REVIEW

The progress and future of Weed Science Research in the Asian-Pacific region

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Editor's Note:

This review paper formed a major part of a plenary presentation made by A. N. Rao at the 27th Asian-Pacific Weed Science Society Conference, held at Kuching, Malaysia during 3-6 September 2019. The authors have added some additional commentary to increase clarity and context of the presentation.

Abstract

Reducing poverty and ensuring future food and nutritional security are significant concerns in the Asian-Pacific region, which is characterized by rapid population growth, food shortages, and an increasing changing climate. Efforts to increase crop productivity and reduce existing crop yield gaps, by identifying constraints, such as weeds and alleviating their negative impacts, are essential to meet the targeted food and nutritional security goals in the region.

The prime objectives of the Asian-Pacific Weed Science Society (APWSS) have been the promotion of Weed Science in the region, by pooling and exchanging information on weeds, and capacity building in weed management. Over the past five decades, APWSS has held 26 Conferences in the region compiling information related to weeds and publishing those in peer-reviewed proceedings. In this review, we assessed the extent of achievement of these prime objective by analyzing the above research published in the APWSS Conference proceedings and related publications under major weed research themes and categories. We then used the results (% numbers of papers published) to understand the status of weed research in the region and the key drivers for the research agendas and to make suggestions for the future weed management research needs in the Asian-Pacific region. Herbicide-led research dominates weed research in the APWSS region. Herbicide use continues to be a critical weed management tool in the gradually developing nations and emerging economies of the region. However, herbicide-resistant weeds, shifts in weed floras, and the emergence of new weeds, such as weedy rice, and climate change, have become significant weed management challenges. The new herbicide molecule development and introduction have slowed down.

Genetically modified Herbicide Tolerant Crops (HTC) have been introduced in some Asian-Pacific countries as a component of packages of Integrated Weed Management (IWM). However, the emergence of herbicide-tolerant weeds, due to gene flow and non-adoption of stewardship guidelines, combined with human health and environmental concerns and lack of trained personnel, are limiting HTC introduction and adoption. Thus, weed research in the region must continue on IWM, to better integrate knowledge of weed ecology, biology, and best management practices into specific cropping situations. Genetic engineering to produce new competitive crops cultivars, weed management through automation, and artificial intelligence, a better understanding of weed responses to climate change, may provide innovative approaches to efficiently, economically, and ecologically manage weeds.

Keywords: Asian-Pacific region, weeds, integrated weed management, herbicide resistant weeds

Introduction

By 2050, the world must feed nearly 10 billion people, and ensure that agriculture contributes to food and nutritional security while reducing greenhouse gas (GHG) emissions, pollution, and other negative environmental impacts of farming (Searchinge et al., 2019). Presently, the Asian-Pacific region is the economically fastest-growing region in the world with declining poverty. However, the Food and Agriculture Organization (FAO) estimates that some 486 million people remain undernourished in Asia and the Pacific, and development progress has stagnated in all sub-regions (FAO, 2018). The current scenario necessitates serious efforts to increase food production in the Asian-Pacific region to meet the demands of the increasing population and ensure food and nutritional security in the region.

Among pests of crops, the highest worldwide potential losses are attributed to weeds (34%), with lesser losses caused by insect pests (18%) and pathogens (16%) (Oerke, 2006). In the Asian-Pacific region too, weeds are major biological constraints limiting agricultural production by causing yield losses, which range from 10 to 60% depending on the specific crop and associated cropping environment (Yaduraju and Rao, 2013). The abundance of weed infestations and losses caused by them in any cropping situation are quite 'site-specific' and depend on the agronomic (cultural) practices used, soil characteristics and a host of other environmental factors operating in the field. The latter include potential impacts of water availability, pathogens and pests and vagaries of the climate. Continuous efforts are needed to understand the responses of weeds to cropping practices and to evolve weed management strategies to reduce their impacts on crops, so that agricultural production can be increased.

Over the past five decades weed scientists in the Asian-Pacific region have undertaken serious research on various aspects of weeds and their management. These include country-wide surveys of weeds, studies on the ecology and biology of weeds, introduction and evaluation of new herbicide chemistries, new herbicide formulations for different crops and different methods of herbicide application, biological weed control, aquatic weed control, environmental impacts of herbicides, changes in weed floras, herbicide resistance development in weeds, effects of climate change on weeds, potential utilization of weeds as biological resources, sustainable farming, and weed risk assessments (Chandrasena and Rao, 2017).

Given that weeds themselves are highly dynamic organisms who can respond to efforts to control them in various ways, weed management approaches must also be dynamic. Weed floras in agriculture keep changing, new weed problems emerge (such as weedy rice), and individual species respond by evolving dynamically with management practices (such as developing resistance to some herbicides Thus, periodically weed research efforts and weed management practices adopted by the farmers must be analysed to re-align future research needs. Identifying future research needs in weed management will help in focussing research accordingly to the needs of farmers and develop weed management approaches and techniques to alleviate emerging weed problems. Hence, in this review, we focused on the weed research in agriculture, carried out during the past 50 years in the Asian-Pacific region, to understand where the past efforts have been and potential areas that may require increased attention in the future. In the analysis, we divided the research published into major themes and categories that would make sense to the reader.

Methodology

The "Asian-Pacific Weed Science Society (APWSS)" was formed in 1967 to facilitate the interchanging of current weed control information and to promote weed science in the region. The primary motivations for founding the APWSS were clarified by Bill Furtick, a founding father, at the Second APWSS Conference, in the Philippines, in 1969.

