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EDITORIAL

Seeing 'Weeds' with new Eyes

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Introduction

Marcel Proust, once said: "*The real voyage of discovery consists not in seeking new lands but seeing with new eyes.*" I suggest we look at weeds in this way in this 21st Century.

In this Editorial for the second issue of the new journal - *Weeds* - I reflect upon some ideas that have shaped our recent discourses on weeds. It seems to me that the emerging generation of weed scientists may benefit from a dip into this history. As someone said: '*without history, man is nothing*'.

> *"…One longs for a weed, here and there, for variety; though a weed is no more than a flower in disguise, which is seen through at once, if love gives a man eyes..."* James Russell Lowell (c. 1890)

> *"…It is time for us to eliminate weeds from our cultivated lands. But we should understand why we do it, and what we're doing. Nature has a reason for allowing weeds to grow where we do not want them. If this reason becomes clear to us, we will have learned from Nature how to deprive weeds from their 'weedy' character; that is, how to eradicate them from cultivated land, or rather, how to improve our methods of cultivation so that weeds are no longer a problem…" Ehrenfried Pfeiffer* (c. 1950)

The first quote pleads for people to 'open their eyes' and appreciate Nature, in which weeds are an essential part. Poetic freedom allowed James Russell Lowell to promote a profoundly sympathetic view of weeds, instead of looking at them negatively, as always causing problems to humans. The second quote, from a soil scientist, who pioneered organic agriculture in the USA, recognized that some plants might become a nuisance when they interfere with the growth of crops or man's other activities. Dr. Pfeiffer suggested that such 'weeds' need to be eliminated from arable land, but we should do so with a good understanding of why they are there in the first place.

Both viewpoints are essential in looking at weeds with new eyes, as intended by our Society's new journal - '*Weeds*'. Many weed scientists and other ecologists would agree that weeds have been poorly understood for the past two centuries. These plants have also been subject to excessive malign, primarily driven by misconceptions and perhaps, even influenced by the prevalent worldview that everything on earth has been created to be subdued and exploited to satisfy man's selfish interests.

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The relationship between weeds and men is an old one; however, it is changing fast. There have been increasing public concerns about the effects of land-clearing, over-development, overuse of herbicides, and other destructive farming practices, as part of our goal of assuring human food security. Such concerns have encouraged some to think critically about whether we ought to and need to continue maximum control programs against plant taxa that only pose problems under certain sets of conditions.

A critical issue for *Weed Science* is the persistent and uninformed slandering of colonizing plants (weeds) by some people, which inhibits others from admiring them and appreciating their redeeming values and thereby welcoming them into our lives and environment. As discussed by Zimdahl (1999), common definitions of a weed include: "*a plant, which has a detrimental effect on economic, conservation, or social values*" and, "*an undesirable plant, which is out of place*". Such definitions are inappropriate in a scientific discipline, because they are anthropocentric and culturally-biased. They mislead by creating a negative perception that all weeds are bad, under all circumstances. Addressing this anomaly requires recognition of the beneficial effects and values of weeds, as part of the Earth's rich bio-diversity.

Are Weeds 'Plants Out of Place'?

In the 1960s, our founding fathers steered the discipline well clear of ludicrous ideas, such as 'plants out of place'. In articulating the scientific and ecological basis for explaining weeds, they pointed out that these organisms are no more than taxa with strong colonizing abilities adapted to natural or human-disturbed habitat (Baker, 1965; Bunting, 1965; Harlan and De Wet, 1965; De Wet, 1966). They are the first occupiers of newly cleared land. The more you disturb the land, the more you create opportunities for these highly successful "*pioneers of secondary succession*" — nothing more; nothing less.

When moved by natural dispersal agents (e.g., wind, water, animals) or by the human agency, and introduced into new environments, 'pioneering' taxa can successfully establish populations and increase in abundance within a short period. Attributes that allow them to do so (see Baker's List of '*The Ideal Weed*', Baker, 1965) include their innate genetic systems and reproductive capacity to produce seeds or other propagules under most conditions, and fast growth to reproductive maturity. Colonizer taxa are also capable of stress tolerance and plasticity, which allow them to adapt quickly to unfavourable biotic or abiotic environments. The absence of natural enemies in the new environment, at least initially, also helps these taxa to colonize a new habitat.

Mis-information is rife on the negative impacts weeds have on the environment or on biodiversity. The negative publicity has been increasing. It is rare to find a biology lecturer, teacher, or an ecologist, who would has the courage to mention the virtues of weeds. They are either scared; or unsure, because there are powerful voices advocating the opposite view. These negative viewpoints also have taken deep root, over a long period. At weed conferences, one often hears speakers flippantly indulge in the use of pejorative terms like "*damned weeds*"; "*bloody weeds*" drawing approval from audiences. It is a fashion, although such words are not in the lexicon of enlightened ecologists or weed scientists.

The overwhelming negative attitudes towards weeds, rampant in some Western countries, including Australia, the USA and Canada, appears to be a form of xenophobia (dislike of anything strange or foreign). The notion, that weeds are plants '*out of place*', is very American, as the historian Zachary Falck (2010) noted. It arose in the 1850s out of the aspirational dream of the American middle-class in creating cities, which needed to look 'sanitary' and 'orderly'. The early American cities, mostly in the East coast, had been influenced by the streetscapes of European cities, from which the ancestors of the settlers had come. As opposed to the attractive and colourful wildflowers, which beautify parks, sidewalks and median strips, untamed growth of weeds was blamed for 'disfiguring' open spaces and for the 'imperfections' of urban life in the cities. Tim Creswell (1996; 1997) explains how inherently flawed the '*out of place*' idea is, as follows:

> *"…the notion that everything has its "place" and that things (people, actions) can be "in-place" or "out-of-place" is deeply engrained in the way we think and act. Such is our acceptance of these ideas that they've achieved the status of common sense or become second nature to us. Common sense produces the strongest adherence to an established order..."*

> *"…People act as they think they are supposed to; they do what they think is appropriate in places that are also appropriate. It is therefore essential for powerful groups in any given context to define 'common sense' and that which goes unquestioned. When individuals or groups ignore this socially-produced common sense, they are said to be "out-of-place" and defined as deviant..."*

We brand some plants '*out of place*', because, we have firstly ourselves defined in some abstract way, elements of our immediate environment as '*proper places*', and these would demand '*appropriate behaviour*'. Such a notion may be satisfactory for some of our living spaces, such as home gardens, flower beds, and turfed lawns, kept neat and tidy, in which weeds may be accused of de-spoiling the tidiness. One may also call agricultural fields '*proper places*', because we use them to produce our food and fibre. By the same argument, one may call natural or pristine areas, with little human interference, as '*proper places*' from a human point of view. But it is a stretch to call all wilderness landscapes with we interact '*proper places*'? Such places, being part of nature, often not interfered by man's activities, pose many challenges to humans, unless you are a skilled survivor in the wilderness. Teeming with life, including wildlife, wilderness areas are not likely to respond in the way we perceive the world to be.

What is "*out of place*" depends on the context and who is making this subjective assessment, based on personal experiences. Thus, within our discipline, we create lists of plants labelling them as 'environmental weeds', 'horticultural weeds', 'agricultural weeds', 'ruderal weeds', 'urban weeds', 'sleeper weeds', and so on. Many of these categories have no scientific basis. They are just descriptors. From an environmental perspective, crops could also be viewed as weeds. From a farmer's perspective, native plants growing in fields could potentially be weeds, particularly if they produce large numbers of offspring and are hard-to-kill. As Radosevich and Holt (1967) said: "*Any plant can be a weed, and no plant is always a weed. As a consequence, some plants may be considered weeds, and hence, undesirable to have at particular places and at specific times*".

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To appreciate weeds, one must look at them through 'new eyes', an ecological lens, and frame of mind. The fact that weeds are colonizers with extraordinary abilities is the accepted wisdom in ecology. Nevertheless, as a group, these plants have been subjected to relentless attacks through negative publicity and the liberal use of militaristic metaphors e.g., ''invasions'. The public can be excused for being scared out of their wits and common sense. Attitudes towards weeds must change, and this will happen only if weed scientists *open their eyes* and look closely at the organisms we have learned to despise.

The resilience of weeds, their tenacity, and the capacity to adapt to environmental disturbances need to be recognized not only as harmful but also as potentially beneficial. I suggest that *the very success of these plant taxa in the environment is also their weakness.* Their verdant growth and abundant presence, in some situations, conflict with human objectives, and this is why they have become targets for our technology. Perhaps, this understanding would help modify our attitudes allowing us to avoid creating conflicts with potentially useful plant taxa and getting into situations from which we cannot win.

It is necessary and good for all scientific disciplines to realign their focus and objectives from time to time. *Weed Science* has reached that stage. While there is a vast amount of disparate literature, the future requires a convincing 'body of knowledge' of the utilization of colonizing species to be established, so that present and future generations will benefit from that knowledge.

Humans - the 'weediest' of all species

> *"…The word weed is taken to mean a species or race, which is adapted to conditions of human disturbance. By this definition weeds are not confined to plants. Animals such as the English sparrow, the starling, the "statuary" pigeon, the house mouse, Drosophila melanogaster, and others are especially fitted to environments provided by human disturbance. Indeed, perhaps no species thrives under human disturbance more than Homo sapiens himself. In this ecological sense, man is a weed…" Harlan and De Wet* (1965).

The reason I cite Harlan and De Wet is to remind the new generation of weed scientists that because we 'thrive on human-modified landscapes' humans are clearly '*weeds par excellence*'.

We are the only species that does not have to adapt to the environment. We change and/or modify our environment to suit our needs. For example: we heat our homes, air-condition them, wear clothes, drive cars, etc. On the other hand, colonizing species have the inherent capacity to adapt fast to any new environment. Often introduced to different continents deliberately or accidentally by humans, weeds are trekking the globe as the' *shadows of men'*.

The same attributes that make a plant highly successful in getting established in new environments (vaguely called 'invasive') will be sought after under a different set of circumstances. The way forward is to broaden our understanding of colonizing plant taxa and their crucial ecological role in biological communities. To achieve this objective, our journal will promote more in-depth ecological studies and critical analyses of weeds, instead of just publishing papers on pure and straightforward weed control.

A '*War with Weeds'* is untenable

The fact that weeds cost farmers more than any other major pest category has engendered a 'war mentality' in dealing with weeds, which is unfortunate. Given that cropped fields are continually-disturbed for production reasons, the occurrence of colonizing taxa is inevitable. But to say that we should deal with weeds like a military campaign is an idea fraught with danger. It is also an inappropriate strategy that includes an unattainable goal – 100% weed control forever.

Developed over centuries, agriculture has ample strategies and tactical tools to deal with weeds, which include tillage, hoeing and other methods of land preparation, active cover cropping, crop rotation, inter-cropping, and maintaining organic residues of even pioneer species to cover the soil and add organic matter, but not to set seed. Declaring 'all-out war' on weeds, mainly with chemicals, may yield 'clean' and 'weed free' fields and good harvests, but *for how long will these last?* Overuse of herbicides has already backfired with the widespread development of herbicide resistance in weeds on a large-scale, across the globe, threatening agriculture in many countries (Heap, 2019).

Biologists need to continuously reflect upon the ethical dimensions of the language they use when communicating with the public on weeds and other species, often derided as 'invasive'. As Larson (2005) questioned: "*Is the language of 'war' likely to promote social cohesion and, consequently, effective and appropriate action towards weeds?*"

The militaristic and combative metaphors used within 'invasion biology' are unsuitable because: (1) they lead to a narrow perception of weeds and certain animals as marauding armies of 'invaders'; the idea is far from the truth! (2) they contribute to a profound social misunderstanding of weeds as nothing but plunderers of our resources, leading to xenophobia, and loss of scientific credibility; and (3) they reinforce militaristic patterns of a 'winnable war' against all weeds, an attitude that is counter-productive for both conservation and restoration of native vegetation.

While 'war' and 'invasion' metaphors may motivate some people into action against weeds in the short term, they are likely to fail in the long term. Alternatives to militarism will better promote realistic weed management and conservation goals in a multicultural context (Larson, 2005). I add that removing such jargon from the *Weed Science* lexicon will allow people to be optimistic about having a better relationship with weeds (Chandrasena, 2015).

'*War with Weeds*'- is the wrong choice of words to describe how we should manage weeds. This phrase is often bandied around in TV, radio, books, and magazines. The attraction is clearly in the alliteration, the repetition of the letter 'w', which makes a snappy phrase. Evans (2002), in his historical analysis of weeds in Canada, used it as his book's title, but to convey a wholly different message.

The 'war' analogy probably got entrenched in the mid-1940s, following the military successes of the Western-allied forces in 1945 in finally annihilating Nazi Germany's war machine. The end of World War II coincided with the discovery of the first synthetic herbicide, 2,4-D in 1944, which then began to be used widely for weed control. Much of the work was done during the war, but the research was not allowed to be published until the war was over. Pest control, those days, was also seen as a requirement for the total annihilation of the target pest, so that the pest populations may not ever recover. The basis for the obliteration mentality was the undisputed success of the large-scale use of the first-ever synthetic insecticide, DDT in 1939, in controlling the malarial mosquitoes and typhus (spread by body lice) among the Allied forces in various battlefronts.

The total annihilation of a pest organism was the main goal, but it was an unachievable one, both scientifically and practically. The possibility of large-scale heavy hitting with synthetic chemicals may have adverse effects on humans, and non-target animals were not generally realized until Rachel Carson's *Silent Spring* (Carson, 1962).

In the early-1960s, Rachel Carson raised the issue of excessive losses of birds, creating a heart-rendering image of a 'silent spring', directly pointing the finger at the overuse of pesticides. Residues of some pesticides persisted in the food chain, reaching higher concentrations (bio-accumulation), which resulted in more severe effects at successively higher trophic levels. Worryingly, pesticide residues were identified as the cause of rapid population decline, particularly in birds of prey, such as the peregrine falcon and sparrow hawk, through the thinning of eggshells. The offending chemicals, mainly organochlorine (OC) pesticides, including DDT (dichloro-diphenyl-trichloroethane), have now been banned in many countries, but they are still used in some poorer countries of the world.

Rachel Carson's observations were quite controversial at that time; she was ridiculed, and her predictions dismissed. The corporate world paid millions to have her silenced. But, eventually, the love of bird songs won out. People read her book, grieved at the prospect of a 'silent spring', spoke up, and insisted on regulations that eventually brought a ban on DDT and strict legislative controls on the uses of all pesticides. Nevertheless, this was a period during which powerful chemicals, insecticides, fungicides and herbicides, were being discovered, and the idea that an *all-out war* would solve pest problems became further entrenched in the minds of the proponents. In the post-war USA, it was common to talk about obliteration or annihilation of the enemy. With a bit more common sense, phrases like '*war*' might have been left out from the lexicon used in communicating weed or pest control messages to the public.

To presents a largely human-caused problem as a confrontation between humans and weeds in a way that alienates each other is ethically wrong. The human culpability (humans, as a major cause of the global spread of weeds) is mostly removed in this narrative. It reflects the flawed prevalent thinking in our modern societies that *all ills are someone else's faults and never ours*.

From a pragmatic viewpoint, this mentality, foolishly describes a situation from which there are no true winners. Humans may *subdue* some colonizing species here and there, but surely, it is unlikely, ever, to eradicate problematic species without causing other types of environmental harm. Hence, instead of pursuing the delusion of winning a war with weeds, we ought to aim for a negotiated peace; a multi-faceted co-operation between weeds and us; and a peaceful *co-existence* (Chandrasena, 2007; 2017). Not to do so would be counter-productive in the long-run. To successfully negotiate peace, a deeper ecological understanding of the strengths and weaknesses of the 'potential foe' is a must. The history of *Weed Science* records that our founding fathers, decades ago, argued most persuasively for such an understanding with more in-depth ecological studies on weeds (Harper, 1960; Bunting, 1960; Baker, 1965; Baker and Stebbins, 1965). They were, of course, motivated by common sense and scientific rigour alone and unburdened with the need for hyperbole.

Speaking at the 22rd Asian-Pacific Weed Science Society Conference, in 2011, David Low challenged the notion of a 'war economy' for weeds. He explained that the primary reason for using this analogy in Australia is that it allows the protagonists (bureaucrats) who control budgets, to shift spending in preferred directions. I agree with him.

> *"…As is the case in any real ''war' situation, "War!" effectively shreds our normal investment priorities, and such a situation can be used to create the urgency needed to bulldoze away the messy contingencies that support future life. One of the most overlooked consequences of this manipulation is that it disconnects the trajectories and social priorities that give rise to weeds from the costs (social and ecological) of controlling or preventing them.*
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> *As such, the taxation imposed by government to prevent and/or control weeds is no longer transparently connected to the dislocating human activities that give rise to weeds. The disconnecting social activities are therefore not subject to social critique. Put in economic terms, we might say that there is a "persistent market failure''. The analysis undertaken here, however, suggests that what is really persistent is a lack of ecological literacy…"*
>
> *"…The centrality of the "war'' analogy in the weed discourse largely explains why weed preventing and/or controlling, presently attracts mass market support and commands the allocation of significant social resources. For example, the wholesale value of herbicide sales in Australia for 2008-09, a drought year, was $1.1 billion. As this figure demonstrates, not only do humans invest a great deal of their time and money extracting victories "over'' nature, but they are also willing to spend a great deal of time and money "protecting'' their preferences for a limited range of life – after all, the purpose of herbicides is to efface future life that "threatens" prevailing human priorities. What perhaps needs to be understood clearly, therefore, is how partial the understanding underpinning the "war on weeds'' analogy really is. Circumspection is required….."*
> David, Low (2011)

Are weeds *Alien*?

Edward Salisbury, a Professor of Botany at University College, London, popularized the use of the term '*alien*' in his book on "*Weeds & Aliens*", published in 1961. He was also the Director of Kew Gardens in London during 1943-56 and someone who had considerable interest in weeds. The term, of course, had been used much earlier by renowned botanists in the mid-19th Century who dealt with extensive collections of plants sent to the Kew Herbarium from various parts of the British Empire. The word *alien* (from Latin, "*alienus*") means belonging to another, not one's own, strange, or foreign. The term first appears among annotations and notes on the side panels of old herbarium specimens of some species that the 19th Century botanists were examining.

Of course, those botanists knew they were studying common species and not aliens from another planet. Their purpose was not to slander plant species, but to draw attention of other botanists on the risks of introducing plants across the continents, particularly with the exchanges of live specimens among botanic gardens. Likely, they were also aware of spreading plant species along with movements of livestock, fodder, people, and military equipment, at that time. It is most likely that Salisbury followed this practice and used the term '*alien*' interchangeably with the term '*introduced*'. Some authors use the term to refer to plants becoming weedy when transferred from their native to an *alien* environment, meaning a new environment. Here, while the emphasis is on the new environment, the organism is also regrettably branded as an *alien foreigner*.

