-diversity values of weeds that may not cause real yield losses, but add to other values (such as nutrient transformations; pollinating insects; pest repellence).

10. Conclusions

The challenge of feeding the world's population sustainably has always been a key issue for human societies. Despite this long success, maintaining rice production at the required levels faces various challenges, some of which are reviewed above, and are also covered in other Chapters of this Volume. There has been a continuing tendency to develop weed control options in isolation of the larger issues of agroecosystem health in the rice-growing regions. Successful weed management cannot be done in isolation of other important factors, which have direct and indirect impacts in the rice-growing environments. Weed management planning in rice must encompass and be based on the application of natural resource management principles, such as holistic catchment management (broadly, water, vegetation and soil conservation and management of catchments), while appreciating the broader socio-economic factors that influence decisions made by rice-farming communities. Effective and environmentally-sound weed management in rice cultivation will only come about by a logical combination of relevant weed control methods (i.e. Integrated Weed Management, IWM).

Greater emphasis on preventative weed control and cultural control methods in rice is needed in the region, to reverse the over-reliance on herbicides. The real challenge is to develop improved, stress tolerant cultivars that can compete with weeds more effectively. Combining improved cultivars with more effective 'site-specific' and 'cultivar-specific' crop protection packages, appear to be the most likely approach to successfully attain yield increases that are sustainable. Better management of agro-ecological factors (such as water and nutrients) in the rice-field environments, and a reduced emphasis on herbicides, will be required to reverse the trends in development of herbicide resistant weeds in rice, and also protect the biodiversity values of the rice-growing environments. The knowledge to make these transformations has been available for at least three decades (Altieri, 1998; 1999).

The focus of rice production in the developing countries of the Asian-Pacific region needs to embrace crop diversification also as a strategic approach to raise farm income, generate more employment, and allow a better use of resources in uncertain times. A change in cropping pattern from a rice monoculture to diversified crops and crop rotations will lessen biotic and abiotic pressure, and conserve soil fertility and water resources. Diversification of rice farming to accommodate other high-value crops (vegetables, medicinal herbs and short growth-cycle fruits) will encourage exports of farm produce, bringing more profits. This will, however, require governmental support by way of infrastructure development (markets, roads, transport and storage, processing mechanisms), policy changes, and technical innovations and sustainable overall farming system.

In pursuit of 'sustainable' highly productive rice-based agro-ecosystems, it is essential focus much more on how ecosystems function – i.e. nutrient cycles, and the close interplay between biotic and abiotic components and agro-ecology and how the next generation of improved rice varieties may perform. Understanding and applying ecological principles will allow us to create or manipulate systems that will last longer and be more productive and ideally, be environmentally sound and profitable to the farmers, as well as consumers.

An important point to remember is that, in the end, sustainable rice agriculture and on-farm productivity for the rice farmer is determined largely by externalities – i.e. economics and politics - falling prices for rice and other farm products; increased cost of inputs; lack of security of land tenure; increased urban expansion, etc. Sustainable weed management practices are likely to remain largely irrelevant, or only marginally useful, until these issues and problems are addressed adequately in different parts of the world.

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WEED MANAGEMENT IN RICE
IN THE ASIAN-PACIFIC REGION

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