> *"…Weed Science suffers because weeds have been an integral part of agriculture from the beginning and their damage is less dramatic than that caused by insects and diseases. However, it is apparent that weed control is a pre-requisite for the development of modern agriculture, which is based on developing high yielding, high quality varieties that can produce their potential only under optimum fertility, water and freedom from pests. This means that without weed control, modern agriculture will end up under a canopy of weeds. It is the duty of the weed societies to get this story across to others in agriculture. It has often been possible for the representatives of industry to convince the farmer whose income is affected, while the professional agriculturist is oblivious to this basic importance of weed control. This cannot continue, but can only be changed by a planned effort…"* Furtick (1969)

Since then, 26 APWSS conferences have been held, so far, this being the 27th Conference. The proceedings of these APWSS conferences have published a very large collection of peer-reviewed papers of the weed research carried out in the region. In this review, we assessed and synthesized information on a total of 2327 papers that have been published in the proceedings of 23 out of the 26 conferences [1]. to summarize the research carried out in the region. For the analysis, the year of APWSS initiation, 1967, was taken as a base year. For convenience, the groupings of research published was done based on the five individual decades (1970s, 1980s, 1990s, 2000s and 2010s).

The papers were enumerated based on the significant topics of interest within weed research and expressed as % number of publications. In our view, these provide a reasonable snapshot of the weed research efforts in the region highlighting areas of particular interest, where the research has been strongest over the long period of five decades. Having assessed the research areas, we provide some relevant commentary, and have also attempted to identify some deficiencies in the research effort and discuss where the future efforts might be expanded to the benefit of the Asian-Pacific region as a whole.

50 years of Weed Research in Asian-Pacific region–An analysis

Fifty-eight countries in the Asian-Pacific region have published weed research in the proceedings of APWSS over the past 50 years. India has contributed the largest number of published papers. Other major contributing countries, in decreasing order of number publications, are Japan, Australia, USA, Malaysia, China, Thailand, Indonesia, Korea, Philippines, New Zealand, Sri Lanka, Pakistan, Vietnam, U.K. Germany, Taiwan, Bangladesh and Iran.

Herbicides

Herbicide research dominate the proceedings in the 1970s, but this interest has gradually declined (Figure 1a). The 1980s saw a significant number of papers on new herbicides, as the herbicide market in the Asian-Pacific region countries expanded, and new chemistries began to be aggressively introduced into the agriculture of the region (Figure 1b). Thus, in earlier years, most of the weed research focused on introducing the existing herbicides to the region, along with potential new herbicide chemistries and formulations for different crops. The published research reported heavily on herbicide evaluations in the field, weed control efficiencies, non-target effects and impacts of herbicides on the environment. This trend was a clear reflection that the region was somewhat slow in adopting new technologies (i.e., herbicides) and would benefit from increased adoption of those herbicides that had been highly effective in the USA and elsewhere (Chandrasena and Rao, (2017).

In the Asian-Pacific region, herbicide research had been systematically conducted since the introduction of phenoxy herbicides (1945); ureas (1951); triazines (1956); paraquat (1960); acetamides (1960); dinitro-anilines (1964); glyphosate (1972); 4-Hydroxyphenylpyruvate dioxygenase (HPPD) inhibitors (1979) and sulphonyl ureas (1982). With time, the average effective rate of herbicides used in the region decreased from 2750 grams of certain urea herbicides to 50 to 100 grams of sulphonyl ureas. The papers highlight the substantial benefit to agriculture achieved through the wide acceptance of efficient weed control offered by these herbicides in rice, corn, wheat, vegetables, row crops and plantation crops.

During recent decades, an increasing trend has been the research on herbicide-resistant weeds and herbicide-tolerant crops (HTCs). In the recent decades (2010s) also, one-third of APWSS proceedings was herbicide based papers (Figures 1a-d) indicating a continued interest on chemical weed control. However, the papers published do indicate an increasing change in focus in recent decades to more sustainable use of herbicides, as a component of integrated weed management (IWM) packages.

Other research areas

The research on weed ecology, taxonomy, biology, physiology, new weed problems, and weed flora surveys in the Asian-Pacific region peaked in the 1990s and 2000s and later declined in 2010s (Figure 2a). The understanding of weeds through those studies, perhaps, prompted an increase in research on integrated solutions for weeds in the 1980s and 90s. The data show further increases in IWM research in the new millennium (Figure 2b).

[1] The authors did not have access to the Proceedings of the 2nd, 7th and 12th Conferences at the time of this review. Hence, those papers are excluded.