This term 'alien' is now often directly attributed to Salisbury's book as if it is original. Inadvertently, he has indeed, given those who dislike weeds and want 100% control of colonizing species the perfect weapon! Taking the cue from him, other senior botanists also used the term, as Hiram Wild, a renowned botanist from South Africa did in discussing *Weeds and Aliens in Africa* and their origin, as potentially *'American Immigrants'* (Wild, 1967). Peter Kloot (1983), an Australian botanist, also borrowed the term for discussing naturalized plants that had been introduced to South Australia from overseas. The term '*alien*' is superfluous in both these historical publications for their key botanical messages.

I often wonder why I hadn't heard these phrases while studying in the School of Plant Biology, University of North Wales in Bangor, U.K. One explanation is that John Harper (see Harper, 1960) and other leaders of the relatively new Plant Biology School those days, considered it an unnecessary embellishment and consciously kept such words out of the discussions in the nurturing of their students.

'*Invasive Aliens*' – a misleading narrative

The concept of 'invasive species' was first raised by the British Ecologist Charles Elton (Elton, 1958). His landmark treatise prophetically suggested that some animal and plant species may spread widely across continents, and potentially "invade" (he really meant, 'colonize') other bio-geographical regions, which are non-native to the original populations.

This term '*invasive*' only became common in *Weed Science* in the late-1980s and it was primarily in the USA (Davis, 2011). I can safely vouch that in the early-1980s, in the UK, it was sufficient to refer to the plants with colonizing abilities just as 'weeds', until the narrative changed. The proceedings of two of the most influential milestone events in the evolution of *Weed Science* as a discipline, put more emphasis on understanding the global spread of weeds and other animals as part of ecological phenomena of plant succession, adaptations and colonization. These books rarely mention 'invasions' in the sense that the term is used nowadays (see the edited books - Harper, 1960 and Baker and Stebbins, 1965).

Following everything American as good is a well-known populist trend, partly due to America's overwhelming economic success and its flow-on effects on the rest of the world. It is undeniable that other countries try to emulate the economic success of the USA and, at the same time, follow American trends without too much thought on their potential socio-cultural effects impacts. Samuel Huntington (1996, p. 310) questioned the potential negative impacts of following everything American, as below:

> *"…Awareness of cultural diversity will lead to understanding and perhaps to challenging the Western, particularly American, belief in the universal relevance of Western culture. This belief holds that all societies want to adopt Western values, institutions, and practices. If they seem not to have the desire and are committed to their own traditional cultures, they are, in the view of many, victims of a false consciousness.*
>
> *Normatively, the Western belief posits that people throughout the world should embrace Western values and culture because they embody the highest, most enlightened, liberal, rational, modern, and civilized thinking of humankind. The Western belief in the universality of Western culture suffers three problems: it is false, it is immoral, and it is dangerous to agricultural progress…"*

Some colonizing plants and animals are now permanently branded as '*invasive species*' because they are capable of successful colonization of new environments. Absurd parallels are drawn with military invasions. In the 1990s, another adjective was added to brand the successful colonizers as '*Invasive Alien Species*' (IAS). The combination of the two terms has been a real game-changer, the second adjective adding a potent but distasteful dimension to an already highly-charged term. With this acronym, there are significant amounts of funds doled out to various bodies to manage the *alien* invader armies, which are rapidly moving across the globe, threatening our existence. Exaggeration is a true reflection of the times we live in, to which this narrative fits well. Nowadays, most issues are prosecuted with hyperbole, instead of thoughtful reflections on the effects emotive words would have on the public.

The term IAS spread fast in English-speaking, 'Westernized' countries, including New Zealand, Australia, the USA and Europe. Regrettably, it is also commonly used in the largely non-English-speaking Asian-Pacific countries, which chose to follow the 'trend' rather than question its scientific basis. The flippant way in which the term is thrown around at weed conferences and also by the media indicates that now we really have a problem on our hands!

Even words and concepts evolve with time. Perhaps, an improved understanding of how some highly successful weeds and animal species can spread rapidly across the globe, crossing borders with or without assistance from humans, may have led some genuine researchers to call them 'invasives', invoking Charles Elton's thesis. But much more likely, it is an artifact of the fierce competition for limited funds, globally, for research. To get a piece of this funding, the narrative must change to fit the prevalent thinking of the time, or a new narrative must be devised, and overstatement helps! Nonetheless, some credit must go to the proponents for placing the human agency at the centre of the argument. The IAS narrative (Convention of Biological Diversity, CBD, 2001) recognizes that disturbed habitats, colonized by these '*alien*' invaders have often been wholly or partially created by man, whose activities are also largely responsible for their global spread.

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Who are these *alien intruders*? Why do we have to use such dramatic words, which have potency to create fear and apprehension? How unfortunate is it that these terms have not been challenged enough by weed scientists? Is it because we fear of retribution and castigation by our scientific peers? Imagine the confusion on the minds of undergraduate biology students if the Ecology teacher does not correctly explain how these terms came about? I know of many weed scientists who are awestruck by these terms, and just go with the flow. Presently, I can only direct them not to be captivated by these powerful words but get more acquainted with the evolution of the terms (see discussions in Colautti and MacIssac, 2004; Shackleton, et al., 2019), the context of their use, and more broadly, on the history of *Weed Science*, well covered elsewhere (Timmons, 1970; Wyse, 1992).

It is quite clear that 'invasion ecology' has enjoyed a rapid ascension in the public domain, owing in part to the extensive use of powerful adjectives like 'invasive', 'alien', 'noxious' and 'exotic' (Colautti and MacIssac, 2004). A species is considered 'native' if it has existed in a given biogeographical area for an extended period of time, and/or if it has undergone significant evolutionary changes in this area, over a long period of time. 'Exotic', 'non-native' and non-indigenous species (NIS) are simply the opposites of 'native'. However, it is not easy to determine which plant species is 'native' to a region, or 'naturalized', and to differentiate native from non-native species.

The confusions and loose terminology lead to the unscientific branding of potentially useful taxa as some sort of villains. Besides, not everyone is convinced that the maligned 'invasive' plant species are harmful to the environment all the time (see discussions on Davis and Thomson, 2000; 2001). Many of the so-called 'invasive' species are highly beneficial to not just humans and animals, but also to the environment, under certain situations.

Mark Sagoff, an environmental philosopher, challenged the idea that 'non-native', 'exotic', or introduced species cause widescale ecological harm in the new environments to which they have been either deliberately or accidentally introduced. He also decried the use of pejorative terms in this discourse, which go against scientific norms, as follows:

> *"…Are non-native species harmful? That depends on your perspective. That non-native species harm the natural environment is a dictum so often repeated that one may assume it rests on evidence. It does not. Biologists often use pejorative terms such as "pollute," "meltdown," "harm," "destroy," "disrupt," and "degrade" when speaking about non-native species. These words, along with metaphors borrowed from war and from cancer pack political punch.*
>
> *"…Insofar as they convey aesthetic, moral, or spiritual judgments, they have a place in political debates and policy discussions. What troubles me as a philosopher is that these value-laden terms and their underlying concepts pervade the scientific literature of conservation biology and invasion ecology. These concepts are not well defined; generalizations based on them are not tested. Indeed, if you try to prove that invasive species harm natural environments, you'll find your-self in a scientific maze of dead ends and circular logic…"* Mark Sagoff (2005)

A longer discussion on the topic is beyond this Editorial However, my view is that the term 'invasive' has been used within the 'invasion' biology theme as a descriptor of a specific capacity that an organism has (i.e., capability to colonize and establish), rather than to describe an ecological phenomenon. Objecting the overreach of the 'invasion' biology theme, Mark Davis (Davis, 2011), also strongly expressed his view, with which I agree:

> *"…Focused and persistent research will always be able to document some adverse effects of any species, native or non-native, on at least some other species. However, even if negative effects on other species are documented, ecologists should not feel empowered to declare a species to be "invasive" (harmful). Declaring harm is a value-based social decision, one that needs to be made through collaboration with the*

larger citizenry. This is not a scientific decision, even if scientists are making it..."

"…But for 30 years, it has been primarily invasion biologists, not their critics, who have been telling just half the story. Only recently has a more balanced perspective begun to emerge, a perspective the public needs to hear, since it is usually the public's resources that are used to manage these species..."

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Regrettably, there is still much confusion about the terminology in the IAS narrative. Despite objections, the provocative metaphors are still widely used in the discussions on weeds, misleading the public. The dominant discourse may also confuse young weed scientists. Therefore, it is time for *Weed Science*, as a mature discipline, to make a change in the use of the term 'invasion' to the more ecologically correct term 'colonization', which is a component of plant succession. Revisiting the attributes of successful colonizers (Baker, 1965) would make people understand weeds better. Attention should then focus on the processes by which weedy taxa 'colonize' new habitat. If one understood the factors that determine the outcome - success or failure of those colonization attempts - that would undoubtedly be helpful in how we may respond to an undesirable colonization event.

Can we change attitudes?

The hardened attitude towards colonizing plants (weeds) in many countries is due to the profits that can be made by landholders through farming. Despite agricultural production representing only a declining percentage of gross domestic product (GDP) in most countries, farmers, particularly in the developed countries form powerful political constituencies and lobby groups. Many growers and farmers who are wary of weeds have deeply entrenched opinions. They often mistrust alternatives and resist change because of personal experiences and biases, as well as property-related and economic factors. Pure and simple, it is a question of money.

Shifting the emphasis of weeds from '*foe' to friend*' requires vigorous campaigning by enlightened scientists, working within or outside governments. Presently, this view is championed mainly by popular websites and patrons of sustainable lifestyles who have not much to do with governments. However, recognition of the potential for utilization of weeds as bioresources by governments in different countries is necessary to have a broad societal effect. Relaxing the attitude towards colonizing species will come with time, but this can be hastened by economic incentives to manage weeds as part of the biodiversity within individual farmlands and vast farming landscapes, rural areas, or countryside.

The collective wisdom of all weed scientists and weed managers across continents may be required to bring about a change in farmers' mind-set, as well as an attitude change among landholders and governments. The recognition of biodiversity values of weeds and the tolerance of beneficial weeds in arable weeds has been recommended in European countries (see Marshall, 2002; Marshall et al., 2003; Storkey, 2006; Storkey and Westbury, 2007; and discussions in Chandrasena, 2007; 2014).

As far back as in 1980s, agro-ecologists Miguel Altieri and Matt Leibman built the case to argue that eliminating *all* weeds from the farming ecosystems can destroy valuable habitat for natural enemies of insect pests, and thereby increase costs for insect pest control (Altieri and Leibman, 1988). Stamping out weeds may even contribute to human malnutrition. In developing countries, replacing traditional poly-cultures that tolerate or even encourage some weed growth with large scale monocultures and near-100% weed control has undermined food security in rural communities (Altieri, 1999). In addition to posing threats to local food production, industrial-scale farming eliminates palatable, nutritious weeds from farmers' fields, robbing low-income communities of important sources of dietary vitamins and minerals. Many rural societies depend on edible weeds for food before their traditional crops mature, and especially in the event of crop failure. Such food systems are not served by an 'all-out war' against weeds.

There is a great deal of evidence of colonizing plants as some of the most useful medicinal plants in traditional medicine, as well as the sources of many modern pharmaceuticals. Although there is a general belief that the primary tropical forests, undisturbed and mystical, are the most likely habitat to discover new pharmaceuticals, perhaps because of their high biodiversity and endemism. However, the evidence from many traditional cultures is that this may not be true as they predominantly rely on non-forested, disturbed habitat for their medicinal plants (Voeks, 1996; Stepp, 2004; Stepp and Moerman, 2001). Stepp's (2004) analysis of 101 plant species from which 119 modern pharmaceuticals are derived, showed that at least 36 species are widely regarded as weeds. The results were an order of magnitude higher than would be predicted by random occurrence of weeds in the modern pharmacopeia.

There is mounting evidence that weeds are relatively high in bioactive secondary compounds and are, thus, likely to hold promise for future drug discovery. Secondary compounds in weeds perform a variety of ecological functions. Chief among these is allelopathy, where such compounds may inhibit the germination and growth of neighbouring plants and also act as chemical defences against herbivory. Many weed species interfere with crops through the release of allelopathic secondary metabolites. However, because allelopathy usually occurs through the complex chemical matrix of the soil, it has been hard to show a causal relationship (Zimdahl, 1999) conclusively. Thus, disturbed environments, even within forests, which are the province of colonizing species, appear to be areas most likely to harbour novel compounds that may become future medicines.

Colonizing species will always be the ultimate survivors in the conflict with man. Rather than a zero-tolerance towards particular taxa, it would be prudent and responsible to ecologically manage problematic weeds, on a 'case-by-case' basis, with an eye on their potential benefits. This requires moving away from autecological, 'species-led' approaches that are reactions to problems posed by single species. The agroecology practices promoted by Altieri (1999) are invaluable ecological risk management models, in the sense that they have long-proven benefits in ecosystems. Agroecology also encourages people to integrate closely with all components of biological diversity, including colonizing species.

An Ethno-biological perspective- Linking Plants and Humans

In discussing the relative variety and intensity of uses of common reed (*Phragmites australis)* by human groups, Kiviat and Hamilton (2001) suggested that the utility of a plant is related to several factors. These include (1) abundance and distribution of the plant; (2) length of time the plant and a human group have been in contact; (3) invention or transmission of traditional ecological knowledge of the plant; (4) ease of managing, acquiring, and processing the plant; (5) physical and chemical qualities of the plant (e.g., pharmaceutical or toxicological properties, fibre characteristics, nutritional composition); and (6) availability and variety of alternate taxa. These ideas reveal why some taxa are much valued, and others much disliked. Discussions of such ethnobiological perspectives would help in building better relationships between weeds and humans, particularly in developed countries where the conflicts between the two are most profound.

The importance of traditional cultures, their wisdom and sustainable interactions with plants and animals are routine subjects in Anthropology, and Social Science. Interactions between the humanities and *Weed Science* are almost non-existent and hence, both sides may gain from a closer exchange of views. Journals dedicated to Ethnobotany and Economic Botany often carry articles relating to human uses of colonizing plants. Increased appreciation of plant taxa can be achieved by studying these ethnobiological appraisals, as well as by exercising more common sense. Improved ecological knowledge and an understanding of a broader range of cultures, societies, and plants of value to humanity may assist those who apply 'weed risk assessments' when deciding whether or not to list particularly resourceful taxa as 'invasives' that should be controlled at any cost. I object to the presumptive 'branding' of taxa, carried out by bureaucrats, which tends to stick in the minds of the public. Applying '*a guilty until proven innocent*' approach to taxa with colonizing abilities, as practiced in some countries, belies common sense. It is also disrespectful to Nature and may not be tenable for long.

In a study in semi-arid areas of Brazil, Dos Santos *et al*. (2013) posed a series of questions: "*Are invasive species considered useful by traditional societies? How are they useful? Are they more or less useful than non–invasive species? Is there a relationship between the use categories and taxonomic groups (families, genera, and species)? What plant parts are preferentially used and how are they distributed by categories of usage? Are there differences in the perceived usefulness of native vs. exotic invasive plants?*"

In their study, a total of 56 invasive species were recorded, of which 55 were considered useful, and invasive species were considered useful more often than non–invasive species. The predominant use was as animal fodder, followed by medicine, food, and raw materials for industries. Nearly half (44%) of the animal fodder species also served as medicine for people. Herbaceous plants were the most common. Uses varied significantly within taxonomic ranks (species, genus, and family). The most recognized plants were also those that were most used locally. This study, just one of many from different countries, underscores the value of invasive species (weeds) in semi–arid Brazil, as well as the need to include local people in regional and national strategies to address invasive species management.

Weeds and Humans– the future

There is no simple remedy for the weed problem in its many manifestations. Therefore, we need to continue our studies on the best management strategies and control tactics to manage their negative impacts. As a discipline, *Weed Science* does understand quite well the reasons why colonizing species come to dominate landscapes. Weed management approaches need to be designed to prevent the introduction of potentially problematic taxa to new habitats and to provide rapid responses to minimize undesirable impacts where conflicts arise between man and colonizing species. I believe that this will be done best with a proper ecological understanding, and with a balanced view of economic implications, but without dramatizing weed issues, and certainly avoiding messages that create a visceral dislike for the colonizing plant taxa.

Evidence-based policy making is a sound goal in any country. However, only a small proportion of agricultural or environmental research has had the desired policy impacts. Most researchers in science are not trained to create policy effects from their work. Engagement with policymakers is not always encouraged, nor is it rewarded in most settings. Communication of scientific findings occurs mostly within the academic community; rarely outside it. There are exceptions, but across the various fields of human endeavour and mainly in science, little is done to link scholarship to policy systematically.

To exemplify, utilization opportunities for weeds is a topic not readily discussed at weed conferences. Is this because of some fear? Is it because weeds are so problematic that looking at them with a fresh set of eyes goes against the grain of *Weed Science*? I tend to agree with others (R. Zimdahl, 2019, *personal communications*, 28 December) who believe that it is mainly an educational problem. Nevertheless, there is a strong case building for investments in the utilization of weeds not least because it is a sensible weed management practice, but also because it provides a positive message for the public on the values of these plants, so severely mismanaged across the globe. Making a case for the utilization of weeds as bioresources is not difficult (see Kim and Shin, 2007; Chandrasena, 2007; 2014). The compilation of existing knowledge from different cultures should assist this task and, there is much to learn from the existing Economic Botany and Ethnobotany knowledge. A renewed attempt to explore weeds as bioresources requires efforts to highlight how traditional societies use all available knowledge of colonizing plants wisely and 'co-exist' with them.

Conclusions

A vast amount of global scientific literature indicates that man has not looked after the Earth's natural resources well. Most findings are that depletion of natural resources (soil, water, and vegetation) is almost unstoppable, and many resources, including tropical rain forests, are being depleted at an alarming rate and will soon reach unrecoverable levels. Continuing population growth in many parts of the world and the quest for profits from growing crops or over-exploiting natural resources (such as minerals, oil and gas and timber) remain the *root causes* of the high rate of biodiversity losses and depletion of those natural resources – not weeds! It is men – and not weeds – who face a profound dilemma.

Kenneth Bolding, an economist at University of Colorado said: "*Anyone who believes exponential growth can go on forever in a finite world is either a madman or an economist*" (see quote in NEF, 2010).

Agreeing with those sentiments, Tim Jackson (2012), a Professor of Sustainable Development at the University of Surrey, argued that the human society is faced with a profound dilemma: '*to refrain from growth is to risk economic and societal collapse; to pursue it relentlessly is to endanger Mother Earth's ecosystems on which our survival depends*.

Science tells us that weeds are only 'colonizing plants', and their management will be best undertaken within an ecological framework. Wherever or whenever man disturbs a habitat, they will be among the first *pioneers* to make use of the opportunity of space (*sensu lato*, Bunting, 1960). Downplaying this ecological emphasis, because of a focus on weed control, is disingenuous. In natural or man-made ecosystems, many weeds serve valuable ecological functions that need more recognition. Examples of their complex biological role, such as providing resources for wildlife, pollinating insects, slowing erosion, building soil, and generally enriching biological diversity, are abundant in global literature; these need to be studied more and given more extensive publicity. In a strategic approach to managing weeds, more people – weed scientists and students – should explore different ways of using these taxa for improving the human condition.

The summary condemnation of plant taxa, because we dislike them in particular situations is not a sensible way to approach a complex man-made problem. The genetic attributes of weeds that confer superior colonizing ability, competitiveness, and survival could be beneficial, not just in repairing damaged ecosystems, but also in sustainably providing food and fibre for both humans and animals. A key to sustainable living is to *learn from weeds* to be more resourceful and *not ask for more*. If all men become thrifty, and asked for less, we could reduce our environmental impacts, both as individuals and as societies. Such a change would make our Earth a much safer place for all species.

To end this Editorial, I would pose the following questions to all weed scientists: ‘*Would you live in a world free of weeds*? Or, would you cherish understanding how our complex interactions with weeds will enrich our lives?

In an environmental ethic that all life is sacred, weeds are no more villainous than man himself!

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PERSPECTIVE

Sustainable Agriculture and Environment - An Ethical Perspective

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Abstract

Agriculture is the largest, most important interaction between humans and the environment. It is an essential human activity. Humans, the Earth's dominant species. Usually, know what we are doing, but we often do not know what we may be undoing. This paper will briefly address some of agriculture's major problems: sustainability, land, production, water, antibiotics, genetic modification, and technology. It asks two questions: How do you know what to do in agriculture and life? How do you know what you choose to do the right thing to do?

Keywords: Agriculture, ethics, philosophy, production, values, Weed Science

Introduction

In my younger years I tried to develop some expertise as a weed scientist. I studied the kinetics of herbicide degradation in soil and weed control in agronomic crops. It was interesting and enjoyable work but because of the issues raised by the Vietnam War, Agent Orange, the environmental movement, and the development of organic agriculture, I was compelled to begin to study moral philosophy.

Philosophy attempts to achieve a wide perspective of life and reality. We study history and philosophy to find out what man is, which we can't learn from science. Philosophers who study moral philosophy and ethics don't tell us what is right and wrong. They show us how to think about what is right and wrong. Today the family has been weakened, religion has been weakened, our educational system is discouraged by class and race war, public opinion loses force through division, fear, apathy and worship of wealth. Even sex seems to be in chaos.

Whether one lives in a developed or developing country, whether one is rich or poor, male or female, formally educated or not, we live in a post-industrial, information-age society. We live in an era of scientific achievement and technological progress, unequalled in human history, which has created the good life many of us, but not all, enjoy and some of the problems from which we suffer.

The achievements include: waking up in the morning to music from your cell phone, preparing breakfast in your microwave as you review the news on your tablet computer, which gives you nearly instant access to information that is orders of magnitude greater than the resources of most of the world's libraries. Many benefit from medical advances that cure what used to kill or cripple. Immunization prevents childhood diseases. Smallpox has been eliminated and polio may be in the near future. We routinely travel at speeds and convenience that were unknown to our grandparents. Finally, for many, but sadly not for all, there is abundant food.

The problems include global climate change, which affects mean temperature, rainfall amounts, and seasonal distribution. Pollution of all forms; social inequality - 26 people on earth are worth the collective labour of more than three billion; and environmental degradation. Agriculture's additional problems and challenges include maintaining production, managing pesticide resistance, loss of biodiversity, and invasive species, addressing concerns about biotech/GMO's, and sustainability. Many know and benefit from the achievements of agricultural science but are concerned about the problems the science and technology have created

We live in a world where progress is frequently equated with growth, which is generally regarded as good. Many want more of the good things of life. We expect the future to be bigger, better, easier, and faster. Many aspects of our lives are changing faster than we are able to keep up.

We may not always know our destination, but we are going there in a hurry. We believe in the efficacy of science and technology, which promises to solve the problems of society, agriculture, and industry. Many involved in agriculture believe that development and use of more and more energy dependent technology is always good and more will be better. The problems caused by the unintended consequences of technology will, many are certain, be solved by improved technology.

We may not always know our destination, but we are going there in a hurry. We believe in the efficacy of science and technology, which promises to solve the problems of society, agriculture, and industry. Many involved in agriculture believe that development and use of more and more energy dependent technology is always good and more will be better. The problems caused by the unintended consequences of technology will, many are certain, be solved by improved technology.

I do not mean to imply that we should abandon science and technology. We humans, the earth's dominant species, are not just figures in the landscape — we are shapers of the landscape (Bronowski 1973, p.19). Having achieved this power, we should think carefully about whether our shaping of the landscape is desirable and sustainable. Although we often know what we are doing, we should consider what we may be undoing. We must develop in ourselves and our students critical thinking about the moral dimensions of what we do and undo.

With that brief introduction I ask two questions (Zimdahl, 2012) that I frequently ask myself: How do you know what to do in agriculture and in life? And how do you know what you choose to do is the right thing to do? How do we decide what to do?

Norman Borlaug (2000 winner of the World Food Prize and Nobel Peace prize - 1970) cautioned that "…agricultural scientists have a moral obligation to warn the political, educational, and religious leaders about the magnitude and seriousness of the arable land, food, population, and environmental problems that lie ahead..."

Agricultural scientists pride themselves on the achievements of the green revolution, but they have not addressed the existing moral problems. The reason for ignoring them was that the costs associated with pollution, environmental damage, and harm to human health were justified by the production benefits. The problems caused by pesticides were unintentional developmental problems (Atreya et al., 2011). Since the mid-20th century the quality of agricultural science in the US has been evaluated almost exclusively in terms of its ability to deliver technological innovations. Agricultural scientists have improved crop production. However, when they claim credit for improving production and keeping the cost of food low, they must also accept society's right to hold them responsible for problems they have regarded as externalities[1.] Agricultural people need to ask and be prepared to respond to what they have not asked often enough—what could go wrong?

Agriculture, the essential human activity, is our most widespread interaction with the environment. We live in a post–industrial, information age society, but no one will ever live in a post-agricultural society. Continuing to justify all of agriculture's activities and technology by the necessity of achieving the moral obligation and the production challenge of feeding a growing population has not been and will not be a sufficient defense for agriculture's negative environmental and human effects (Mann, 2018).

[1] An externality is a cost that is not reflected in price, or more technically, a cost or benefit for which no market mechanism exists. It is a loss or gain in the welfare of one party resulting from an activity of another party, without there being any compensation for the loss. From a self-interested view, an externality is a secondary cost or benefit that does not affect the decision-maker.

Humans, the world's dominant species, are no longer just a part of nature; we are a force of nature "…that is disturbing and changing the climate and our planet's ecosystems at a pace and scope never seen before in human history…" (Friedman 2016, p. 87). "…We cannot rebuild the Greenland ice sheet, the Amazon rain forest, or the Great Barrier reef or the Koalas. When the macaws, the rhinos, and the orangutans are gone, no 3D printer will bring them back to life…" (Friedman 2016, p. 183).

I am compelled to add at this point that cultural diversity challenges the Western, particularly American belief, in the universal relevance of Western culture (Huntington 1996, p. 310). This belief holds that people in all societies want to adopt Western values, institutions, and practices. It suggests that people throughout the world should embrace Western values and culture because they embody the highest, most enlightened, most liberal, most rational, most modern, and most civilized thinking of humankind. It is my view that the Western belief in the universality of Western culture suffers three problems: it is false, it is immoral, and it is dangerous.

Concerns about Agriculture

1. Sustainability

Everyone is in favour of sustainability. Within the agricultural community to sustain usually means protecting the productive resource (soil, water, and gene pools). It is not clear why that legitimate goal always outranks sustaining environmental quality. Agriculture has a major responsibility because it is so widespread and has the potential to care for or harm so much land. This is a different view from protecting only the productive ability of land. Because of increasing urbanization, there will be less land to feed the expected 9+ billion who will soon be here. We create places for people to live and simultaneously destroy agricultural land. Concrete is the land's last use.

Land must be regarded as something more than other productive resources (fertilizer, machines, irrigation water, pesticides, or seed). To harm or destroy the land is to destroy something essential to life, and that certainly raises a moral question.

The pursuit of agricultural sustainability is commonly viewed as mainly or wholly a technical problem that simply requires changing farming methods and adopting new, alternative technologies. Agricultural system sustainability will not be accomplished by tinkering at the fringes with new technology. It will require re-thinking how we practice agriculture and emphasizing more than production.

Some believe that current agricultural practices may threaten future global food security and will have negative effects on global food production (Liu et al. 2015). The total agricultural area has decreased since 2000, pesticide consumption has increased, water use efficiency has increased. Available water sources are already being used for irrigation. In the US, 60% of irrigated crop production depends on groundwater (Siebert et al., 2010). It is forecast that agriculture's demand for water could rise to 10 to 13 trillion cubic meters by 2050, which is two and a half to three and a half times greater than the total human use of freshwater today (Fox and Fimeche, 2013). Water use for agriculture peaked in 1980 and has decreased every year since due to improved irrigation system efficiency, in spite of an increasing number of acres irrigated (Donnelly and Cooley, 2015).

Economic growth has acquired the power and scope of a new religion and it drives agricultural expansion (Worster, 2016, p. 147). Should there be limits to agricultural expansion?

2. Pesticides

The agricultural enterprise uses a vast array of synthetic organic chemicals to manage insects, weeds, fungi, and other organisms that sometimes just bother, and other times may cause significant yield losses and harm to humans. Pesticides have made it possible to feed a growing human population and protect millions of people from malaria and other insect- borne diseases. Of the pesticides used in the world, 80% are used in agriculture: approximately 40% are herbicides — (Kraehmer et al., 2014), 33% insecticides, and 10% fungicides. Sales and use have been expanding rapidly throughout the world, although the development of new modes of actions has become rare (Lamberth et al., 2013).

There is no question that pesticides increase crop yields and <u>may</u> harm the environment, people, and other creatures. For example, there are 42% fewer species of invertebrates in streams with severe pesticide contamination and 85% fewer new queens in beehives exposed to pesticides. Pesticides have been aggressively promoted and are generally accepted within the agricultural community, as essential to maintaining yields and feeding a growing world population. There are also legitimate global human rights concerns because of their detrimental effects. The UN General Assembly (2017) report denies the claim that pesticides are necessary to feed the world and regards them as a short-term, unsustainable solution.

A common view among the general public is that synthetic, organic chemical pesticides are dangerous, overused, and should not be present in food, soil, and water. It is also widely acknowledged within the agricultural community that they have made our lives easier and more enjoyable by reducing mosquito, ant, and cockroach populations (Enserink et al., 2013). In spite of the 2015 conclusion of the International Agency for Research on Cancer that glyphosate probably causes cancer, more than 94% of soybeans and roughly 90% of cotton and corn grown the United States are resistant to glyphosate. In 2000 in the US, 287 million pounds were sprayed - 20 times more than in 1992. Roundup's sales have proved resistant to lawsuits.

Modern pest management is highly dependent on pesticide science. Weed science has been slow to "catch up" with progress toward precision agriculture that has been made in irrigation and fertilizer management (Reddy and James 2018). It is clear from any current issue of Weed Science and Weed Technology that herbicides continue to dominate weed science research and lead to one of agriculture's moral dilemmas. True integrated weed management requires a high level of plant ecological and biological knowledge, technological machinery, and decision-making algorithms that can respond rapidly to changes in weeds and the environment Young (2018).

3. Antibiotics

There is great concern about the increasing incidence of poor performance of antibiotics for treatment of human diseases due to bacterial resistance because of their use in livestock enterprises. It is estimated that approximately 80% (a disputed number) of all antibiotics used in the US are fed to farm animals.

There is disagreement about the quantity and patterns of antibiotic use in food animals. These very effective, necessary medicinal products originally developed to protect human health, have become less and less useful as resistance to them has become more common due to widespread use in animal/poultry production for disease prevention and growth promotion and over-prescribing for human problems. It is estimated that global antimicrobial use in food animals could increase 67% by 2030 (Van Boeckel et al., 2015) One can argue that antibiotics helped to create modern agriculture and changed the way we eat (McKenna, 2017).

4. Loss of biodiversity

There is a well-documented, continuing loss of ecological biodiversity, species, and genetic diversity. Between 0.01 and 0.1% of all known species become extinct every year. If the low estimate is correct, we are losing between 200 and 2,000 species every year. If the high estimate is correct, the earth is losing between 10,000 and 100,000. The earth is undergoing a sixth extinction (Kolbert 2014). Between 1.4 and 1.8 million species have been identified. We don't know how many more there may be. One estimate is 8.7 million species on our planet. The high estimate is 100 million. It is important to know that we don't know how many species the earth has. Therefore, it is hard to know how many are being lost. Scientists estimate that we are losing species at a rate 1,000 to 10,000 times higher than the natural extinction rate, the rate that would occur if humans were not involved.

5. Biotechnology and GMOs

The first genetically modified crops were planted in 1996. The initial global area was 1.7 million ha. In 2019, after 23 years, the biotech area is 2.5 billion ha - the most rapidly adopted crop technology in recent times. Agricultural scientists have been using conventional plant breeding techniques to improve food crops for hundreds of years to create plants that have higher yield and are more responsive to fertilizer. However, an intense debate continues about GMOs. Both sides are convinced they are right, and the others are wrong, at least partially misinformed, and don't understand. Many argue that misinformation and over-regulation are stopping or slowing GM foods with the potential to save lives. They claim that the technology is proven, and rigorous safety studies have been done. Partisans on both sides are convinced they are in an all-or-nothing battle.

The proponents have faith that limitless technological progress will finally solve the problem of feeding a growing population. Science will solve the problems. Others deny this and claim that "it is likely that there will be a permanent difference in opinion that cannot be solved with more data or new facts"

(Mampuys and Brom, 2015). Others remind us that many of those who see only the benefits of biotechnology do not remember or refuse to acknowledge, that nature "…requires respect, a kind of reverence, and deference before Nature's ultimately mysterious forms and processes…" (Berry 2017, p. 211).

I suggest this is correct and reflects past optimism about human and environmental safety, which was proclaimed by the agro-chemical industry and, which was ultimately proven to be wrong. The current strategy is unlikely to solve the problems and the focus should shift to "managing permanent different viewpoints and providing a platform for a broader conversation on agriculture and food production" (Mampuys and Brom 2015). Proponents claim that it is not unjust to use GMO's to alleviate hunger and malnutrition and achieve the goal of feeding an expanding population (Toft 2012), a reasonable argument that is weakened because more than half of the US general public (57%) say that GM foods are generally unsafe to eat. It is an enduring gap between the public and scientists and depicts a moral challenge for the agricultural community. It is not an argument to determine who is right and wrong. It should be seen as a discussion that seeks understanding between right and right points of view.

The comment of James Davidson (Emeritus Vice President for Agriculture and Natural Resources, University of Florida) illustrates the agricultural community's optimism and difficulty of responding to past errors (Kirschenmann, 2010). Davidson's comment lends support to those who believe that GMO's portend other problems which agriculture's practitioners will have to recognize and eventually apologize for.

With the publication of Rachel Carson's book entitled *Silent Spring* (Carson, 1962) we, in the agricultural community, loudly and in unison, stated that pesticides did not contaminate the environment— we now admit they do.

When confronted with the presence of nitrates in groundwater, we responded that it was not possible for nitrates from commercial fertilizer to reach groundwater in excess of 10 parts per million under normal productive agricultural systems— we now admit they do.

When questioned about the presence of pesticides in food and food quality, we reassured the public that if the pesticide was applied in compliance with the label, agricultural products would be free of pesticides— we now admit they are not.

The claim that GM crops will feed growing numbers of people in the third world has great moral appeal. It is responsible, even altruistic. But the claim is deeply misleading because it is based on the incorrect but popular assumption that we don't produce enough food to feed starving people.

People are hungry because they do not have enough money to buy food, do not have access to land to grow food, or do not live in a country where the government provides adequate help. Agricultural scientists have essentially said to the public, trust us, we know what we're doing.

6. The environment

Some claim that agriculture encroaches on and harms the natural environment (Berry, 1977; Brei, 2013, Gebhard et al., 2015). Over the last 200 years an estimated 30% of US farmland has been abandoned because of erosion, salinization, and waterlogging. Since the 1960s one third of the world's arable land has been lost to erosion. Some US crop land loses soil, the essential agricultural resource, at an average rate of 5 tons/acre/year from water and wind erosion (Jackson, 2000).

If these are only concerns of a radical fringe of society, they may be ignored. But if they are general societal concerns about agriculture that justifies everything because it increases production, then we - agriculture's practitioners - have a responsibility to ourselves and to society to confront, discuss, and debate the issues of concern - our ethical dilemmas. We must ask and be willing to discuss whether or not production is a sufficient criterion. Does increased production justify all agricultural practices?

Concluding Comments

Within the agricultural community, feeding the 9+ billion is the primary, if not the only, goal that justifies technological innovation. Demographers agree that there will be nine billion inhabitants on the earth. They also agree that while the rate of population growth has and continues to decline the population will not stop growing when it reaches nine billion. Agriculture's practitioners and the agricultural industry must feed 228,000 more people today than yesterday.

The social, environmental, and economic costs of a developed country's capital, energy, and chemically dependent agricultural system, and the challenge of sustaining the environment and other species are recognized as important, but the necessity of increasing production dominates the agricultural domain. Feeding 9+ billion is undeniably a good thing, but is it only a production problem? The world now produces enough food to feed everyone a minimally adequate daily diet. Feeding all is partly a production challenge, but it is also a distribution, waste, and poverty problem.

It is becoming obvious to anyone who listens to, reads, or watches the news that citizens of many societies are becoming reluctant to entrust their water, their diets, and their natural resources blindly into the hands of farmers, agribusiness firms, and agricultural scientists.

Ethicists and agricultural practitioners must participate in the dialog that leads to social consensus about risks. In the past most of the risk was borne by users of the technology. Now there is widespread concern that the risks and short- and long-term consequences of agricultural technology are borne by others. Agriculturalists must begin to contribute the time and resources needed to listen and understand their positions and those of their fellow citizens. For most non-agricultural segments of society, these are not new demands. For agriculture they are. First, we must listen. Then we learn. Then we help. Only then can we lead.

Because agriculture is the essential human activity, it is essential that it rest on a firm ethical foundation. It is not just about results. The prevailing assumption within the agricultural enterprise is that technological solutions will continue to reduce and eventually eliminate hunger because the productive progress of the green revolution was proof that the key to agricultural success was faith in scientific knowledge and technological know how.