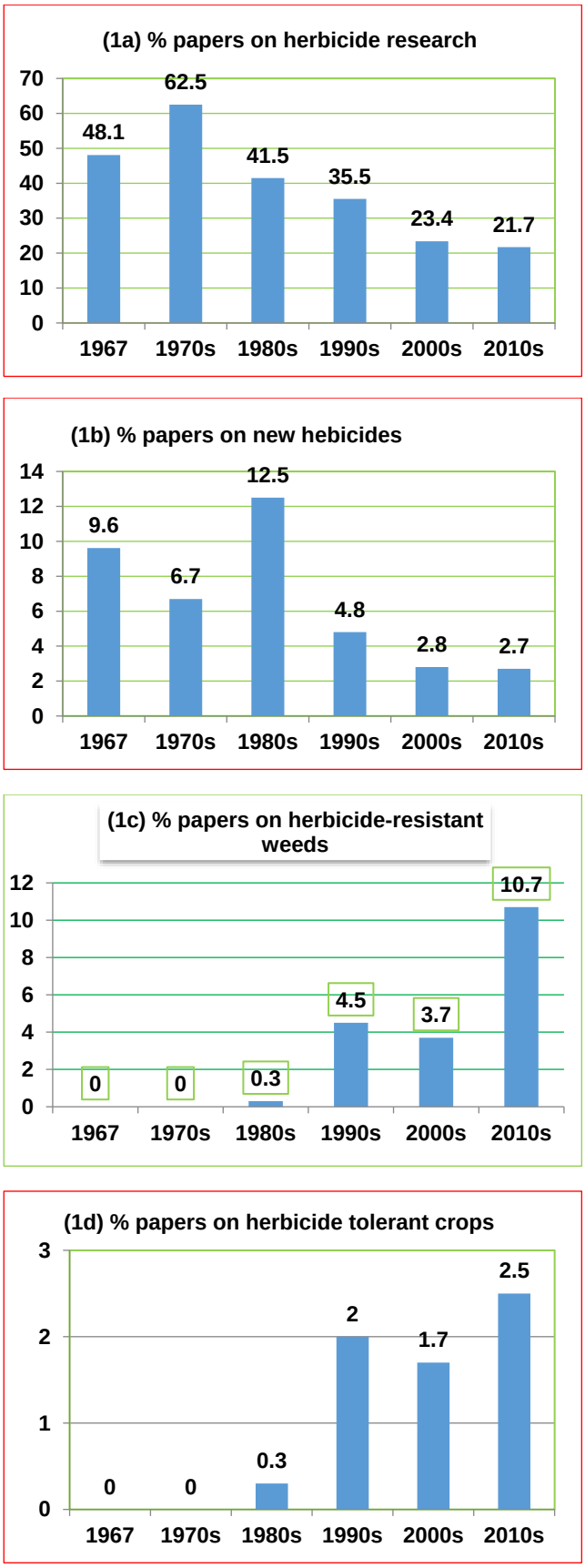


Figure 1. Trends in herbicides based weed research in the Asian-Pacific region

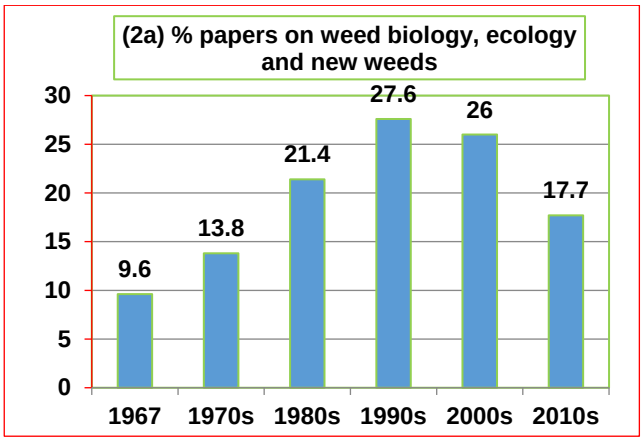
It is important to note that in inaugurating the APWSS, our founding fathers promoted more extensive weed surveys, as well as the adoption of herbicides, along with increased research into the biology and ecology of weeds, which they felt were inadequate in the Asian-Pacific region (Chandrasena and Rao, 2017; Chandrasena, 2019). More than 25% of papers published in the APWSS proceedings over the past 50 years have been on biology, ecology, ecophysiology, and general aspects of understanding weeds, which bodes well for the region.

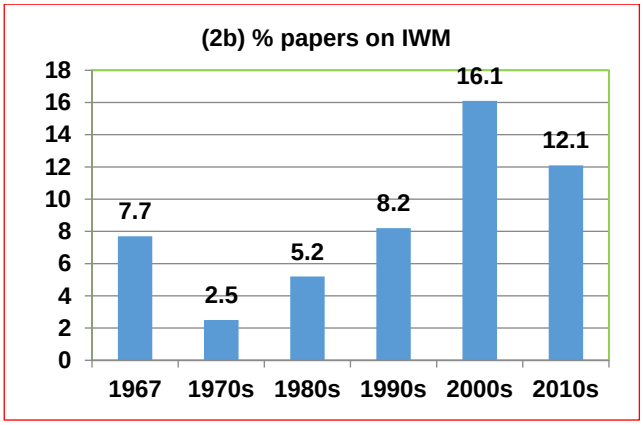
Despite significant successes in biological control of weeds in the 1960s and 70s, research on bio-control agents of weeds was slow to develop across the region and also, more globally (Charudattan, 2017). The number of APWSS papers (Figure 2c) reflected a cautious progress among countries in investing bio-control research with Australia leading in this effort. Apart from Australia, most other APWSS countries were slow in adopting bio-control agents. Among the most like factors, discussed in the papers, were deficiencies in the training of bio-control researchers and some degree of institutional apathy because the benefits of the released agents is typically not immediately apparent.

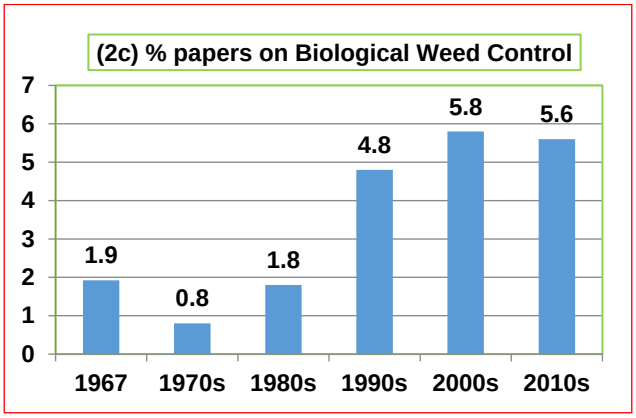
Another factor might be that the organizations required to implement biological control have to be of a much higher level of sophistication than required for the adoption of herbicide-based solutions, which are promoted and supported by the herbicide industry.

Allelopathy has been a subject within Weed Science that received wide recognition in the 1970s (Jabran et al., 2015). The potential to use allelopathy phenomena for weed control also made a slow entry to the Asian-Pacific weed research agenda. Apart from the opportunity to manipulate crop residues for controlling weeds in crops, this research was mostly aimed at demonstrating allelopathy phenomena as part of interference in the field between weeds and crops and to discover strongly bioactive, potential natural products from allelochemicals.

Some of the developing countries in the Asian-Pacific region have had a long association with non-chemical weed control, primarily because the entry of herbicides into the region was slow and the majority of farmers could not afford them. Over centuries, weeds in most APWSS countries were controlled as part of land preparation, tillage, animal power, and by manual methods (hand-weeding) using various implements, such as cono-weeders and hoes and by flooding (in the case of rice).







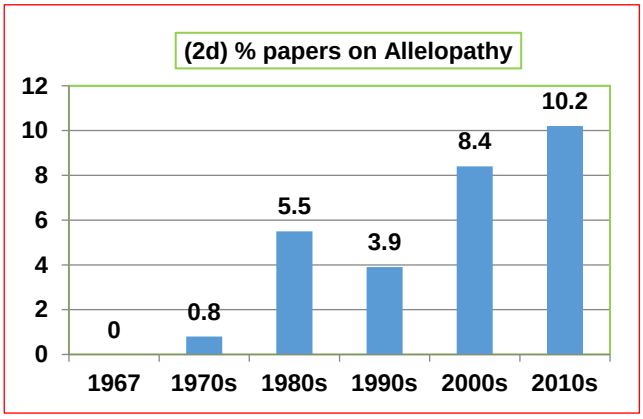


Figure 2. Trends in research on weed biology, ecology, new weeds, weed surveys, IWM, biological control and allelopathy in the Asian-Pacific region

In our view, the discipline of Weed Science took some time to evolve within the different countries of the region, both terms of understanding and accepting the broader principles of weed management, and the adoption of associated practices (Chandrasena and Rao, 2017). Preventative weed control has been of significant interest as tools for weed management (Rao et al., 2018), as have been various non-chemical methods of weed control.

The latter include cultural practices, including the manipulation of crop seeding densities, row-spacing, the timing of sowing and fertilizer applications, and other interventions, such as crop rotations, mixed cropping, and cover cropping. Despite these interests, our review finds a relatively small number of papers on such topics presented for discussion at the APWSS conferences and proceedings (Figure 3). The interest in herbicides as quick-fix solutions and aggressive marketing by the industry may have been factors in this trend.

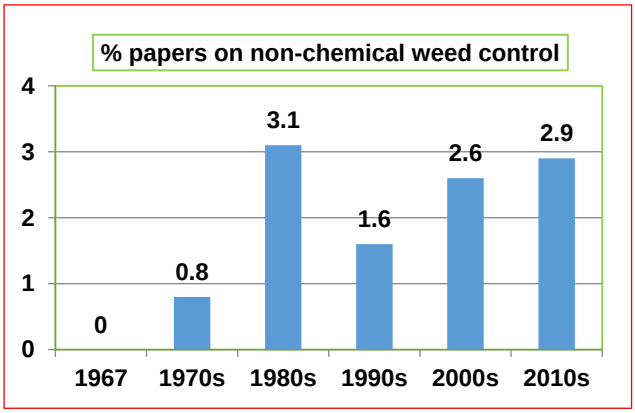


Figure 3. Trends in research on preventative and non-chemical methods of weed control in the Asian-Pacific region

Utilization of weeds as biological resources, particularly, within traditional South Asian, South-East and East Asian societies, has been a topic of considerable interest in the Asian-Pacific region (Chandrasena, 2008; Chandrasena and Rao, 2017). However, the research and discussions on the topics have been sporadic (Figure 4) and limited to mostly the uses of weeds as animal fodder or material suitable for composting and reuse as organic manure in agricultural settings. A renewed effort to promote the redeeming values of weeds as biological resources for food, medicines and raw materials for industry was made by Kim and Shin (2011) building on an earlier material published in South Korea on the same topic (Kim et al., 2008).