The dominant focus of those involved in agriculture is how to achieve the moral obligation and challenge of feeding the human population projected to be 10-12 billion by 2,100. However, many people throughout the world, in both developed and developing countries, have concerns about agriculture and our food system that have ethical dimensions beyond the central need to feed humanity. Agriculture's manifold responsibilities include the following:

Achieving sustainability.

Addressing corporate farming and the power and lack of transparency of agri-business and corporate food processors, the effects of and public concern about biotechnology and GMO's, the loss of crop genetic diversity, the loss of small farms and rural communities, and the nutritional value of foods provided by the food system.

Assuring future availability of surface and ground water.

Preventing cruelty to animals, exploitation and inhumane treatment of farm labour, habitat destruction, harm to other species, and pollution of water, soil, and humans.

All of agriculture is involved in ethical questions. What should be done? How should it be done? Who should be considered? The way agriculture is practiced, development projects are chosen and conducted, and the kind of research and teaching done involves scientific and ethical values and a view of a future we expect, desire, or fear. Because agriculture is the essential human activity, it must rest on a firm ethical foundation.

What is the right thing to do?

From an ethical perspective, feeding the growing world population is clearly a very good thing, but it does not absolve the agricultural community from critical, ethical examination of the totality of agriculture's effects.

What can our universities do?

A place (Zimdahl, 2000, Zimdahl and Holtzer, 2018) to begin is the classroom. The agricultural curriculum lacks courses in agricultural ethics that focus on general ethical principles, their application to agricultural issues, and ethical expectations of agricultural professionals. Such courses are available at only nine US universities with agricultural colleges. It was fifteen in 1999.

I suggest this is because those who determine curricula and advise undergraduates do not regard studying the ethical values of agriculture as important preparation for agricultural professionals. Classes on agricultural ethics and encouraging students to enrol will not alone quickly increase the emphasis on agricultural ethics. They will be a recognition of the need for agriculture to recognize and discuss its ethical dimensions. Agriculture's economic problems have focused attention on production while our education and practice have ignored agriculture's human dimensions.

I conclude with two questions and a bit of advice. How do you know what to do in agriculture and in life? How do you know what you choose to do is the right thing to do? There is no reasonable moral argument that requires you to do something you are not able to do. I suggest you are able to do something about agriculture's ethical dilemmas. As you go the way of life, you will often encounter great intellectual chasms. Jump. They're not as wide as you think.

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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.

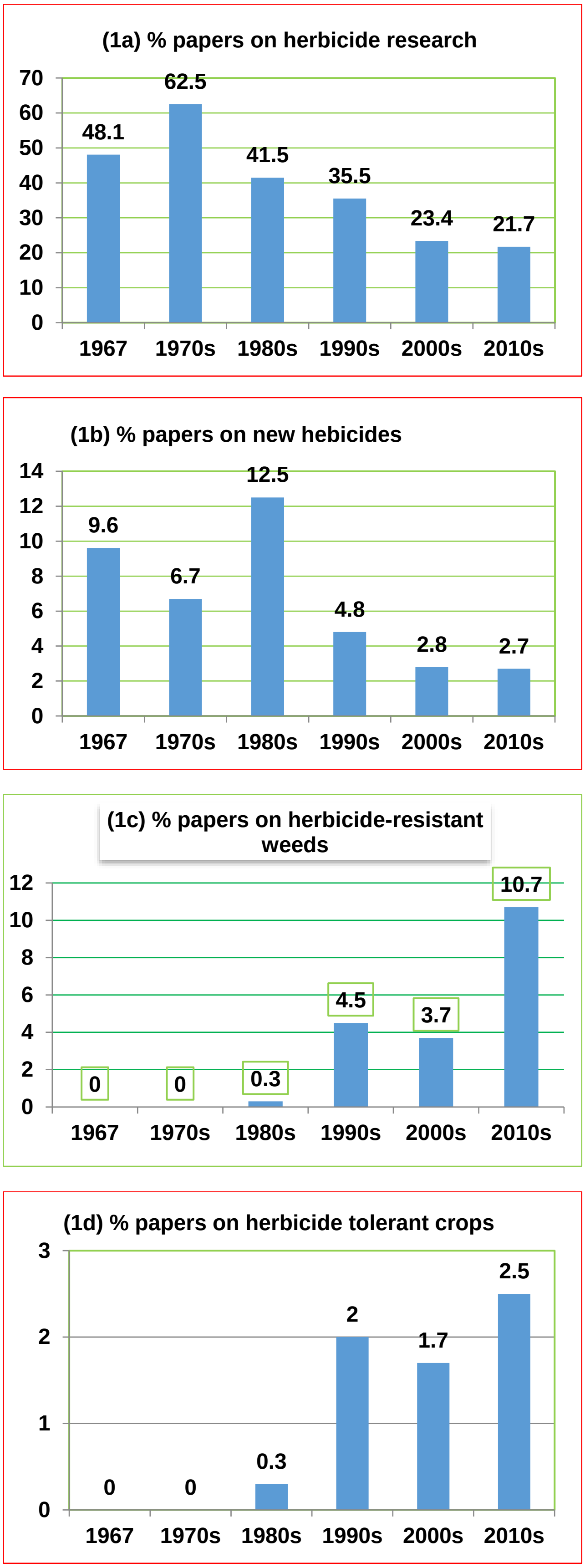


Figure 1. Trends in herbicides based weed research in the Asian-Pacific region

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).

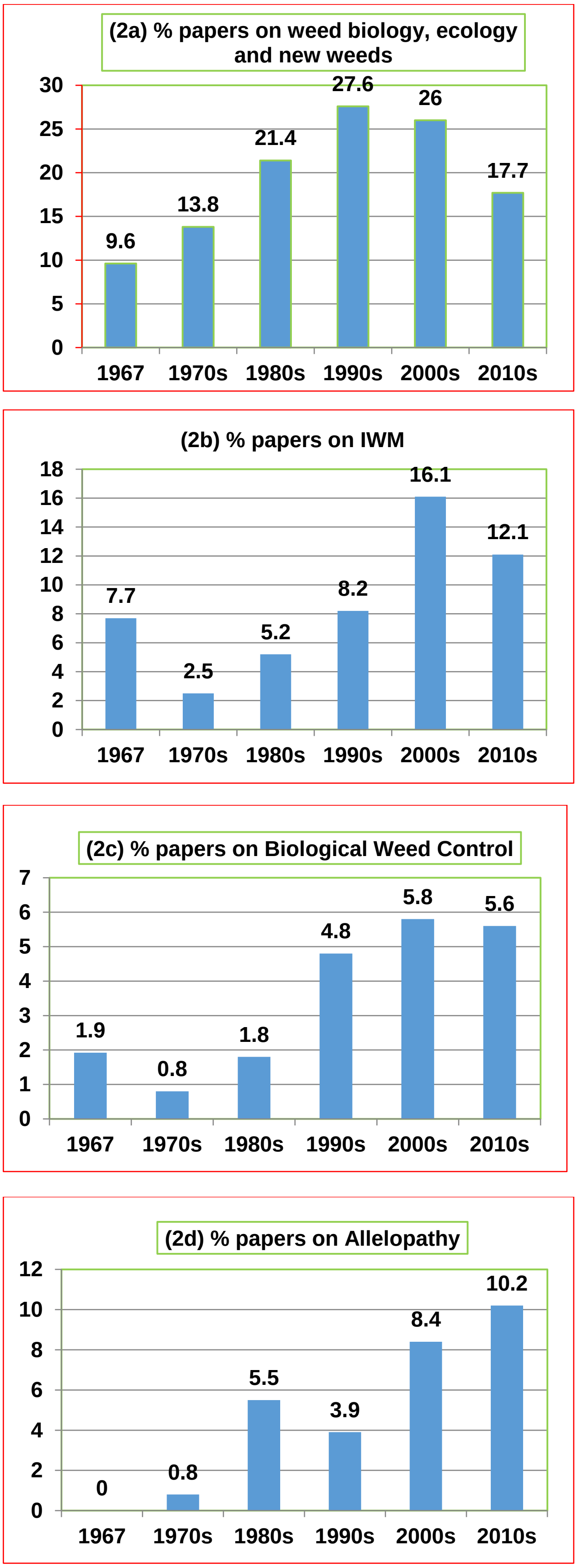


Figure 2. Trends in research on weed biology, ecology, new weeds, weed surveys, IWM, biological control and allelopathy in the Asian-Pacific region

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.

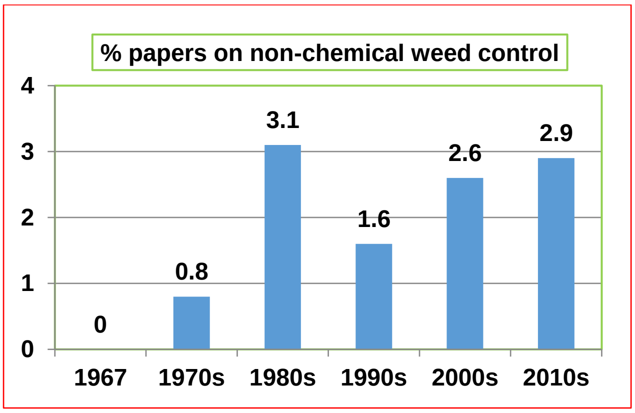


Figure 3. Trends in research on preventative and non-chemical methods of weed control in the Asian-Pacific region

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).

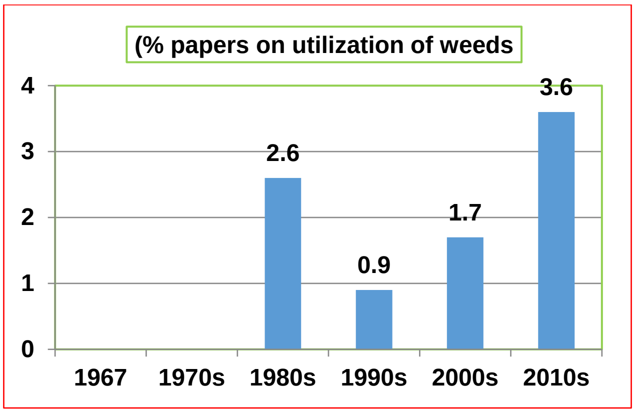


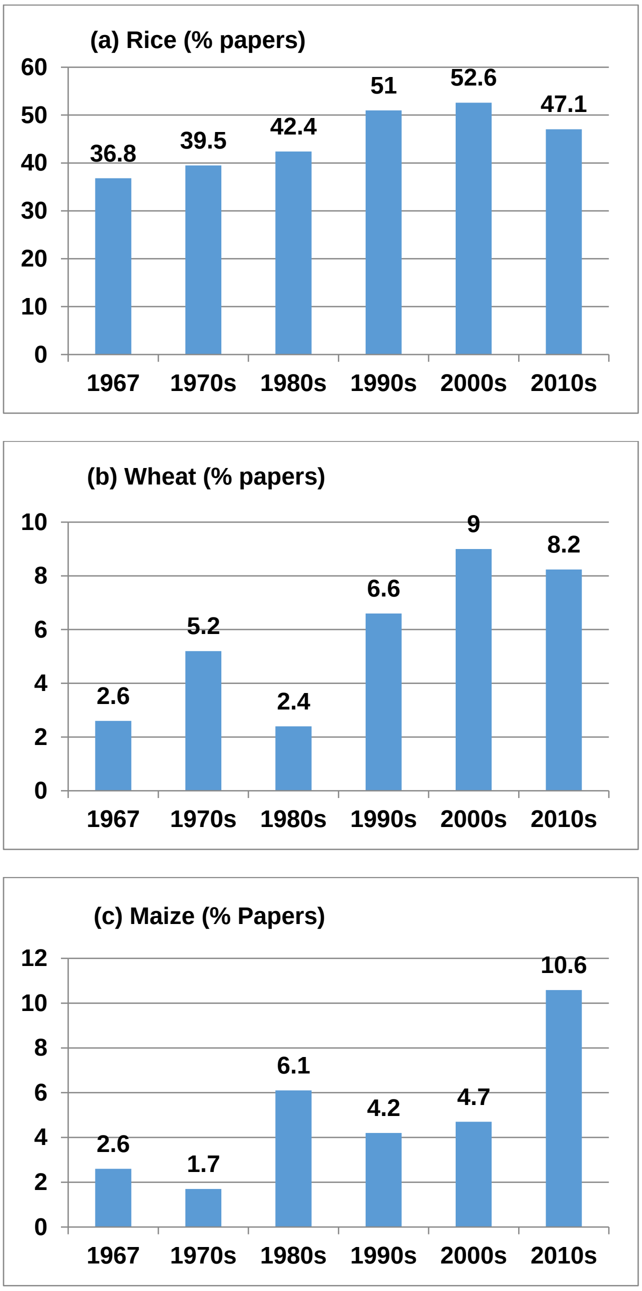
Figure 4. Trends in research on utilization of weeds in the Asian-Pacific region

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:

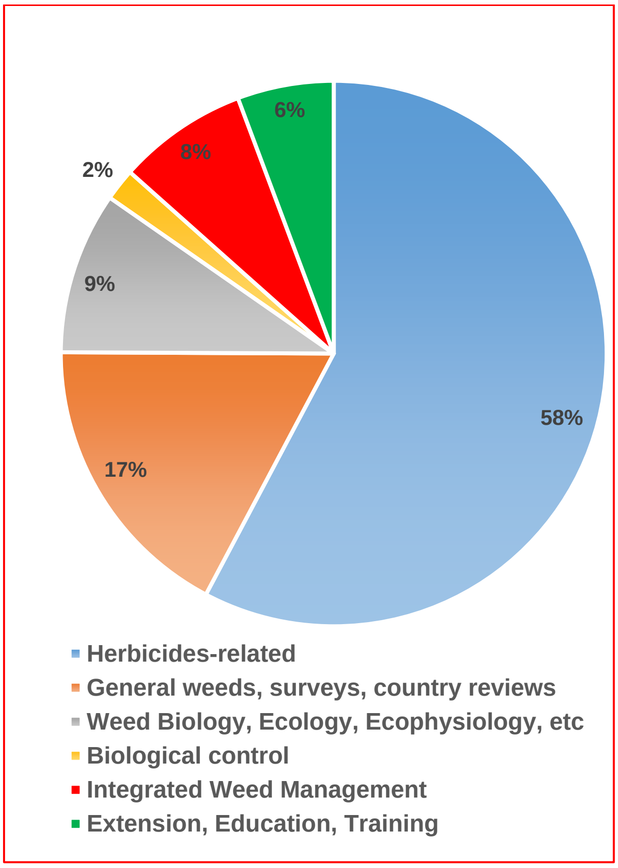


Figure 9. A summary of papers assessed in different categories of weed research (%) indicating where the Asian-Pacific efforts lie

- 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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REVIEW

Weed Biological Control: Challenges and Opportunities

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Abstract

Biological control of weeds has been conducted since 1902, resulting in over 500 biological control agents being intentionally released against nearly 200 weed species in over 90 countries. Collectively, 15 countries in Asia and 17 of the 22 countries and territories in the Pacific region have intentionally released over 80 biological control agents to help manage over 30 of their most invasive weeds. Many of these programmes, have been highly successful. In fact, globally, over a third of all weed biological control programmes have resulted in some form of control of the target weed, resulting in huge benefit: cost ratios of up to 4,000:1. In addition, there have been very few (<1%) unpredicted, sustained non-target impacts on native or economic plants by weed biological control agents. This is because biological control agents have co-evolved with their host plants and are thoroughly tested, sometimes collectively across numerous countries, against up to 280 plant species, before being released. Moreover, many biological control agents that have proved to be successful in one country have now been released in over 30 countries, with no recorded non-target impacts.

Yet, despite these successes, many countries are still reluctant to implement weed biological control. Even countries that have had tremendous successes with weed biological control in the past have shied away from implementing biological control in recent times, stating that it is too risky or doesn't work. Unfounded and unscientific statements such as "biological control agents could evolve or mutate to attack other plant species" or "climate change may affect their host range" are often used to justify not implementing biological control. As a result, landowners continue to spend millions of dollars to purchase and apply herbicides, when an integrated approach, which includes biological control, can reduce management costs and enhance control. The challenge, therefore, is to educate all stakeholders, including communities, in the safety and cost-effectiveness of weed biological control. There are numerous opportunities to introduce highly specific and very effective biological control agents from countries where they are being utilized successfully, into other countries where the target weed is problematic to help manage these species.

Keywords: benefit: cost ratios, host specificity, low-risk, integrated control, biological weed control

Introduction

Biological control of weeds has had a rich and successful history since the first intentional movement of an insect to control a weed in India in 1836 and the first dedicated programme to control a weed in Hawaii in 1902. Since then, 200 weed species have been targeted for biological control, resulting in the intentional release of over 500 biological control agents. Over 90 countries have intentionally released at least one biological control agent (Winston et al., 2014). About 66% of the target weeds have been controlled or at least partially controlled, depending on the criteria used, in at least one country where the respective biological control agents have been released (Schwarzländer et al., 2018).

Most weed biological control research has been conducted in only five countries: Australia (202 agents released against 56 weed species), Canada (85 agents against 30 weed species), New Zealand (53 agents against 23 weed species), South Africa (103 agents against 51 weed species) and USA (199 agents against 74 weed species) (Schwarzländer et al., 2018). Elsewhere, weed biological control efforts have been minimal, with most participating countries releasing only 1-3 biological control agents (Winston et al., 2014). Intentional releases in most countries have usually been as a result of introductions from one of the five main practicing countries, based on host specificity testing deeming the biological control agent as being suitable and effective for release.

In Asia, 15 countries have intentionally released 42 biological control agents against 19 weed species, with 11 weed species (58%) deemed under some level of control in some countries or regions. India has been the most active in this field, intentionally releasing 20 biological control agents against 10 weed species, resulting in five weed species deemed under control (Winston et al., 2014). *Alternanthera philoxeroides* (Mart.) Griseb. (Amaranthaceae), *Ambrosia artemisiifolia* L. (Asteraceae), and *Salvinia molesta* D.S. Mitchell (Salviniaceae) have all been successfully controlled in Asian countries where their respective agents have been released (Winston et al., 2014).

In the Pacific region, not including Australia, New Zealand or Hawaii, 17 countries have intentionally released 64 biological control agents against 24 weed species, resulting in the successful control of 14 weed species (61%). Major weeds, such as *Chromolaena odorata* (L.) R. M. King and H. Rob. (Asteraceae), *Eichhornia crassipes* (Mart.) Solms (Pontederiaceae), *Mimosa diplotricha* C. Wright (Fabaceae), *Pistia stratiotes* L. (Araceae), *Salvinia molesta*, and *Sida acuta* Burm. f. (Malvaceae) are now considered under control in Pacific island countries where their respective biological agents have established. Fiji has been the most active, releasing 30 biological control agents against 11 weed species (Day and Winston, 2016). The biological control agents released for some of the above mentioned weeds are shown in Figures 1-6.