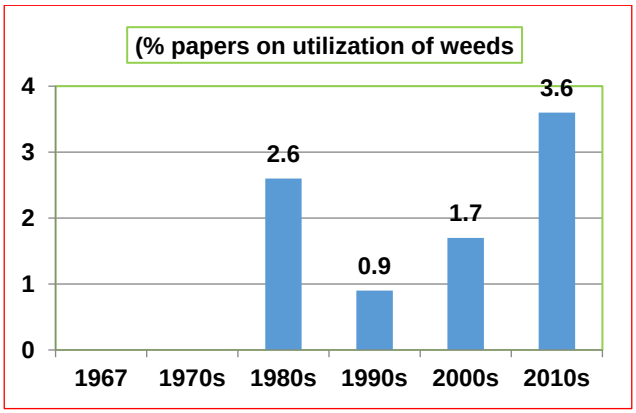


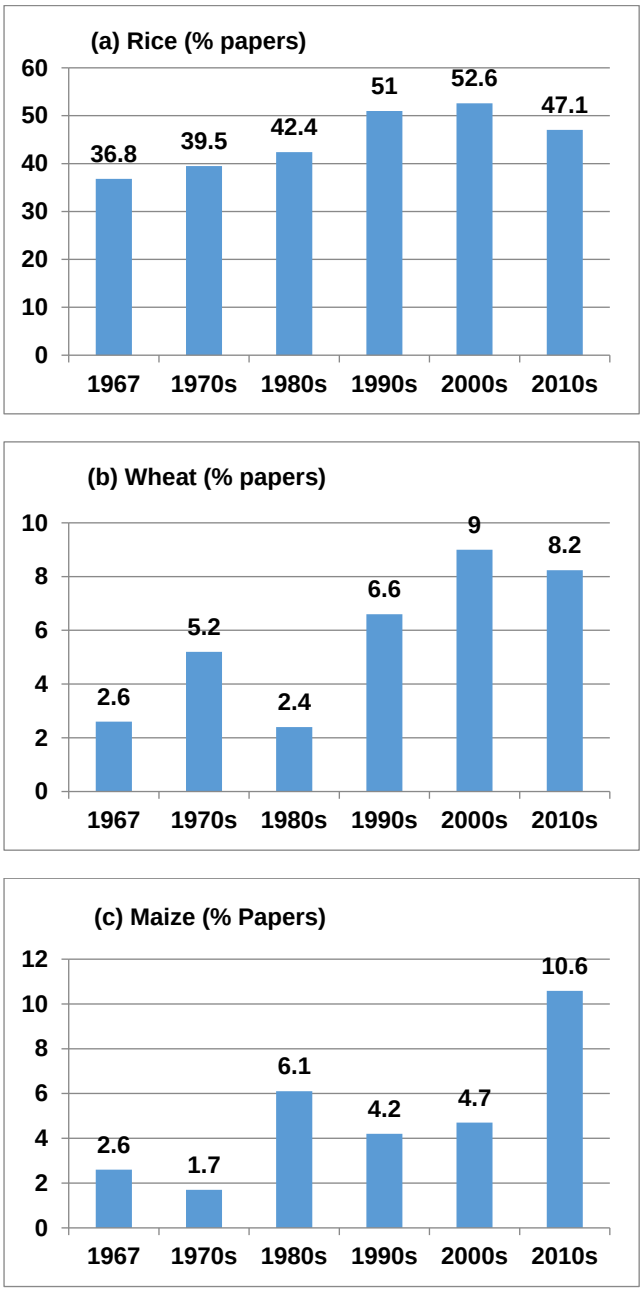
Figure 4. Trends in research on utilization of weeds in the Asian-Pacific region

Research on specific crops and weeds

Weed research has been rightly focused on several crops that are predominantly grown in the Asian-Pacific region. It is not surprising that the majority of weed research has been on rice (Figures 5), the most dominant staple food crop in the region. Research efforts on maize and wheat showed a significant increase in recent decades, compared with previous decades, particularly because wheat has become a major crop in India, Pakistan and China, while Maize has also been increasingly grown in India, Indonesia, China, Philippines, Pakistan, Vietnam and Thailand.

Among weeds, rice weeds have received the greatest attention and focused research effort. Among them, barnyard grasses [*Echinochloa crus-galli* (L.) P. Beauv.]; *Echinochloa colona* (L.) Link], the major grass weeds of rice, were the most studied, on aspects of their taxonomy, biology, eco-physiology, competition with rice and control. The research on the taxonomy of barnyard grasses, published in the APWSS proceedings, was recently updated by Michael (2019). The relatively new 'weedy rice' was the next most studied weed, as it has emerged as the most problematic weed in several rice-growing countries of the Asian-Pacific region, including Malaysia, Vietnam, Thailand, Sri Lanka and India.

The shift in methods of rice establishment from transplanting to direct-seeding of rice in Asian countries (Rao et al., 2007) has led to increased predominance of weedy rice, which explains the increased research interest on weedy rice. The evolution of resistance in littleseed canarygrass (*Phalaris minor* Retz), the predominant weed of wheat, particularly in the wheat-growing districts of India and Pakistan, led to a heightened focus on this specific weed and the herbicide-resistance development as a research topic. The research in the region also contributed heavily to the global efforts to manage several major weeds, including purple nutsedge (*Cyperus rotundus* L.), cogongrass [*Imperata cylindrica* (L.) P. Beauv.]; and the giant sensitive plant (*Mimosa pigra* L.).



Figures 5. Trends in weed research in (a) rice, (b) wheat and (c) maize in the Asian-Pacific region

Invasive weeds in non-cropping situations, such as parthenium weed (*Parthenium hysterophorus* L.), mile-a-minute (*Mikania micrantha* Kunth); and Siam weed [*Chromolaena odorata* (L.) R. M. King & H. Rob.] also feature prominently in the Asian-Pacific weed research. The reports on the biology, ecology, economic, environmental and social impacts and

management options (herbicides and biological control) for these weeds, add considerably to the global knowledge on how to effectively manage them. Other major weeds that feature prominently in the proceedings, in the decreasing order of number of publications, include goose grass [*Eleusine indica* (L.) Gaertn.]; red sprangletop [*Leptochloa chinensis* (L.) Nees] and parasitic weeds (e.g., *Striga* spp.).

Aquatic weeds have long been major problems in the Asian-Pacific region countries, many of which have tropical and sub-tropical climates, which favour their growth. As a consequence, there has been targeted research in the region on major aquatic weeds and potential management options, including those for water hyacinth [*Eichhornia crassipes* (Mart.) Solms] and salvinia (*Salvinia molesta* D. S. Mitchell). Biological control options and country-based success evaluations of the released bio-control agents for these weeds are prominent in the research from several countries in the APWSS region.

Our assessment finds significant contributions from the APWSS region countries for the management of aquatic weeds and many other weeds in crops, such as rice, wheat, maize, sorghum, sugar cane, pulses, vegetables, pineapple etc. and several plantation crops (i.e. citrus, tea, rubber, coconut, oil palm). A relatively low number of papers on managing weeds in non-agricultural situations reveals that the research agenda in the region is firmly focused on agriculture. Research on potential impacts of climate change on weeds in the Asian-Pacific region has been limited up to the period covered in this assessment (data not presented), although the topic has been recognized as a major emerging issue (Adkins, 2017).

The scarcity of water, insufficient labour and other resources and the introduction of more effective herbicides, encourage farmers in many countries to shift from transplanted to direct-seeded rice. This is primarily for reducing cultivation costs and potentially, increasing farmers' income (Rao et al., 2017). This change has led to a shift in the weed flora to more competitive grasses and some very difficult-to-control broadleaf weeds in many rice-growing countries (Rao et al., 2007, Rao et al., 2015; 2017; 2018).

Shifts in the weed floras, increased labour and cultivation costs then led to the introduction of new herbicide chemistries (e.g., aryloxyphenoxys and sulfonylureas), with very low use rates. This major change in the availability of highly effective, low dose herbicides caused shifts from sequential applications of two or more herbicides in the 1970s to 'one-shot treatments' by late 1980s. While Japan has led this technology, similar, developments have occurred with respect to other crops in the Asian-Pacific region.

In the early 1980s, the evolution of herbicide resistance in some weeds became a major subject of concern and research in many countries of East Asia, Southeast Asia and Australasia. Sulfonylurea resistant sedges and broad-leaf weeds, and 2,4-D and triazine-resistant broad-leaf weeds were among the first to be reported. Several research papers were published on propanil-resistant barnyard grass (*Echinochloa crus-galli*) and isoproturon-resistant littleseed canarygrass (*Phalaris minor*).

In the current decade, weed resistance problems have increased significantly in many countries. Presently, 510 unique cases (species x site of action) of herbicide-resistant weeds have been reported globally (Heap, 2019). These cases reveal 262 species of which 152 are dicotyledonous weeds and 110 monocotyledonous species. Weeds have evolved resistance to 23 of the 26 known herbicide sites of action and to 167 different herbicides (Heap, 2019). Herbicide resistant weeds have been reported in 93 crops in 70 countries and these numbers are increasing all over the world. Within the Asian-Pacific region, USA has the greatest problems with herbicide-resistant weeds, followed by Australia, China, Japan, Malaysia, New Zealand, Turkey, South Korea, Iran, Thailand, India, Philippines, Indonesia, Sri Lanka, Taiwan, and Fiji (Heap, 2019).

In Asia, unique cases of herbicides resistance occur mostly in weeds associated with (in decreasing order) rice, wheat, non-crop situations, orchards, vegetables and soybean. Several barnyardgrasses (*Echinochloa* spp.), littleseed canarygrass, goosegrass, red sprangletop are among the most prominent herbicide-resistant grasses (Heap, 2015). Among others, monocotyledonous species to show herbicide resistance are species of *Monochoria* C. Presl; arrowheads (*Sagittaria* L.)., some sedges and rushes (i.e., *Schoenoplectus* (Rchb.) Palla; *Cyperus brevifolius Rottb; Cyperus difformis* L.) and yellow bur-head [*Limnocharis flava* (L.) Buchenau].

Heap (2015) also suggested that biggest threats to sustainable weed management come from multiple resistance in the genera - *Lolium*, *Alopecurus*, *Avena*, *Amaranthus*, *Conyza* and *Echinochloa* species. As all of these genera and species are major Asian-Pacific weeds, the herbicide resistance issue and related research will dominate the research agendas for some time to come in a number of countries, including Australia.

Impact of Integrated Weed Management (IWM) technologies and adoption by farmers

Over the years, a wide variety of tools, techniques, and tactics to manage weeds have been developed for the benefit of the farmers in the region. Weed research has championed the integration of the knowledge of weeds from diverse fields, including biology, ecology, physiology, biochemistry, genetics, and taxonomy (Chandrasena and Rao, 2017). The research in Asian-Pacific region has led to the development of both non-chemical and chemical weed management technologies, which are used either alone or in integration.

Hand weeding was the most common weed control method used by the majority of farmers in the developing world in the earlier years. These practices continue to date (Figures 6 and 7), along with other labour-intensive methods (Figures 8 and 9). However, the decreased availability of labour and increased cost of manual weeding has resulted in searching for more effective and affordable alternatives. Manual methods are still used as components of IWM in the majority of Asian-Pacific countries (Rao and Chauhan, 2015), except in the most advanced economies (i.e. Japan, Australia, South Korea and New Zealand).

Figure 6. Manual weeding in rice, India. The hand-weeding tasks are mostly undertaken by women

Several mechanical weeders (e.g., cycle-weeder, cono-weeder, push-hoe) were developed in developing countries of the region. Either used manually or with the assistance of animal power, these have been found to be highly effective in managing weeds (Figures 8 and 9).

Figure 7. Manual weeding in upland crops, India

Figure 7. Cono-weeder used in rice in India

Figure 8. Inter-row cultivation using a mechanical weeder and animal power. India

Rao and Ladha (2013) reported that the cost of weeding by female labourers could be reduced by 4 and 5.2 times, respectively, by using the rotary weeder and the cono weeder, compared with hand weeding alone. Mechanical weeders have always been an important component of IWM, particularly, in India (Rao and Nagamani, 2010; Rao et al., 2015).

Recently, power weeders have also been introduced and these are extensively used by farmers in all Asian-Pacific countries (Rao et al., 2015; 2017; 2018).

The extent of herbicides use for weed management varies by crop and country. The farmers in the Asian-Pacific region use herbicides in combination with tillage and land preparation, along with mechanical and manual weeding. Herbicides continue to be a dominant component of weed management in all crops in Australia, China, Thailand, and Vietnam but are less predominant in India, Pakistan, Bangladesh, Sri Lanka, Indonesia, and the Philippines. In these latter developing countries, herbicides are more widely used in commercial plantation crops and much less used in subsistence crops. The primary forms of weed management methods are hand and mechanical weeding in India. In Philippines and Vietnam, herbicides are commonly used as a secondary or supplementary form of weed control to mechanical and hand weeding. In Thailand, even though all the methods of weed control are used, herbicides are predominantly used in most crops. Of the total active ingredients of herbicides used, glyphosate accounts for 50% in Australia, 13% in China; 37% in India; 73% in Indonesia; 33% in Thailand; 36% in Vietnam (Graham Brookes, 2019).