In Africa, not including South Africa, 29 countries have intentionally released 38 biological control agents against 17 weed species, resulting in the successful control of 12 weed species (71%), according to local expert opinion. Zambia has been the most active, intentionally releasing 16 biological control agents against four weed species, resulting in the control of two species (Winston et al., 2014). Most biological control efforts in Africa have been against the three main water weeds; *E. crassipes*, *P. stratiotes* and *S. molesta*, with control or partial control achieved in most countries where the respective agents have established (Mbati et al., 2005; Coetzee et al., 2009; Julien et al., 2009; Neuenschwander et al., 2009; Winston et al., 2014).

Figure 1 The gall fly *Cecidochares connexa* adult, a biological control agent for *Chromolaena odorata*

Figure 2 The weevil *Cyrtobagous salviniae*, a biological control agent for *Salvinia molesta*

Figure 3 The weevils *Neochetina bruchi* (left) and *Neochetina eichhorniae* (right), biological control agents for *Eichhornia crassipes*

Figure 4 The psyllid *Heteropsylla spinulosa*, a biological control agent for *Mimosa diplotricha*

Figure 5 The weevil *Neohydronomus affinis*, a biological control agent for *Pistia stratiotes*

Figure 6 The rust pathogen *Puccinia spegazzinii*, a biological control agent for *Mikania micrantha*

These biological control efforts and successes have resulted in enormous benefits to communities and the environment through reduced costs of weeding, including the reduction of herbicide use and increased food production and rangeland productivity (e.g., Thomas and Room 1986; Doeleman 1989; Day et al., 2013). Moreover, there have been no off-target impacts where intentionally released weed biological control agents have caused significant unpredicted impacts on non-target species (Suckling and Sforza 2014; Hinz et al., 2019). Any attack by a biological control agent against another plant species is usually predicted in host range testing before the agent is released. For example, the flea beetle *Agasicles hygrophila* Selman and Vogt (Coleoptera: Chrysomelidae) was known to feed on other *Alternanthera* species prior to its field release in China (Wang et al., 1988; Lu et al., 2010).

Despite these successes, only a small percent of the weeds present in Africa, Asia, and the Pacific regions for which biological control agents are available, have been targeted for biological control. In addition, only a few countries in each of the regions, have intentionally released a biological control agent in the past five years and 12 of the 32 countries in the Asian-Pacific region who have intentionally released a biological control agent previously, have not released a biological control agent for over 20 years (Winston et al., 2014).

Most countries, other than the five main practicing countries that conduct weed biological control research, have released only a few biological control agents, released agents on only waterweeds, or not undertaken biological control at all. There are still some perceptions that weed biological control is risky and that biological control agents may mutate or evolve or develop new strains and feed on other plants, such as crops. There are also perceptions that the exotic weed could be controlled by utilizing organisms that are native in the country where the weed is a problem. Other factors that appear to have impeded biological control efforts include the lack of resources and capacity, awareness on the impacts of invasive plants, regulations, processes, and infrastructure to facilitate the importation of biological control agents, all of which will affect opportunities for funding for biological control (Julien et al., 2007; Witt et al., 2014; Barratt et al., 2018).

This paper discusses the most significant factors affecting the adoption of weed biological control, the challenges to promote biological control in the Asian-Pacific region, and the opportunities, if countries wish to implement weed biological control. Examples from African countries have been included where relevant.

Knowledge and awareness of the impacts of invasive plants

There is a general global acceptance that weeds have negative impacts, among others, on biodiversity, water resources, human health, and agriculture (van Wilgen et al., 2001; Dovey et al., 2004; Early et al., 2016). In many countries, landowners may be aware of the impacts of weeds, but grossly underestimate the impacts on yield and rangeland productivity (Day et al., 2012; Shackleton et al., 2017a, b, c, d; Witt et al., 2018).

For countries such as Australia, New Zealand, and South Africa, which have active weed biological control programmes, studies on the impacts and costs of weeds are essential to help prioritize which particular weed species to target for biological control.

However, formal studies on the impacts of weeds by many governments have often not been conducted and many countries are, therefore, not aware of the real impact of weeds on communities, a country's economy and environment (Pimentel et al., 2001; Ellison et al., 2014; Early et al., 2016; Xu et al., 2006; Nghiem et al., 2013). In India, *Lantana camara* L. (Verbenaceae) costs the economy in terms of impact and control costs, close to US$1 billion per annum (Rao and Chauhan 2015). For China, the cost of invasive alien species, which includes pest animals, is about US$14 billion p.a. (Xu et al., 2006).

Without knowing the cost of weeds and their impacts, it is difficult for countries to prioritize how funds for research and/or infrastructure should be allocated. Even if countries were aware of the actual impacts and costs of weeds, weed management is often given a lower priority due to many other issues, such as ensuring the availability of clean water, health, and education (Labrada 1996), despite weeds also impacting on these issues.

Knowledge and awareness of weed biological control

Across Africa, Asia, and the Pacific, there are often few policies or co-ordinated efforts in managing invasive plants, leaving the management of weeds up to individuals or communities. There are also widespread views that if weeds are a problem, they can easily be controlled by manual removal or utilization. This is partly supported by the view that labour is often not considered a cost, as family members conduct weeding or labour is paid for by means of accommodation or food (Day et al., 2012; Ellison et al., 2014; Day et al., 2016). Consequently, without knowing the actual cost of controlling weeds, there is a lack of incentive by governments to explore more sustainable means of managing them.

Herbicides are also widely used to manage weeds in some countries, especially in intensive cropping in Asia. However, while the negative impacts of herbicide use on human health and the environment have been well-documented, herbicides are still used indiscriminately in many regions (see Igbedioh, 1991). While widely used, both manual and herbicide control practices are costly and not sustainable, particularly in perennial ecosystems, such as plantations and grazing lands.

Although 91 countries have undertaken weed biological control, there is still some scepticism about the discipline, even in those countries that have undertaken weed biological control previously, and/or have undertaken insect biological control (Cock et al., 2016). There seems to be less concern over insect parasitoids or predators attacking native insect species than herbivores attacking other plants. This is understandable because the consequences of non-target impacts in weed biological control could affect crops and other valuable plant species, despite research that shows that possible non-target impacts are predictable and unlikely (Suckling and Sforza 2014; Hinz et al., 2019).

Common concerns are that weed biological control agents may attack other plant species once the weed is controlled, biological control agents could mutate and start attacking other plant species, or that they may evolve to attack other plant species. Such views are often based on the perception that after biological control "eradicates" the weed, the agent may then attack other plant species. These views reflect a lack of knowledge in the principles of weed biological control, which involves the use of co-evolved organisms collected from the target weed in its native range. Furthermore, there appears to be a lack of understanding of plant-insect interactions or that the host range of a specialist herbivore, i.e., a biological control agent, is a conservative phylogenetic trait (Lonsdale et al., 2001). Quite often, there are the inappropriate comparisons with the introduction of the cane toad [*Rhinella marina* L.; Anura: Bufonidae], mongoose [*Herpestes javanicus* É. Geoffroy Saint-Hilaire; Carnivora: Herpestidae] or Indian myna bird [*Acridotheres tristis* L.; Passeriformes: Sturnidae], all of which are generalist predators, which were expected to control some pests in some countries and which subsequently became pests in their own right.

Even in countries that have implemented weed biological control in the past, there can still be negative views. There are several possible reasons for these. First, the plant may still be around, albeit in lower numbers, while the previous premise was that the weed would be eradicated. The second is that there was no baseline data on the weed, so the impacts of the weed before and after the biological control agent was released cannot be determined. Part of the problem also stems from the long time (up to 20 years) since biological control agents have been introduced into some countries in the past. Previous researchers may have retired, resulting in the loss of institutional memory on the distribution and impacts of the weed, as well as the theory, procedures, and practices of biological control.

Also, the current researchers may have little knowledge of biological control, as it is seldom taught in schools or universities or, if so, only sparingly. At numerous workshops, when asked by the authors, if any of the participants were aware that weed biological control had been implemented in their country, most have replied in the negative. This lack of knowledge could also be as a result of some weeds no longer being a problem due to earlier biological control efforts. Another reason for not implementing biological control is the perception that the biological control agent may not work in all areas where the target weed is present. This is a possibility for many countries, such as Australia, New Zealand, and South Africa, where the weed may have a wide geographical range. However, some countries believe investing in biological control efforts is not worth the risk if the weed is not going to be controlled in all areas.

Infrastructure and capacity to implement biological control

Most countries are signatories to the Convention on Biological Diversity (CBD) (McGeoch et al., 2010) and as such, are obligated to manage invasive alien species. However, having invasive species embedded in the CBD means that governments in many developing countries think that invasive species are only a biodiversity issue. As such, invasive species are not always prioritized for action, despite their significant impacts on people and livelihoods. Besides, most countries either do not have policies or are unable to manage invasive species effectively due to a lack of capacity and resources (Dovey et al., 2004; Boy and Witt 2013; Early et al., 2016).

The infrastructure and capacity in the regions vary considerably. In many parts of Asia, infrastructure is generally better than in the Pacific or Africa, especially in the main centres, where populations tend to be higher. Asia also has many institutions that are involved in agricultural research, such as the Chinese Academy of Agricultural Science, the Kerala Forest Research Institute in India, or BIOTROP in Indonesia. However, some research centres do not have adequate post-entry quarantine facilities to import biological control agents safely.

In the Pacific region, there is considerable variation among the Pacific countries. This region consists of 22 Pacific Island Countries and Territories (PICTs), consisting of 7,500 volcanic islands and coral atolls, spread over 30 million km^2, of which only about 2% is land. The population of these countries varies from less than 100 in the Pitcairn Islands to over seven million in Papua New Guinea, with over 75% of the people being involved in agriculture (Shine et al., 2003).The capacity to manage weeds in the region is limited in terms of infrastructure and skills (Dovey et al., 2004). There are only a few specialized research institutions, e.g., National Agricultural Research Institute in Papua New Guinea and the Ministry of Primary Industries in Fiji, with most countries having officers who hold multiple positions. Many countries do not have adequately-equipped laboratories, glasshouses, or a post-entry quarantine suitable for the introduction and testing of biological control agents (Ellison et al., 2014). Thus, most biological control agents released into the Pacific are those that have been tested elsewhere, such as Australia, New Zealand, or Hawaii, prior to their introduction into one of the PICTs.

In Africa, many countries are some of the poorest on earth, with the majority of people involved in agriculture. General infrastructure in many of these countries is extremely limited, especially once out of the major centres. There are a few international research centres, such as the International Institute of Tropical Agriculture, the International Centre for Insect Physiology and Ecology, the Centre for Agriculture and Biosciences International (CABI), and others, that undertake biological control research, with very few to no national research institutions taking the lead. However, these international agencies often focus on the management of crop pests, and biological control of weeds is often not a priority. Therefore, it is not surprising that facilities for conducting biological control research on invasive weeds such as post-entry quarantines, glasshouses, and laboratories, are either poorly equipped or non-existent in many countries. This is because facilities are often built through donor funds but not maintained once the projects are finished. As in the Pacific, there is a heavy reliance on donor funding (Dovey et al., 2004; Boy and Witt 2013).

Apart from infrastructure and capacity, many countries who have not undertaken weed biological control, do not have the required regulations or understanding to import, test, mass rear and release host-specific biological control agents. For some countries, rather than trying to develop procedures to implement biological control, it is less risk-averse to deny the importation of biological control agents (Barratt et al., 2018). Regulators often do not want to shoulder the responsibility of approving the release of a biological control agent. So, the norm is not to act.

For some countries that have approved the release of biological control agents, there is a lack of understanding in weed biological control. Regulators assessing applications can include conditions to release permits that are impossible to meet (Sankaran and Day 2018). One government agency wanted a process in place to destroy the biological control agent if non-targets impacts occurred in the field. Given that biological control is usually irreversible once an agent has established, it will be hard to eradicate, and the condition was unrealistic. Another government agency wanted the biological control agent to be removed or eradicated once the host plant was brought under control. This shows a lack of understanding of weed biological control because the agent does not eradicate the target species but reduces its populations to levels where the weed is no longer considered to be a problem. Removing the agent would result in populations of the weed increasing again. The approval process in some countries can be confusing or require permissions from various Government Ministries, a process that can be cumbersome, time-consuming, and costly (Barratt et al., 2018; Sankaran and Day, 2018).

On the other hand, numerous countries such as the Cook Islands, Vanuatu, Ethiopia, Namibia, and Uganda, have regulations that support the importation of biological control agents and all have intentionally released biological control agents in the past few years (Winston et al., 2014; Day and Winston, 2016). In fact, in one country, the regulators wanted to help facilitate the release process while still being accountable. Together, with the various participating agencies, a robust process to assess biological control agents was developed, and biological control agents have been released recently. It is not clear in some cases, what is the limiting factor in gaining approval to release biological control agents. First, many countries do not implement biological control because introducing anything exotic is considered unfavourably. Also, they do not have adequate processes, regulations, and facilities to do so, or such processes and facilities are not present because of the reluctance to implement biological control.

Conflict species

Another concern limiting weed biological control is that some weeds are also considered to be beneficial. Several introduced Australian *Acacia* species in Africa have social and commercial benefits (Impson et al., 2011), while the biological control of *Chromolaena. odorata* in West Africa was hampered by the perception that the plant had medicinal properties and was an excellent fallow crop and shortened the fallow period (Aigbedion-Atalor et al., 2019). One of the reasons that biological control of *Mikania micrantha* Kunth (Asteraceae) was not implemented in some countries in the Pacific was that the plant is used to treat cuts (Day et al., 2012; 2016). Some farmers also use *M. micrantha* as a cover crop. Thus, biological control was not implemented by some countries, despite *M. micrantha* also smothering crops such as bananas, papaya, and cocoa, significantly reducing yields (Day et al., 2012; 2016).

These examples are based on the perception by some people that biological control will eradicate a particular weed, and that the plant will not be available for other uses. There is a lack of understanding that biological control does not eradicate but reduces weed populations to a low level, hopefully to where it no longer causes significant impacts. This means that there will still be plants available for use in traditional medicine or other purposes. In fact, in the case of introduced Australian *Acacia* spp., biological control can actually resolve possible conflicts. In South Africa, some *Acacia* spp. are valued for their biomass but are also significant weeds. To resolve these conflicts, biological control agents that attack the flower-buds and seeds were introduced to reduce the propagule production, leaving the biomass undamaged. Therefore, the plants could still be grown commercially, but seed production is significantly reduced, which reduces the rate of spread, particularly in riparian zones (Impson et al., 2011).

Funding

Adequate funding for research into weed biological control is a problem for all countries despite the high benefit: cost ratios achieved (e.g., Page and Lacey, 2006; de Lange and van Wilgen, 2010). Julien et al.,

(2007) stated that there was more funding in Australia for salinity than for weed biological control, despite the impacts and costs of weeds being an order magnitude higher than for salinity. In many countries, within-their country priorities, lack of awareness of the negative impacts of invasive plants across sectors, such as human and animal health, water availability and crop and pasture production, has limited funding to undertake on-ground weed management, let alone weed biological control.

One of the limiting factors is the lack of funding to build expensive infrastructure and fund lengthy research projects: biological control projects often run for 10+ years. Hence, many of the biological control programmes in most countries have focused on using biological control agents that have already been tested and released elsewhere (Dovey et al., 2004; Winston et al., 2014). These transfer projects are highly cost-effective, as most of the research, such as foreign exploration, host specificity testing, field release protocols, and evaluation has already been conducted in other countries (Julien et al., 2007). Therefore, countries can take advantage of introducing only those agents with a proven record, not only of specificity, but also effectiveness against the target weed. There is little advantage and a waste of resources to import biological control agents that are not effective at reducing weed populations. For example, many of the biological control agents for *L. camara* provide little or no impact on the target weed (Day et al., 2003). As such, many of these species are not recommended for release elsewhere.

Another limiting factor is that biological control programmes, even for those using previously tested agents and known to be specific and damaging, are long-term, and many donors want to see results in shorter timeframes and are reluctant to fund such lengthy programmes (Cock et al., 2000). In fact, some donors, even those that have previously funded weed biological control projects, have been reluctant to fund biological control programmes in recent times. Similar arguments around risk and effectiveness have been used despite their organizations commissioning reports showing that not only is biological control low-risk and effective, but the return on investment is huge (e.g., Lubulwa and McMeniman, 1997).

Discussion and Opportunities

Given the high cost of physical and chemical control, coupled with the negative impacts of herbicides, and that importing tried and proven biological control agents is relatively cheap and low-risk, more countries should be availing themselves to the vast number of proven biological control agents currently utilized elsewhere (Greathead, 1995; Labrada, 1996; Julien et al., 2007). It is for these reasons that biological control is so appealing. Once the agents have established, the target weeds are controlled to varying degrees, providing significant benefits to the economy and the environment. Day and Winston (2016) documented numerous opportunities to move host specific and effective biological agents around the Pacific. Likewise, Day et al. (2018) listed numerous agents that could be moved around the Greater Mekong Subregion in Southeast Asia, and Winston et al. (2014) catalogues all weed biological control efforts globally.

Some of the more effective biological control agents target major weeds, such as *C. odorata*, *E. crassipes*, *M. micrantha*, *M. diplotricha*, *P. stratiotes*, and *S. acuta*. These successful agents are already in some countries in Asia and the Pacific region and could be introduced into other countries where the respective target weeds are present.

Prior to the release of any biological control agent, governments need to be aware of the cost and impacts of invasive plants, not just on biodiversity, but on agriculture, food security, and livelihoods. For countries that have never introduced a biological control agent, or at least not for a long time, awareness campaigns may be required to educate governments in the low-risk and benefits of weed biological control as part of an integrated weed management strategy (Labrada 1996). Highlighting benefits also assist in attracting funding from donors. The challenge is not so much the science of weed biological control, although some may disagree, but communicating and trying to allay the fears of weed biological control (Lonsdale et al., 2001).

The first step could be to highlight the theory and science behind weed biological control, i.e., the use of co-evolved host-specific organisms and that monophagy and oligophagy in insects and pathogens are common and that even the most serious insect pests often have a limited host range. In fact, of the 500+ weed biological control agents released, only a few have caused non-target impacts at a population level, and these were known before their release (Schwarzländer et al., 2018; Hinz et al., 2019). This is quite different from that of the mongoose and cane toad, which were known generalist predators before their introduction into various countries.

Weed biological control researchers and managers need to promote the successes, in that twothirds of the weeds targeted for biological control are at least under partial control (Winston et al., 2014; Schwarzländer et al., 2018). In doing so, the critics of biological control, who claim biological control doesn't work, could be silenced. They claim that there is no supporting data, despite Winston et al. (2014), providing numerous examples. However, the critics themselves have no supporting data to state biological control doesn't work. Humans seem to have an appetite for bad news and are suspicious of good news, and so the negative comments gain traction. If biological control is going to be challenged, then those who oppose biological control also need to be challenged and held accountable.