For every two-to-three year period, a new herbicide mechanism of action (MOA) was commercialized until the early 1980s (Duke, 2012). However, of late, no new MOAs have been introduced, while the development of herbicide resistance has been increasing in weeds, since the mid-1970s (Heap 2019). Thus, until herbicides with new MOAs are identified and commercially developed, the herbicides with current MOAs need to be used judiciously in agriculture to prevent further resistance development in major arable weeds. This can be achieved by adopting strategies, which include using a range of existing herbicides in new mixtures, combinations and/or sequences, combined with crop rotations. There is also recognition that the integration of herbicides with non-chemical weed control measures would be essential to reduce the rate at which herbicide resistance is developing across the globe (Kraehmer et al., 2014).

The average application rate of herbicides in the 1950s was 2,400 grams of active ingredient (a.i.) per hectare. By the 2000s, the average use rate decreased to 75 g/ha (Phillips McDougall, 2018). Thus, the amount of a.i. used by farmers today is about 5% of the rate used in the 1950s. The discovery and development costs of a new crop protection product has increased from US $152 million in 1995 to US $ 286 million during 2010-2014. The time taken to develop a new crop protection product also increased from 8.3 years in 1995 to 11.3 years during the period 2010-2015 (Phillips McDougall, 2016).

With the reduction in investments for discovering new herbicides, research emphasis, led by the industry, has shifted to herbicide-tolerant crops (HTCs) during recent decades, as evident in the APWSS proceedings. In 2018, herbicide tolerant soybean, canola, maize, alfalfa, and cotton covered 46% of the global area cultivated in those crops (ISAAA. 2018). Nine countries in the Asian-Pacific region grew 19.13 million hectares of HTC biotech crops. The area planted to biotech crops with stacked traits increased by 4% and occupied 42% of the global biotech crop area.

Controlling ‘weedy rice’ (*Oryza sativa* L.) in rice in the USA was made effective with introduction of Clearfield® rice technology in 2002, in which imidazoline-resistant rice cultivars have been used. These cultivars allow the application of a suite of imidazolinone herbicides (imazethapyr, imazamox, imazapic, imazapyr) as a package in rice to suppress weedy rice and produce high yields (Burgos, 2015). Later, for the first time in Asia, imidazolinone tolerant rice varieties (MR 220CL1 and MR 220CL2) were launched during 2010 in Malaysia as the Clearfield® Production System (Azmi et al., 2017). By utilizing proper agricultural procedures and practices, such as those recommended in the Clearfield® System stewardship guidelines, the occurrence of resistant weedy rice biotypes can be minimized.

Burgos (2017) reported that farmers in the USA, using the Clearfield® rice technology produced the cleanest rice in the US mid-south (Burgos et al., 2017). However, the greatest challenge with HT rice technology is the evolution of herbicide-resistant weedy rice via gene flow (Burgos et al., 2015).

Provisia rice™, a mutant rice variety, was released by BASF in 2018 for use in the USA, adding to innovative HTC technologies. Featuring a non-genetically modified (non-GM) herbicide-tolerant rice, comprised of Provisia seed™ containing the Provisia trait, the system allows farmers to safely apply the broad-spectrum Provisia herbicides™ for the post-emergence control of a wide range of weeds, including acetolactate synthase (ALS) resistant grasses and weedy rice (BASF, 2018). Provisia rice™ is also tolerant to quizalofop-p-ethyl, a selective grass herbicide that inhibits acetyl-coenzyme A carboxylase (ACCase). BASF experts leveraged proprietary research to develop this system, which complements the Clearfield® rice production system. Using the Provisia Rice System, farmers can rotate different

herbicide modes of action (ALS, ACCase) for sustainable management of resistant rice types and annual grasses to enhance their ability to plant successfully on more acres.

There is considerable interest in the Provisia rice technology in the Asian-Pacific region as well, because it can be integrated into the existing Clearfield rice-soybean-conventional rice rotation system to manage both weedy rice, other herbicide-resistant weedy rice outcrosses and volunteer plants that may survive from Clearfield varieties (Burgos et al., 2017). The discussions on herbicide-tolerant crops have been increasing within the APWSS conference proceedings (see Figure 1d) as well as in associated APWSS publications. The topic has been well discussed recently (Adkins, 2017; Burgos et al., 2017), with possible applications for the region.

Conclusions and Future Outlook

Figure 9 shows a summary of the APWSS papers categorized in this assessment. The predominance of herbicide-based research in the region is evident. However, some notable changes are occurring.

The reports on negative environmental impacts of herbicides, including concerns about human safety and increasing number of herbicide-resistant weeds have resulted in the shift in the emphasis of weed research in the Asian-Pacific region from herbicides to IWM approaches. There have been increasing numbers of papers on IWM, involving, greater efforts to combine mechanical, ecological and biological control approaches with herbicides to manage weeds. The use of IWM packages for effective management of weeds, developed by weed researchers in the APWSS region countries, have resulted in improved crop production, reduction of other agricultural pests, including insects and plant pathogens and reduced risks to human and animal health in Asian-Pacific region (see Rao and Matsumoto, 2017).