It is worth mentioning again that weed biological control doesn't eradicate the target species, and conflicts between whether a weed is also considered beneficial can often be resolved using cost: benefit analyses. Finally, it is worth mentioning the consequences if biological control is not implemented, the impacts of those weeds will most likely continue to increase, along with the costs of managing them (Julien et al., 2007). Also, land clearing of new areas for agriculture and herbicide use will most likely continue to rise in the future (Ghosheh, 2005) Thus, there is also a significant risk of not implementing weed biological control. There is also scope for weed biological control to be introduced into the curriculum of schools and universities to build capacity and raise awareness. Such moves are already being considered in some countries such as Pakistan and the Philippines. Other opportunities to promote weed biological control include the conduct of workshops and training courses for both researchers and regulators.

From 1993-2005, initially under the Cooperative Research Centre (CRC) for Tropical Pest Management, a two-week international course on biological control of weeds was run in Brisbane, Australia, every two years (Julien and White, 1997). The course attracted participants from Africa, Asia, and the Pacific. It had strong field components, with presenters from the Queensland Government, CSIRO and the University of Queensland. The workshops included demonstrations in host specificity testing and field monitoring, to highlight the safety and impacts of weed biological control. Similar courses have since been run in South Africa and New Zealand, as well as by CABI to increase awareness. As well as formal courses, there have been numerous international exchanges of scientists, particularly between Australia and New Zealand, and China, Cook Islands, Myanmar, Solomon Islands, Thailand, and Vanuatu. However, there is scope to expand the exchanges further and involve more countries. Additionally, organizations, such as the Association of Southeast Asian Nations (ASEAN) and the Southeast Asian Regional Centre for Tropical Biology (SEMEAO-BIOTROP) in Asia, and the Secretariat of the Pacific Community (SPC) and Secretariat of the Pacific Community Regional Environmental Programme (SPREP) in the Pacific, could play key roles in increasing the awareness of the low risk and effectiveness of weed biological control.

While there is already an International Symposium on the Biological Control of Weeds, which is held every four years, there is scope to expand the biological control component in other international conferences and symposia. Weed biological control accounted for only a small percentage of talks at the most recent Asian-Pacific Weed Science Society Conference in Kuching. It accounted for a tiny fraction of the presentations at the last few Ecology and Management of Alien Plant invasions conferences. Both these conferences had strong herbicide and/or herbicide resistance components but little in the way of sustainable management strategies. Expanding the biological control components creates awareness and initiates discussions among researchers, academics, and policy people who may have had little exposure to weed biological control. To highlight the effectiveness of such meetings, following recent conferences and workshops in the Philippines and Malaysia, discussions have since been held with one of the authors (MD) on how to expand weed biological control in various countries of the region. Academics are now considering how to promote biological control and encourage students to undertake small projects.

While weed biological control is not the panacea for all weeds or even all situations, the fact that over 270 weed species are resistant to herbicides, suggests that biological control has a vital role in future integrated weed management programmes. Weed biological control has a proven track record over 100 years and has helped control some of the world's most important weeds. However, effective biological control agents have been introduced into only a fraction of the countries where the respective target weeds are present. This creates numerous opportunities to expand the use of these agents to help manage the weeds in countries where the agents are not present. There is scope for greater engagement between biological control practitioners and recipient countries to take advantage of the tremendous benefits of weed biological, and safely manage some of their worst weeds.

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ORIGINAL RESEARCH

Flumioxazin and Flufenacet as possible options for the control of multiple herbicide-resistant littleseed canarygrass (*Phalaris minor* Retz.) in wheat

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Abstract

We conducted field trials and pot experiment to evaluate the effectiveness of two herbicides - flumioxazin and flufenacet - for weed control in wheat (*Triticum aestivum* L.), particularly targeting littleseed canarygrass (*Phalaris minor* Retz.). In the field studies, conducted over four seasons (2012-13 to 2015-16), the littleseed canarygrass populations encountered in the fields were sensitive to herbicides. In the pot studies, the responses of both multiple herbicide-resistant (resistant to isoproturon, clodinafop, and sulfosulfuron) and sensitive populations were examined against flumioxazin and flufenacet. In the field trials, application of pre-emergence flumioxazin at 125-150 g a.i./ha effectively controlled littleseed canarygrass and several broad-leaved weeds, such as toothed dock (*Rumex dentatus* L.) and bur clover (*Medicago denticulata* Willd). However, flumioxazin was less effective against a second dominant grass weed, wild oat (*Avena ludoviciana* Dur.), which infested the field plots. Pendimethalin, which was used in the trials for comparison, at 1000 g a.i./ha, was less effective than flumioxazin in controlling wild oat. Compared with the unweeded control (weedy check) and the plots that received the pendimethalin treatments, the treatments with flumioxazin, at 125-150 g a.i./ha, produced much higher grain yields (i.e., up to 159% and up to 49% increased yield gain, respectively). The highest rate of flumioxazin (250 g a.i./ha) did not increase the weed control achieved, compared with the lower rates, but caused average crop phytotoxicity of 31% at 40 days after the herbicide application or 20 days after the first irrigation. In other field experiments, flufenacet (200-300 g a.i./ha), applied as early post-emergence at 20 days after sowing (one day before the first irrigation), was highly effective in the control of both littleseed canarygrass and wild oat. However, flufenacet was not effective in controlling broad-leaved weeds. Overall, the weed control and the wheat yield obtained with flufenacet 250 g a.i./ha were not significantly different from those obtained with the standard treatment used in the study (i.e., clodinafop, 60 g a.i./ha at 35 days after sowing).

In pot bioassay studies, flumioxazin and flufenacet were tested against multiple herbicide-resistant littleseed canarygrass, known to be resistant to acetyl-coA carboxylase (ACCase), acetolactate synthase (ALS) and photosystem II site A (PS-II) inhibitor herbicides, such as clodinafop, sulfosulfuron, and isoproturon, respectively. The results of the pot study indicated effective control (up to 100%) of the herbicide-resistant littleseed canarygrass population by both flumioxazin and flufenacet. Our combined studies of field trials and pot experiment, therefore, indicate that both flumioxazin and flufenacet have the potential to be alternative herbicide options in wheat, particularly for littleseed canarygrass control. As discussed in this paper, while we have demonstrated the potential, further studies are needed, incorporating other agronomic practices in wheat cultivation with flumioxazin and flufenacet, to explore their full potential for the control of multiple herbicide-resistant littleseed canarygrass.

Keywords: wheat, flumioxazin, flufenacet, littleseed canarygrass, *Phalaris minor*, clodinafop, herbicide resistance, isoproturon, pendimethalin, sulfosulfuron.

Introduction

Globally, the evolution of a large number of herbicide-resistant weeds in wheat (*Triticum aestivum* L. emend. Fiori and Paol.) has restricted the effective chemical weed control options for the crop. Heap (2019) reported that, globally, in wheat, there are 72 cases of resistance development in weeds, which primarily show resistance to acetyl-CoA carboxylase (ACCase) inhibitor herbicides. In addition, there are also 19 cases of resistance for acetolactate synthase (ALS) inhibitors across many of the wheat-producing countries.

In India, among herbicide-resistant weeds infesting wheat, the most problematic is the multiple herbicide-resistant littleseed canarygrass (*Phalaris minor* Retz), which has evolved resistance against PS-II (photosynthesis at the photosystem-II site-A), ACCase and ALS inhibitor herbicides (Chhokar and Sharma, 2008; Chhokar et al., 2018). It is known that littleseed canarygrass infests about 50% (15 million ha) of the cultivated wheat areas in India. Of this area, the multiple herbicide-resistant littleseed canarygrass affects about three million ha of wheat. The affected area is increasing every year, posing a significant threat to wheat production and profitability of farmers (Chhokar et al., 2018; Singh and Chhokar, 2015). For managing populations of the herbicide-resistant littleseed canarygrass, it is essential to evaluate and identify alternative herbicides, which have different mechanisms of actions to those that are commonly used in northern Indian plains, such as, clodinafop, sulfosulfuron, and pinoxaden.

Flumioxazin is a contact herbicide, which belongs to a protoporphyrinogen oxidase (Protox) inhibitor (an enzyme important in the synthesis of chlorophyll) group. It is absorbed by both roots and foliage of treated plants (Dayan and Duke, 1997). So, when applied to the soil, susceptible weed seedlings die as they begin to emerge, whereas foliar contact of susceptible plants results in rapid desiccation, followed by necrosis (Hutchinson, 2007). Previous research has reported the effectiveness of flumioxazin in a range of crops, such as cotton (*Gossypium hirsutum* L.), corn (*Zea mays* L.), peanut (*Arachis hypogaea* L.), soybean [*Glycine max* (L.) Merr.], field peas (*Pisum sativum* L.), potato (*Solanum tuberosum* L.) and wheat, as well as in bermudagrass [*Cynodon dactylon* (L.) Pers.] turf and in other non-crop situations (Bunting et al., 2003; Cranmer et al., 2000; Hutchinson, 2007; Senseman, 2007; Flessner et al., 2013).

Although flumioxazin is recommended for use in many crops, its most common use is for pre- and post-emergence weed control in legume crops (Senseman, 2007; Howey, 2012). Also, flumioxazin is known to significantly increase the speed of kill of various grasses and broad-leaved weeds when applied with glyphosate, paraquat or diquat, before sowing (Howey, 2012). This herbicide has also demonstrated effective control on some of the hard-to-kill weeds, such as wild radish (*Raphanus raphanistrum* L.), capeweed [*Arctotheca calendula* (L.) Levyns] and wireweed (*Polygonum aviculare* L.). Despite such knowledge about the strengths of flumioxazin, up to now, not much work has been done on its potential use for weed control in wheat, which is an objective of our present studies.

Flufenacet, an oxyacetamide herbicide, has also been shown to control many kinds of grass and broadleaf weeds by inhibiting long-chain fatty acid biosynthesis in plants (Senseman, 2007). Flufenacet has also been registered for use in various crops, such as corn, soybean, wheat, barley (*Hordeum vulgare* L.), rice (*Oryza sativa* L.), peanut, and potato, either alone, or in combination with other herbicides (such as diflufenican, metribuzin, metosulam, or triallate) depending on the crop (Diehl and Benz 1998; Brinkmann and Dahmen, 1997; Chhokar et al., 2006b; Kleemann et al., 2016; Koepke-Hill et al., 2011). In wheat, flufenacet combinations with diflufenican and metribuzin have been shown to control a range of weeds (Koepke-Hill et al., 2011; Lawrence and Burke, 2014). Our early studies (Chhokar et al., 2006a) showed that flufenacet, in wheat, can be applied pre- or early post-emergence, for effectively control of isoproturon-resistant littleseed canarygrass, although the crop may suffer from some phytotoxicity. In rice also, flufenacet phytotoxicity had been noted, but effects varied depending on the cultivars. We found that scented rice cultivars, such as Taraori Basmati and Sugandha, were more sensitive to flufenacet, compared with the coarser rice cultivar IR-64 (Chhokar et al., 2006b).

In the northern Indian plains, the reduced efficacy of post-emergence herbicides against herbicide-resistant littleseed canarygrass and other weeds in wheat has forced the farmers to use herbicides more frequently and at higher rates. Many farmers currently use three or four herbicides in sequence, or in combinations, thus, incurring heavy costs of weed control and risks of crop injury (Chhokar et al., 2018; Singh and Chhokar, 2015).

Therefore, to address the problems of managing herbicide-resistant littleseed canarygrass and other weeds in wheat, it is essential to identify new or alternative effective herbicides, with different mechanisms of actions. Flumioxazin and flufenacet have different mechanisms of action. With their usage in numerous crops, only a few cases of resistant weeds against these herbicides have been reported up to now (Heap, 2019). These two herbicides, therefore, have the potential to be alternatives to manage littleseed canarygrass and other weeds in wheat in India. Figures 1 and 2 are photographs showing wheat fields severely infested with herbicide-resistant littleseed canarygrass.

Figure 1. Littleseed canarygrass infesting a wheat field in Haryana, India

Figure 2. Multiple herbicide-resistant littleseed canarygrass infesting a wheat field harvested for fodder in Punjab, India

Given the above, the primary objective of our studies was to evaluate the potential of flumioxazin and flufenacet for the control of littleseed canarygrass and other weeds in wheat. To achieve this objective, we conducted both field trials and pot experiment. Firstly, we conducted a series of field trials, over four growing seasons (2012-13 and 2015-16), to evaluate the effectiveness of flumioxazin and flufenacet for controlling littleseed canarygrass and other weeds, infesting wheat.

Secondly, we conducted separate pot studies on population of known, multiple herbicide-resistant (PS-II, ACCase and ALS inhibitor) littleseed canarygrass, to ascertain the potential of the two herbicides for the control of such populations.

Materials and Methods

In this research, we conducted field and pot studies to determine the efficacy of flumioxazin and flufenacet for weed control in wheat with an emphasis on littleseed canarygrass (*P. minor*) control. The studies were conducted at the Resource Management Field Block of the Indian Council of Agricultural Research (ICAR)-Indian Institute of Wheat and Barley Research, Karnal (29° 42' N, 76° 59' E and 235 m AMSL), India. The field site had been in a rice-wheat rotation during and prior to the present experiments. The soil of the experimental field was a sandy loam, with a pH in the range of 8.1-8.3 and an organic carbon content in the range of 0.37-0.42%. In the fields, the populations of littleseed canarygrass encountered were demonstrably susceptible to herbicides; hence, not known to be herbicide-resistant.

However, for the pot studies, we used two populations of littleseed canarygrass, known to respond differentially to herbicides. One population (Sagga-1) was collected in April 2015 from a farmer's field in the village Sagga of the District Karnal, Haryana State. It was known to be multiple herbicide-resistant (resistant to isoproturon, clodinafop, and sulfosulfuron). The second was from a population of herbicide-susceptible (IIWBR population) canarygrass collected from our institute's Resource Management research block. The seeds of both these populations are maintained at ICAR-IIWBR, Karnal.

Field studies

Evaluation of pre-emergence flumioxazin in wheat

The field experiments were conducted in a randomized block design with three replications during two seasons, i.e., the 2014-15 and 2015-16 cropping seasons, to evaluate flumioxazin 50% SC

(Sumi Max) for weed control in wheat. Wheat cultivars, WH 1105 and HD 2967, were sown using a seed rate of 100 kg/ha at 20 cm row spacing on 5 November 2014; and, then, in the following season, on 21 November 2015. The wheat cultivar, HD 2967 was selected during the second season (2015-16), because of its known stability under varied sowing timing, different tillage and irrigation levels, as well as broader adoption by farmers, compared to WH 1105 (Chhokar et al., 2018).

The weed control treatments (see Table 1) consisted of pre-emergence applications of flumioxazin at 100, 125, 150, and 250 g a.i./ha. For comparison, pendimethalin 30 EC (Stomp), a standard herbicide of wheat, was also included in the study (applied at 1000 g a.i./ha). The trials included standard, un-weeded control plots ('weedy' check) and 'weed-free' check control plots. For the 'weed-free' treatment, all weeds in the plots were manually removed, starting at 20 DAS, followed by hand weeding at every 10-15 days intervals.

The pre-emergence flumioxazin and pendimethalin treatments were applied at one to two days after sowing (DAS) using a carrier volume of 400 L water/ha with a knapsack sprayer fitted with two flat fan nozzles on a boom at 50 cm distance. Visual assessment of crop phytotoxicity was conducted at 40 days after application (DAA) of flumioxazin on a 0 to 100% scale, where 0% is no injury, and 100% means complete kill. The crop phytotoxicity assessments were based on necrosis, chlorosis, and suppression or stunting of wheat crop plants in the herbicide treated plots, compared with the untreated control plots.

Evaluation of early post-emergence flufenacet in wheat

During two consecutive winter seasons (2012-13 and 2013-14), flufenacet was evaluated for weed control as an early post-emergence application at 20 DAS. In these studies, wheat cultivars. PBW 550 and HD 2967 were sown on 31 December 2012 (season 1); and on 10 November 2013 (season 2), respectively. The cultivar PBW 550, a short duration variety, was selected for delayed sowing (31 December 2012) during the first season of studies. However, in the second season of the studies, the longer duration (5 months to maturity), high yielding, double-dwarf cultivar (HD 2967) was grown, because of early sowing time (10 November 2013) of the experiment.

At 20 DAS (one day before first irrigation), flufenacet rates of 200, 250 and 300 g a.i./ha, were applied with a knapsack sprayer fitted with two flat fan nozzles, using a carrier volume of 350 L water/ha (see Table 3). For comparison, plots of a 'weedy' check (un-weeded plots), and 'weed-free' check were included in the field trials, along with other plots that received treatments of a widely used, post-emergence, graminicide (grass-killing herbicide)– clodinafop, 60 g a.i./ha, applied at around 35 DAS. Clodinafop was also applied as spray solutions in carrier volumes of 350 L/ha, using a knapsack sprayer, fitted with two flat fan nozzles. In the 'weed-free' control plots, all weeds were manually removed, by hand weeding, initially at 20 DAS, and thereafter, at every 10-15 days intervals.

Visual assessments of crop phytotoxicity (%) were conducted at 30 days after application (DAA) of flufenacet, on a 0 to 100% scale, where 0% is no injury, and 100% means complete kill, based on the growth reduction of wheat plants, compared with those in the un-weeded control.

General

The fields used for the wheat experiments were prepared after pre-sowing irrigation, to have a fine tilth and for which cross operations, each of harrow, cultivator, rotary tiller, and planker/leveller were performed in a sequence. The selected wheat cultivars for each experiment were sown using a seed-cum-ferti-drill, with an inclined plate seed drilling mechanism, which delivered a seed rate of about 100 kg/ha (The seed rate was adjusted by considering 38 g, as the weight of 1000 seeds). The size of each field plot was 2 m × 11 m, with 10 rows per plot and a row-to-row spacing of 20 cm. Fertilization and irrigation applications for the fields were made according to the recommended package of practice for wheat in India (Coventry et al., 2011). The fertilizer application consisted of 150 kg N, 60 kg P_2O_5, 40 kg K_2O/ha. One-third N and full P and K were applied at the time of sowing. The remaining 2/3rd of nitrogen was applied in two equal splits, at the time of first and second irrigations, which were applied at 21 and 42 DAS, respectively.

In the flumioxazin evaluation studies, the observations on the abundance of the weed populations (no/m^2) were taken at 58-60 DAS by placing a quadrat of 50 cm x 50 cm at two locations in each plot and counting the number of plants of significant weed species present. Weed dry weights were recorded at 120 DAS in all of the studies, except during 2012-13 (season 1) in the flufenacet studies, where they were recorded at 100 DAS. To obtain the dry weed weights, weeds within each quadrat were cut close to the ground and separated according to the significant weed taxa. After initial air drying, the weeds were dried in an oven to a constant weight (drying at 60±2 ºC for three days). For data analyses and reporting, the population and dry weights of minor weeds, which appeared in low abundance, were pooled as 'other weeds'.