Weeds will continue to be major biotic constraints in agriculture production in the Asian-Pacific region, due to their dynamic nature. Weed management research and technologies to manage weeds need to be equally dynamic and innovative. Several reviews have identified future weed management requirements and targets (Shaner and Beckie 2014; Rao and Yaduraju, 2015; Westwood et al., 2019). In concluding this paper, we highlight the following as among priority weed research needs that are relevant to the Asian-Pacific region, for possible inclusion in a future research agenda:

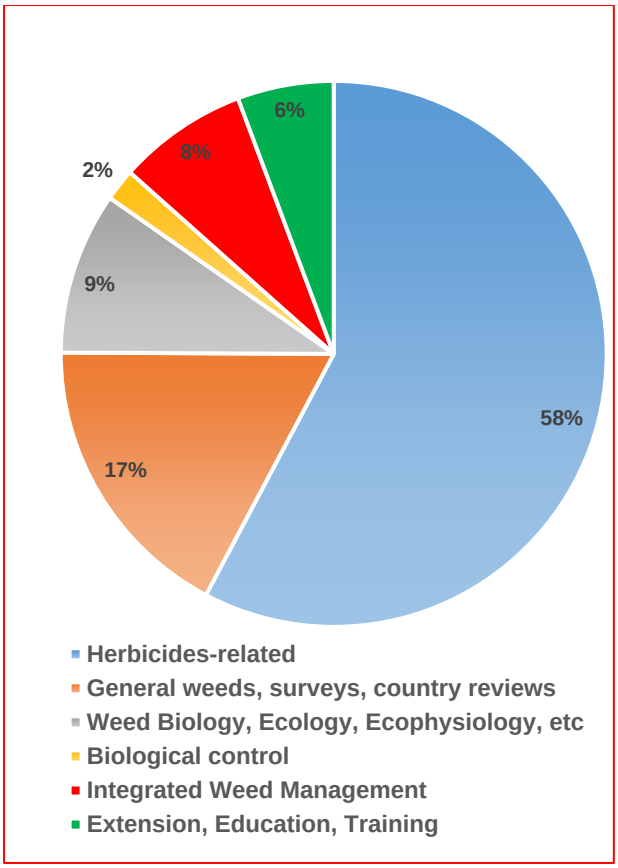


Figure 9. A summary of papers assessed in different categories of weed research (%) indicating where the Asian-Pacific efforts lie

- We find that the Asian-Pacific region, apart from Australia, New Zealand, Japan and South Korea, do not regularly update crop yield losses with sufficient accuracy. We therefore recommend better estimations of crop yield losses due to weeds in the Asian-Pacific region countries. For this, novel technologies (GIS, GPS and Remote sensing) may be used and countries may collaborate either as regions, or do individual estimates for the major crops.
- The monitoring programmes, country-wide reporting and management of changing shifts in weed problems and emerging weeds are also inadequate in many Asian-Pacific countries. Taking a leaf out of the APWSS proceedings in the 1970s and 1980s decades, we recommend individual countries to collect reliable data on weeds affecting both agriculture and non-agriculture on a regular basis. A uniform template for country-wide reporting on different categories and priorities needs to be developed, learning from previous experiences. could

- Climate change and its impacts are perhaps the greatest future challenge for all sectors of the societies and countries in the region. For farmers and land managers who deal with weeds, understanding how weeds will respond to the changing climates in different countries is vitally important for adaptation responses. Research on this topic is already well underway (see Ziska and Duke, 2011; Jugulam, et al., 2019), and needs to increase in different ecosystems. Weeds will adapt easily to selection pressure imposed by climate change and management tactics. Developing climate resilient IWM strategies will necessitate the inclusion of a variety of cultural, mechanical, biological and chemical methods to manage weed floras in different situations.
- The Asian-Pacific region is yet to benefit from special weed management techniques, such as remote-controlled weed detection and mapping technologies and Unmanned Aerial Vehicle (UAV) technologies. UAVs are capable of capturing high spatial resolution imagery, which will provide more detailed information for weed mapping (Peña et al., 2013). The technologies are fast developing in the region, led by China (Huang et al., 2018). We recommend countries to explore such opportunities as they are already well developed in developed countries. Research on robotic weeders may be developed to improve weed control options for specialty crops.
- New herbicides alone will not solve food shortages or sustain sufficient food production. Weed researchers will need to use novel technologies, together with other tools that have already been developed. We are of the view that both herbicide and HTC technologies will continue to advance; however, it is also equally important that tolerance to abiotic and biotic stress and competitive traits be incorporated into HTCs. Thus, in addition to stacked herbicide resistance traits, future crop varieties will need to contain improved agronomic traits (e.g., high yields, multiple stress tolerance, competitiveness against weeds and allelopathic potential). As Burgos et al. (2017) suggested, implementation of stewardship and best management practices, aimed at disrupting the biology of weedy species, will be necessary to keep in step with the evolution of herbicide-resistant weeds.

We believe that the Asian-Pacific region will also benefit from climate modelling and weed responses, along with the modelling of other related changes, such as changes in vegetation cover as part of weed research. Development of climate resilient, novel IWM approaches, with herbicides as a component, combined with biotechnology, appear essential to assist farmers in coping with the challenges of weeds in the future.

A half-century has passed after APWSS became established in 1967. With the launch of a new Journal - *Weeds*, dedicated to weed research and Weed Science, APWSS is taking a significant forward step and expanding its contribution to knowledge-sharing and networking throughout the region, as envisaged by our founding fathers (see discussions in Chandrasena and Rao, 2017).

As the Society is now quite mature, having celebrated more than 50 years of its existence, we are of the view that the research agenda should expand. There are still many areas and opportunities for Weed Science researchers in the Asian-Pacific region to develop effective, economical and ecologically safe integrated weed management strategies through interdisciplinary research.

In agriculture, the primary focus in weed research should be to develop solutions to increase the net income of the farmers through improved resources use and reduced costs of weed management. Away from agriculture, weed research would benefit by improved weed detection and mapping and systematic 'asset-based' and 'weed-priority-based' approaches for managing weeds.

Many countries of the region can benefit from following the national approaches that have been developed in the advanced economies, such as Australia (Chandrasena and Johnson, 2015). However, instead of relying excessively on herbicides, the Asian-Pacific countries should look for affordable and sustainable solutions to weed problems, learning from the 50 years of research that has already been conducted.

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