In each field trial, the wheat grain yield data were obtained by harvesting the central nine rows of each plot excluding the border area (two outer rows and 1.5 m across rows from both sides of a plot). The plots were manually harvested, and the grains were threshed using a small plot thresher. The final grain yields were corrected to 12% seed moisture.

Pot bioassays

Evaluation of flumioxazin and flufenacet against multiple herbicide resistant P. minor

The responses of multiple herbicide-resistant (resistant to ALS, ACCase, and PS-II inhibitor) and susceptible (S) populations of littleseed canarygrass were studied against flumioxazin and flufenacet in pot experiment during 2015-16. Three other herbicides (sulfosulfuron, clodinafop, and isoproturon), commonly used in wheat in India, were also included in the studies, for comparison.

For this herbicide-resistance study, 50 seeds per pot of the herbicide-resistant or susceptible littleseed canarygrass were sown in pots at about two cm depth. The soil for filling pots (4.5 kg soil per pot) was taken from the field, which had no previous littleseed canarygrass infestations. Pots were filled with this soil, mixed at a ratio of 6:1 (v/v) with decayed Farmyard Manure (FYM), which passed through a 2-mm sieve. The pot studies involved the determination of the relative growth reductions of the two littleseed canarygrass populations (resistant and susceptible) by nine herbicide treatments, in comparison with the un-weeded controls.

There were 20 treatment combinations, and each treatment was replicated four times, and the experiment arranged as a completely randomized design. The herbicide treatments consisted were: (1) pre-emergence flumioxazin (25 and 50 g a.i./ha) applied at three DAS; (2) early post-emergence flufenacet (37.5, 75, 150 and 300 g a.i./ha) applied at 15 DAS; and (3) post-emergence sulfosulfuron (25 g a.i./ha), clodinafop (60 g a.i./ha) and isoproturon (1000 g a.i./ha), evaluated at 21 DAS. The measured quantity of each dose of herbicide for an area of 20 m^2 was dissolved in the 800 mL water and applied on to the pots after placing the pots randomly within the 20 m^2 area (2 m × 10 m).

The herbicide applications were made using a knapsack sprayer fitted with two nozzles on a boom with a swath of one meter. Spraying was done in such a manner that each pot had only one pass of spray. The control evaluation was based on percentage reduction of fresh biomasses of *P. minor* per pot at 42 DAS, compared with untreated pots.

Statistical analyses

We used the Statistical Analysis System (SAS, version 9.2) software for data analyses. The data on the field evaluation of flumioxazin were statistically analyzed in a combined block design, whereas, the flufenacet experimental data were analyzed as simple block design. Since the effects of the year and year x treatment interactions were not significant, the data of the flumioxazin studies were pooled by treatment over a year. The pooling of the results did not alter the interpretations. In contrast, in the flufenacet studies, pooling of data was not done, since, there were notable variations in the abundance of weeds, as a result of which, the statistical interpretation varied between pooled analysis and individual (year to year) analysis. In the combined analysis, the variances were partitioned into the fixed effects of herbicide treatments and the random effects of the study year.

The experimental data from the pot studies were statistically analyzed in a factorial completely randomized design (CRD), in which the two factors in the 20 treatment combinations were evaluated. Weed and crop data in various experiments were subjected to analyses of variance, and the Fisher's Protected Least Significant Difference (LSD) was used to separate treatment means (P=0.05). The data on the weed population, weed dry weight, and visual crop phytotoxicity (%) were square root $\{\sqrt{(x+1)}\}$ transformed before analysis. The original weed data are presented in the results tables with a comparison of means for significant differences. In the flumioxazin evaluation studies, results from the weed-free plots were not included in the statistical analysis of weed data. However, data from the weed-free plots were included in the flufenacet evaluation studies to have a sufficient degree of freedom for estimation of error variances. To avoid the bias in the data analysis, due to the inclusion of the two controls (weed-free and un-weeded control) and also, to determine the relative treatment efficacy for the reduction in weed dry weights and gains in crop yields in the flufenacet experiments, a single degree of freedom contrasts were also performed (Onofri et al., 2009; Gomez and Gomez, 1984)..

Results

Field evaluation of pre-emergence flumioxazin in wheat

Since no significant year-by-treatment interactions were observed, the data were pooled, and the results of the analysis of pooled data on weeds and crop are presented in Tables 1 and 2. The main weeds infesting the experimental plots were: littleseed canarygrass, wild oat (*Avena ludoviciana* Dur.), and a range of broad-leaf weeds, mainly, bur clover (*Medicago denticulata* Willd), toothed dock (*Rumex dentatus* L.), and lesser swine cress (*Coronopus didymus* L.). Among these, the most dominant weed during both seasons was littleseed canarygrass. The mean population and dry weight of littleseed canarygrass in the un-weeded control (weedy check) were 360 plants/m^2 and 346 g/m^2, respectively (Table 1). Wild oat was the second most dominant grass weed (dry weight accumulation 111 g/m^2). Compared to the weedy check, all the herbicide treatments caused significant reductions in the total densities of weeds and their dry weights.

Pre-emergence treatments of flumioxazin drastically reduced the littleseed canarygrass densities, and dry weights in the treated plots, and the reductions increased as the dose of flumioxazin increased from 100 to 250 g a.i./ha. Flumioxazin applications at 150 and 250 g a.i./ha were significantly superior in littleseed canarygrass control achieved compared with the lower dose of 100 g a.i./ha. Weed control achieved by the two higher doses were, however, not significantly different. Also, there was no significant difference between the littleseed canarygrass control achieved by flumioxazin doses of 125 and 150 g a.i./ha. Flumioxazin was less effective against wild oat, but, compared with pendimethalin (1000 g a.i./ha), control was significantly higher. However, pendimethalin was quite effective in controlling toothed dock. Also, flumioxazin, at 125 g a.i./ha, or higher rates was better than pendimethalin in reducing the densities and dry weights of littleseed canarygrass and bur clover. Some flushes of weeds, which emerged along with the crop, were killed by the flumioxazin treatments after the first irrigation.

Based on the total weed dry weights, the weed control efficiencies of flumioxazin at 125 and 150 g a.i./ha were approximately 79 and 86%, respectively, compared with weed dry weights in the un-weeded control. In contrast, the weed control efficiency of pendimethalin 1000 g a.i./ha was considerably low (overall, 48%) compared with the un-weeded controls. Overall, based on the reduction of weed dry weights compared with the un-weeded check (Table 1), the control of littleseed canarygrass obtained by the applications of flumioxazin at 125-150 g a.i./ha was superior to pendimethalin and ranged from 94-97%. The reduction of littleseed canarygrass obtained by pendimethalin (1000 g a.i./ha) was significantly less than flumioxazin and was about 71% only, compared with the un-weeded check.

With regard to the effects of the herbicide applications on wheat, as shown in Table 2, the various herbicide treatments significantly influenced the tillering, crop biomass, and grain yield of wheat. The yield attributes (effective tillering and 1000 grain weight) were significantly higher in the flumioxazin treated plots than with plots, which received the pendimethalin applications. The uncontrolled weed growth throughout the crop season (un-weeded check) resulted in the lowest wheat biomass and grain yield (Table 2). The 1000 grains weight was also significantly lower in weedy-check control (34 g). Although pendimethalin significantly improved the grain weight (35 g) compared to the weedy control, its weed control effectiveness was significantly lower than the range of flumioxazin rates tested.

The highest wheat grain yield was obtained with the weed-free check (5.12 t/ha). In comparison, season-long competition from weeds (un-weeded check) produced a 62.7% lower grain yield (1.91 t/ha). All herbicide treatments increased the wheat grain yields over the unweeded check by at least 74%. Flumioxazin at 125-150 g a.i./ha, provided increased grain yields (1.12-1.62 t/ha higher) compared to pendimethalin (1000 g a.i./ha) but these increased yields were statistically not different to the weed-free check. Among the herbicide treatments, the highest average grain yield was with the application of 150 g a.i./ha flumioxazin (4.95 t/ha), which was not statistically different to the productivity obtained with application of 125 and 250 g a.i./ha flumioxazin (4.77 and 4.94 t/ha, respectively).

The application of flumioxazin caused phytotoxicity on the wheat crop, which became much distinct in the form of leaf necrosis after the first irrigation. Phytotoxicity symptoms on the crop increased as the dose rate of flumioxazin increased from 100 to 250 g a.i./ha. The flumioxazin at the rate of 250 g a.i./ha provided the lowest weed dry weight (34 g/m^2) but caused phytotoxicity to wheat, which was rated as 31% visual damage. In contrast, at lower doses (125-150 g a.i./ha), the phytotoxicity was visually 8-12% at 19-20 days after first irrigation i.e., around 40 days after herbicide application (Table 2). However, over time, the crop recovered sufficiently, and the yields in the flumioxazin 125-150 g a.i./ha treated plots were finally not significantly different to those attained by the weed-free check.

Evaluation of early post-emergence flufenacet in wheat

Flufenacet (200, 250, and 300 g a.i./ha) applied as early post-emergence (20 DAS) was tested for the control of two major grass weeds, which infested the field plots, namely, *P. minor* and *A. ludoviciana.* Among broad-leaved weeds: *Medicago denticulata, Rumex dentatus*, and *Coronopus didymus* were also present but less abundant. The two years of weed dry weights and wheat yield data are presented year-wise, in Table 3, because of the variations in the weed flora (*A. ludoviciana* was present in the second year only) and the significant herbicide treatment and year interactions observed for data on crop and weeds. There were significant weed dry weights differences among the various treatments. In the un-weeded control plots, the total weed dry weights accumulated were 211 and 403 g/m^2, respectively, during the first and second year (Table 3).

Littleseed canarygrass was the most dominant weed, which accounted for 99% (209 g/m^2) and 73% (294 g/m^2) of weed abundance, respectively, during the first and the second year of field trials. Based on weed dry weights, wild oat was the second-most dominant weed during the second year. The early post-emergence applications of flufenacet drastically reduced the dry weights of both these grasses, although, flufenacet was not effective against broad-leaved weeds (Table 3). The dry weight reductions in littleseed canarygrass on the flufenacet treated plots at 200, 250, and 300 g a.i./ha were 88, 97, and 99%, respectively, compared with the unweeded control. Much higher weed control was obtained by the higher doses of flufenacet (250-300 g a.i./ha) compared with the lower dose (200 g a.i./ha).

During the second crop season (2013-14), the wild oat dry weights in the plots were reduced by 81%, 94%, and 95%, respectively, by the rates of 200, 250, and 300 g a.i./ha, of flufenacet. However, the wild oat control with flufenacet at the higher dose range (250-300 g a.i./ha) was not statistically different to that obtained with clodinafop 60 g a.i./ha, which indicated that clodinafop, at the tested rate, was equally effective as flufenacet in wild oat control.

Also, littleseed canarygrass control with the highest rate of flufenacet 300 g a.i./ha was not significantly different from the control achieved by the standard check herbicide– clodinafop, during the trials in both years. However, 250 g a.i./ha flufenacet was equally effective as 300 g a.i./ha flufenacet and clodinafop 60 g a.i./ha in reducing the dry weights of littleseed canarygrass in the treated plots during the crop season of 2012-13 but was inferior during the second season of 2013-14. Overall, based on reductions of dry weights of all weeds dry weights, the control achieved by the two higher rates of flufenacet (250 and 300 g a.i./ha) was not significantly different from that obtained by clodinafop. Weed abundance in the study plots in 2013-14 (Table 3) also showed that flufenacet was ineffective against the broadleaf weeds infested the plots, but it achieved the effective grass weed control. The field trials showed a tendency for broadleaf weeds to grow in greater abundance in the flufenacet treated plots, compared with the unweeded control plots, as the herbicide reduced the occurrence of the grasses infesting the plots.

Weed control with flufenacet had significant effects on the gains in wheat grain yield ($p<0.0001$) compared to un-weeded control. As shown in Table 3, uncontrolled weed growth throughout the season resulted in the lowest grain yields of 3.58 and 2.33 t/ha, during the first and second crop seasons, respectively. The maximum wheat grain yields were obtained from the weed-free control plots (5.82 and 5.70 t/ha, respectively, in 2012-13 and 2013-14 seasons). Wheat grain yields under flufenacet treatments increased by 51% to 145% over the unweeded check. Treatments with flufenacet, at the two higher dose rates (250 and 300 g a.i./ha), resulted in significantly higher grain yields compared to the lowest dose of 200 g a.i./ha. As shown by the contrast analyses, these yield levels were not significantly different from the yields in the plots treated with the standard herbicide – clodinafop and the weed-free control plots.

Table 1. Influence of pre-emergence application of flumioxazin on weed density and dry weight in wheat (Pooled data of two years)

Herbicide	Dose/ha (g a.i.)	Weed Density (no/m²)						Weed Dry Weight (g/m²)					
		Phalaris minor	*Avena ludoviciana*	*Rumex dentatus*	*Medicago denticulata*	Other weeds	Total	*Phalaris minor*	*Avena ludoviciana*	*Rumex dentatus*	*Medicago denticulata*	Other weeds	Total
Flumioxazin	100	43.0 BC	10.3 ABC	2.3 B	10.0 B	12.7 A	78.3 C	30.7 C	88.7 AB	1.3 B	10.1 B	1.5 A	132.4 C
Flumioxazin	125	27.7 CD	9.7 BC	1.3 B	4.3 BC	6.7 AB	49.7 CD	20.3 CD	74.7 AB	0.1B	2.2 CD	1.5 A	98.9 CD
Flumioxazin	150	16.3 DE	6.0 C	0.3 B	3.0 C	3.7 B	29.3 DE	9.5 DE	52.4 BC	0.0 B	2.3 CD	1.4 A	65.6 DE
Flumioxazin	250	6.3 E	2.3 D	0.0 B	1.7 C	3.0 B	13.3 E	1.8 E	29.9 C	0.3 B	0.3 D	1.4 A	33.7 E
Pendimethalin	1000	71.3 B	16.0 A	0.0 B	43.3 A	11.7 AB	142.3 B	99.9 B	125.0 A	0.0 B	22.0 A	0.7 A	247.6 B
Weedy-check (control)	-	360.3 A	12.7 AB	23.7 A	39.0 A	17.0 A	452.7 A	346.0 A	110.7 A	5.6 A	8.1 BC	1.8 A	472.2 A
p-Value		<0.001	0.0005	<0.001	<0.001	0.0582	<0.001	<0.0001	0.0040	<0.0001	<0.0001	0.8377	<0.0001

Original values were square root transformed (√x+1) for statistical analysis and based on which the upper-case letters have been mentioned with original values for interpretation. Means within column having at least one letter common are not significantly different according to Fisher's Least Significant Difference at 5% level of significance.

Table 2. Performance of pre-emergence application of flumioxazin in wheat (Pooled data of two years)

Herbicide	Dose/ha (g a.i.)	Phytotoxicity % 40 DAA†	Tiller/m²	Biomass (t/ha)	1000 Grains weight (g)	Grain Yield (t/ha)
Flumioxazin	100	3.3 D	346.3 B	12.08 B	36.72 A	4.44 C
Flumioxazin	125	7.9 C	369.2 AB	12.70 AB	36.92 A	4.77 B
Flumioxazin	150	11.7 B	367.8 AB	12.73 AB	37.02 A	4.95 AB
Flumioxazin	250	30.8 A	347.2 B	12.55 AB	36.37 AB	4.94 AB
Pendimethalin	1000	0.0 E	295.1 C	10.50 C	35.21 B	3.32 D
Weed-free check (control)	-	0.0 E	372.6 A	12.88 A	36.86 A	5.12 A
Weedy-check (control)	-	0.0 E	232.9 D	9.14 D	33.56 C	1.91 E
p-Value		<0.0001	<0.0001	<0.0001	<0.0001	<.0001

Means, within a column, with at least one letter common, are not significantly different at P<0.05. Mean separations were performed using Fisher's Least Significant Difference at 5% level of significance; ŤDAA= days after application.

Table 3. Performance of early post -emergence application of flufenacet against weeds in wheat

Herbicide	Dose/ha (g a.i.)	Time of application (DAS)†	2012-13				2013-14				
			‡Weed Dry Weight (g/m^2)			Wheat Grain Yield (t/ha)	‡Weed Dry Weight (g/m^2)				Wheat Grain Yield (t/ha)
			Phalaris minor	Broadleaf weeds	Total weeds		*Phalaris minor*	*Avena ludoviciana*	Broadleaf weeds	Total weeds	
Clodinafop	60	35	1.0 ^{C}	14.4 ^{A}	15.4 ^{C}	5.66 ^{A}	0.2 ^{D}	0.0 ^{B}	16.3 ^{A}	16.4 ^{C}	5.42 ^{A}
Flufenacet	200	20	24.8 ^{B}	13.4 ^{A}	38.2 ^{B}	5.40 ^{B}	35.0 ^{B}	19.1 ^{B}	17.6 ^{A}	71.7^{B}	4.96 ^{B}
Flufenacet	250	20	5.7 ^{C}	10.3 ^{AB}	16.0 ^{C}	5.64 ^{A}	12.6 ^{C}	6.7 ^{B}	18.8 ^{A}	38.1 ^{BC}	5.38 ^{A}
Flufenacet	300	20	1.5 ^{C}	15.^{A}	17.3 ^{C}	5.61 ^{AB}	2.6 ^{D}	5.2 ^{B}	20.9 ^{A}	28.7 ^{C}	5.42 ^{A}
Weed-free check (control)	-	-	0.0 ^{C}	0.0 ^{C}	0.0 ^{D}	5.82 ^{A}	0.0 ^{D}	0.0 ^{B}	0.0 ^{B}	0.0 ^{D}	5.70 ^{A}
Weedy-check (control)	-	-	208.5 ^{A}	2.8 ^{BC}	211.3 ^{A}	3.58 ^{C}	294.3 ^{A}	102.3 ^{A}	6.2 ^{AB}	402.9 ^{A}	2.33 ^{C}
p-Value			<0.0001	0.0059	<0.0001	<0.0001	<0.0001	0.0006	0.0227	<0.0001	<0.0001
Contrasts*				p-Value					p-Value		
Flufenacet 200 g/ha vs Flufenacet 250 g/ha			0.0013	0.5043	0.0196	0.0493	0.0068	0.2760	0.9175	0.0629	0.0194
Flufenacet 250 g/ha vs Flufenacet 300 g/ha			0.2497	0.4821	0.9633	0.7838	0.0212	0.9061	0.5998	0.6267	0.7877-
Flufenacet 200 g/ha vs Clodinafop 60 g/ha			0.0001	0.9895	0.0156	0.0326	<0.0001	0.0752	0.8110	0.0039	0.0122
Flufenacet 250 g/ha vs Clodinafop 60 g/ha			0.2240	0.5125	0.9106	0.8321	0.0034	0.4241	0.8929	0.1337	0.7927
Flufenacet 300 g/ha vs Clodinafop 60 g/ha			0.9443	0.9607	0.9471	0.6277	0.3014	0.4926	0.5120	0.2847	0.9958
Weedy check vs Herbicides			<0.0001	0.0450	<0.0001	<0.0001	<0.0001	<0.0001	0.2002	<0.0001	<0.0001

† DAS= days after sowing; ‡ Original weed dry weight values were square root transformed ($\sqrt{x+1}$) for statistical analysis and based on which the upper-case letters have been mentioned with original; *Single degree linear contrast analysis (p-value)

Pot Study Evaluation of flumioxazin and flufenacet against multiple herbicide resistant *P. minor*

Of the five herbicides evaluated in the pot study against the two populations of littleseed canarygrass (susceptible population and the multiple herbicide-resistant population), only, flumioxazin and flufenacet were effective in controlling both these populations. As shown in Figure 3, the results indicated that sulfosulfuron, isoproturon, and clodinafop were not effective against the multiple herbicide-resistant littleseed canarygrass. These three herbicides did not kill the littleseed canarygrass plants and only caused fresh weigh biomass reductions of 31, 28, and 16%, respectively. However, plants from the susceptible littleseed canarygrass population were readily controlled by all of the tested herbicides. Isoproturon, at 1000 g a.i./ha; sulfosulfuron, at 25 g a.i./ha; and clodinafop at 60 g a.i./ha; provided >99% biomass reductions of the susceptible littleseed canarygrass population (Figure 3). The results of the study showed that both the susceptible and herbicide-resistant populations were well controlled by flumioxazin and flufenacet.

The application of flufenacet, at a range of rates (75-300 g a.i./ha) as early post-emergence, and flumioxazin, at less than (50 g a.i./ha) the optimum field rates (125-150 g a.i./ha), as pre-emergence, provided excellent control (98-100% biomass reductions) of both types of littleseed canarygrass populations.

Discussion and Conclusions

Our studies indicated that pre-emergence applications of flumioxazin effectively controlled littleseed canarygrass and several broad-leaved weeds, but the herbicide was less effective against wild oat. In earlier studies, Grichar and Colburn (1996) and Askew et al. (1999), had reported the effectiveness of flumioxazin for the control of several grasses and broad-leaved weeds. Some of the weeds flushes in our plots, which emerged with the crop, were killed by the pre-emergent flumioxazin after the first irrigation application, which indicated its soil residual activity against specific weeds.

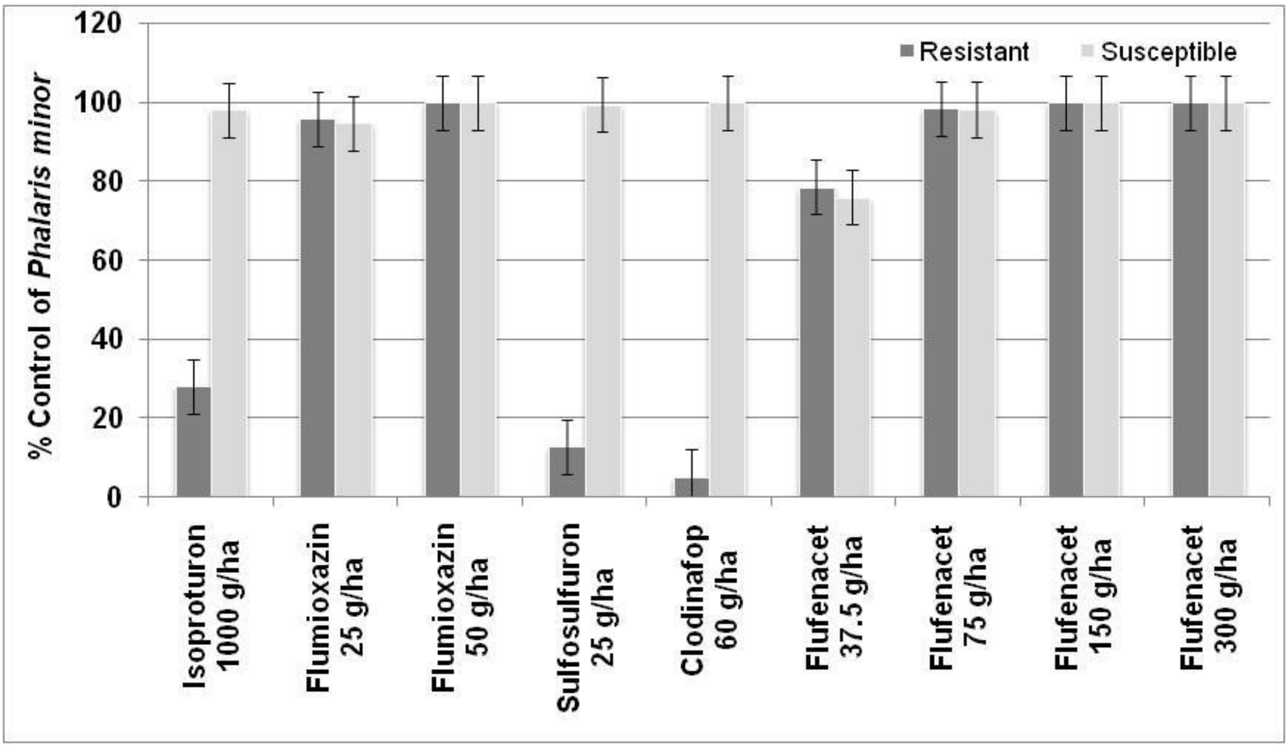

Figure 3. Control of susceptible and multiple-herbicide resistant populations of littleseed canarygrass (*Phalaris minor*) with flumioxazin and flufenacet. Vertical bars represent ± LSD (0.05) =6.92 for population x herbicide interaction

The various herbicide treatments had significant effects on the tillering and the wheat crop biomass, influencing the wheat grain yield. Overall, flumioxazin was more effective than pendimethalin in controlling littleseed canarygrass, wild oat and bur clover, and as a result, flumioxazin usage (100-150 g a.i./ha) also produced 34-49% higher grain yield over pendimethalin, applied at 1000 g a.i./ha. Therefore, flumioxazin is a better alternative to pendimethalin.

Nevertheless, phytotoxicity to wheat was noted with pre-emergence flumioxazin applications after the first irrigation. Flumioxazin rates of 125, 150 and 250 g a.i./ha caused respective crop phytotoxicities of 8, 12 and 31% at 40 DAA, or 19 days after first irrigation However, the wheat grain yields obtained with 150 and 250 g a.i./ha flumioxazin were similar to the standard weed-free treatment, indicating no adverse effect of flumioxazin phytotoxicity on the wheat yield. Similar results have been reported by others. For instance, Taylor-Lovell et al. (2001), Swann (2002), Price et al. (2002), Askew et al. (2002), Jordan et al. (2009), have all reported flumioxazin phytotoxicity to different crops, with no particular adverse effect on yields. The crop phytotoxicity due to flumioxazin may vary, depending on its rate and timing of applications (Johnson et al., 2006; Jordan et al., 2009), crop cultivars (Main et al., 2003) and specific environmental conditions (Taylor-Lovell et al., 2001; Main et al., 2003; Berger et al., 2012; Belfry et al., 2016).

Swann (2002) reported that the splashing of flumioxazin-treated soil or surface water containing flumioxazin on to the emerged peanut seedlings causes herbicide injury if rainfall occurred between flumioxazin application and peanut emergence. The rainfall before emergence would likely move flumioxazin from the soil surface into the soil profile and this reduces the potential of herbicide injury due to rain splash. Also, pre-emergence flumioxazin treated peanut, when irrigated immediately after flumioxazin application, or 12 days after crop emergence, caused less injury to peanuts compared to irrigated at emergence, or 2, 4 and 8 days after emergence (Price et al., 2004). These results show the effect of irrigation timing and method are critically important factors, which need further investigations in relation to flumioxazin applications in wheat.

The usage of herbicide safeners is a promising solution to prevent or minimize crop injury from herbicides (Davies and Caseley, 1999). Recently, Steppig et al. (2018), reported a reduction in crop injury from flumioxazin application, when soybean seeds were treated with the insecticide thiamethoxam. Moreover, there are also possibilities of improved crop safety and weed control if reduced doses of flumioxazin are combined with other herbicides. Grichar and Colburn (1996) reported improved weed control in peanuts with flumioxazin combined with either pyroxasulfone, pendimethalin or trifluralin. These studies have reported superior weed control with the application of pre-emergence flumioxazin + pyroxasulfone (90%) to flumioxazin alone (66%) or pyroxasulfone alone (61%) at 8 weeks after treatment.

As pendimethalin, pyroxasulfone, and trifluralin are also selective herbicides in wheat, their combinations with flumioxazin can also be viable herbicide options. However, if flumioxazin is applied alone, some weeds, such as wild oat, might escape, and may need to be controlled by a post-emergence herbicide. A combination strategy of a pre-emergence herbicide, followed by a post-emergence herbicide, may reduce the antagonism and crop phytotoxicity that may be encountered with post-emergence tank mixes to control a broad spectrum of weeds (Zhang et al., 1995). Presently, such crop phytotoxicities are being noted in northern Indian plains, where farmers are tank mixing metribuzin with either pinoxaden or clodinafop or sulfosulfuron to control multiple herbicide-resistant *P. minor* and other broad-leaved weeds. Also, where farmers are tank mixing 2,4-D or metsulfuron with clodinafop or fenoxaprop, there is reduced grass weed control due to antagonism of the herbicides in tank mixtures (Chhokar et al., 2012; Singh and Chhokar, 2015).

In addition to pre-emergence applications, flumioxazin can also be a pre-planting (PP) option, either alone, or in combination with foliar-acting herbicides, to improve the control of existing weeds, before planting in a no-till system. Such an option would broaden the weed control spectrum, as well as extend the weed control potential for a longer period.

The soil residual activity of flumioxazin is an additional advantage, which is missing with many foliar-applied herbicides, such as glyphosate or paraquat, commonly used pre-plant in no-till wheat cropping. However, the time duration between the pre-planting herbicide application and crop seeding should have a minimum residual adverse effect on the crop. Askew et al. (2002) reported that no-till cotton, planted in cotton and corn stubbles, was injured 12% if flumioxazin was applied as pre-emergence on the day of planting. This injury was much less (3%), if the application was made at least two weeks before planting.

Similarly, Price et al. (2002) reported that the pre-planting flumioxazin as a 'burn down' option at 71 g a.i./ha should be used at least 30 d before planting cotton. The inclusion of a residual herbicide, such as flumioxazin in a pre-planting treatment, can reduce the early-season weed interference in conservation agriculture, which does not use tillage at planting. Research trials in peanut with flumioxazin have also shown useful levels of residual weed control (Askew et al., 1999).

Although no-till wheat production system under a rice-wheat sequence reduces the incidence of littleseed canarygrass in wheat (Chhokar et al., 2007), the inclusion of pre/pre-plant flumioxazin in such a system has the potential to further improve littleseed canarygrass control, due to the residual soil activity of the herbicide. However, the application timing and doses of flumioxazin, as a pre-planting option in no-till wheat, need to be optimized and standardized, to avoid causing crop injury.

Also, to lower the risks of flumioxazin injury to wheat and any potential grain yield reductions, the role of other agronomic factors, such as increased seeding depth, higher seed rates (125-150 kg/ha) and the use of crop safeners need to be investigated. Additionally, other interventions, such as sub-surface drip irrigation and bed planting options, may also be explored for reducing any phytotoxicity on wheat, in comparison to standard methods of irrigation. Swann, (2002) had shown increased phytotoxicity, when flumioxazin comes in to contact with the crop foliage, either as splash after rainfall, or applied as a solution after irrigation.

The results of the second field experiment showed that early post-emergence applications of flufenacet at 250-300 g a.i./ha were very effective in controlling both the dominant grass weeds, but was ineffective against broad-leaved weeds, which infested the fields (Table 3). Nevertheless, the effectiveness of flufenacet for controlling a wide variety of economically relevant weeds in maize, soybean, potato, cotton, peanuts, rice (*Oryza sativa* L.), sunflower (*Helianthus annuus* L.), tomato (*Lycopersicon esculentum* L.**)** and wheat is well documented (Bloomberg, 1997; Brinkmann and Dahmen, 1997; Kremer, 1997; Diehl and Benz, 1998). The grass weed control with flufenacet at 300 g a.i./ha did not significantly differ with the standard graminicide check of clodinafop at 60 g a.i./ha.

The flufenacet treatments recorded higher broad-leaved weeds dry weight compared to the un-weeded control due to the removal of grass weed competition in flufenacet treated plots whereas, in the un-weeded control plots, the competition from dominant grass weeds decreased the broad-leaved weeds biomass. Earlier studies had also showed the effectiveness of flufenacet against grasses and not on broad-leaved weeds in wheat under Indian conditions (Chhokar et al., 2006a).

Keeping in view the ineffectiveness of flufenacet against broad-leaved weeds, a broad-leaved herbicide partner may be required, and it would be better if it is from different chemical group presently being used and is also effective against grass weeds. This strategy, in addition to providing broad-spectrum weed control, may also help in managing the existing resistance problem and delaying the further extension of herbicide resistance in grass weeds, thereby improving the opportunities for sustainable wheat production.

Also, the wheat grain yields under flufenacet 250-300 g a.i./ha, clodinafop, and weed-free check treatments were statistically in the same group but significantly better (57 to 63% and 133 to 144% higher grain yield) than un-weeded control. The better yields under these treatments were due to excellent control of dominant competitive weeds (littleseed canarygrass and wild oat). The highly competitive nature of littleseed canarygrass has also been reported earlier (Chhokar and Malik, 2002; Chhokar et al., 2008). Slight stunting (about 6-8%) was observed in flufenacet treatment after the first irrigation did not affect grain yield. Earlier studies also reported flufenacet phytotoxicity (stunted growth) in wheat (Ritter and Menbere, 2002; Chhokar et al., 2006a; Kleemann et al., 2016).

Our studies indicated the effectiveness of pre-emergence flumioxazin and early post-emergence flufenacet in controlling littleseed canarygrass, including the multiple herbicide-resistant populations. Presently, the multiple herbicide-resistant littleseed canarygrass is spreading continuously and impacting the large wheat acreages in north-western Indian plains. Still, farmers are widely using clodinafop, pinoxaden, and sulfosulfuron at higher rates in resistant prone areas due to the non-availability of effective alternative herbicides. As a result, there are yield penalties. To curtail the yield losses due to herbicide resistance, there is an urgent need for suitable alternative herbicides. Our studies show that flufenacet and flumioxazin can be alternative options in the resistance management programs in wheat, particularly against canarygrass.

Flessner et al. (2013) reported the control of annual bluegrass (*Poa annua* L.) with the post-emergence application of flumioxazin in bermudagrass [*Cynodon dactylon* (L.) Pers.] turf. Annual bluegrass also infests late-sown wheat crop, and most of the widely used herbicides in wheat (clodinafop, fenoxaprop, and sulfosulfuron) are not effective against this weed (Chhokar et al., 2012). Annual bluegrass is also known to be resistant to several herbicides, including glyphosate, sulfonylureas, and triazines (Heap, 2019). Therefore, we contend that flumioxazin can be helpful in resistance management, as well as in controlling this problematic weed in wheat fields.

Compared to flumioxazin, which is more suited as pre-plant and pre-emergence applications, flufenacet has a more extensive window of applications, as it can be applied as pre-plant, pre-emergence or early post-emergence (Bunting et al., 2003; Chhokar et al., 2006a). Moreover, its combination with other herbicides, such as diflufenican, metribuzin, or triallate, gives an opportunity to manage a broad spectrum of weeds in wheat (Koepke-Hill et al., 2011; Lawrence and Burke, 2014; Kleemann et al., 2016).

Bunting et al., (2003) reported that Giant foxtail (*Setaria faberi* Herrm.) control with flufenacet plus metribuzin applied at 60, 45, 30, and 15 days before planting and at planting (pre-emergence). The control achieved was insensitive to application timing from 60 days before planting to pre-emergence. In contrast, Koepke-Hill et al. (2011) reported higher levels of Italian ryegrass (*Lolium multiflorum* Lam.) control with post-application of flufenacet plus metribuzin (77 to 99% control) than pre-application of the herbicide mixture (73-77% control). Therefore, further studies are required to identify the suitable application timing and companion herbicides for flufenacet to control a broad spectrum of weeds.

In fields, having wild oat infestations, particularly the ALS and ACCase resistance, flufenacet should be opted, as both flumioxazin and pendimethalin are ineffective for its control. Since flufenacet and flumioxazin are also selective in soybean and other pulses, these herbicides can also be useful tools for the management of ACCase and ALS inhibitor-resistant grasses in legume crops. Recently, in India also, jungle rice (*Echinochloa colona* L. Link) in soybean and rice has shown resistance to ALS inhibitor herbicides, and these herbicides (flufenacet in rice and both flumioxazin and flufenacet in soybean) can also be targeted for management of herbicide-resistant jungle rice in these crops. Although flufenacet and flumioxazin have been registered for use in multi crops, yet low incidences of resistance in weeds have been reported against these herbicides (Heap, 2019).

Our studies indicate that both pre-emergence flumioxazin and early post-emergence flufenacet are quite effective for the control of littleseed canarygrass, including populations, which are multiple herbicide-resistant (resistant to isoproturon, clodinafop, and sulfosulfuron). Therefore, these herbicides can be alternative options for resistance management programme in wheat. A comparison between flumioxazin and flufenacet showed the edge flumioxazin has over flufenacet for the control of the broad-leaved weed flora. However, in fields infested with wild oat, the application of flufenacet should be preferred over pre-emergence applications of either flumioxazin or standard pendimethalin, as these two herbicides are not adequate for wild oat control.

It should be noted that in the past two decades, herbicides with new modes of action have not been introduced (Green, 2014). Therefore, we suggest that the few effective, available herbicide options should be used judiciously, integrated with non-chemical methods, in such a manner that their effectiveness is prolonged. As discussed by Norsworthy et al. (2012), Walsh et al. (2013) and Shaner and Beckie (2014), the effective herbicides should be integrated with all possible non-chemical options, such as cover crops, tillage, crop rotation, and harvest and destruction of weed seeds to reduce weed seed banks. In addition, managing herbicide-resistance in wheat-growing areas would also require crop rotation, including the use of 'break crops', such as oilseed, pulses, corn or sugarcane or fodder crops, in those fields, which have herbicide-resistant weed populations.

Broadly, the integration of chemical and non-chemical tools would provide an opportunity to use the alternative herbicide chemistries, thereby reducing the risk of resistance evolution and further build-up of herbicide-resistant weed populations.

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