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EDITORIAL

Promoting the Utilization of Weeds – A Way Forward

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Abstract

The utilization of 'weedy' colonizing species for direct human benefits and other practical applications is a much-neglected area within *Weed Science*. It results from an inadequate 'eco-literacy' (i.e. ecological understanding of weeds), which I call 'weed-illiteracy'. Most weed scientists have been brought up hearing a flawed myth that '*all weedy species are bad all the time*', and some may even engulf the world.

Humans present the greatest threat to biodiversity, of which people and weedy species are constituent parts. However unpalatable this message is, it needs to be given much more publicity to achieve a better balance between human greed, the development aspirations of nations, and global biological diversity. A change in attitude and a focus shift are required to redress the issue.

The *Boundary Object* concept provides an opportunity to have meaningful discussions about weedy taxa that have been used as a scapegoat for too long to hide human follies (related to disturbances caused by land-clearing, deforestation, inappropriate forms of agriculture, and excessive population growth). Consensus helps but is not always necessary for cooperation in successfully conducting investigative research. The boundary object approach allows collaborations on investigations of weedy species without always agreeing on divergent viewpoints. These may help ease the tensions and *change our perceptions* of colonizing species. It will also allow weed scientists, trained to think negatively about weeds, to explore the benefits of a positive relationship with a vast array of such taxa and their unique capabilities. Weeds should not be accused as guilty (of harm) until proven innocent!

Colonizing species could assist in achieving the *U.N.'s Sustainable Development Goals* (SDGs) and *Millenium Development Goals* (MDGs), whose visions have been renewed. These globally-accepted frameworks seek to re-align investments and direct research efforts to improve societal benefits. Seeking ways to derive benefits from weedy taxa should be the basis of their fuller integration into societal needs. Instead of waging an unwinnable war against weeds, there is a convincing case for *living with weeds* for societal and environmental benefits.

Weed Science education must be re-aligned to increase 'weed literacy' by providing a much deeper biological and ecological understanding of weeds among agriculturists and environmentalists. Fast-growing and robust weedy taxa are at the forefront of providing *ecosystem services* in all habitats they occupy. Their ecological roles, including pollination and stabilization of degraded landscapes, are much undervalued within Weed Science. There is also compelling evidence that calls for broadening the mandate and the direction of *Weed Science* research to include the utilization of colonizing taxa. A 're-think' on how we perceive weeds and weed research should be a priority for everyone concerned about the Planet's future and preserving its biological integrity and diversity.

Keywords: Colonizing species, weeds, utilization of weeds, Weed Science, weed research

The Colliding 'Worldviews' on Weeds

Most weed scientists are trained from their early careers to 'see' weedy species as 'enemies' and to fight them so that agriculture can be made profitable. This pessimistic 'worldview' on weedy species was purely from an agricultural perspective. The view that we must declare *war* on weeds and 'exterminate' them from our lands was first mooted by William Darlington, 1859) in the mid-19th Century [1]. However absurd the thought was, it became entrenched in the early decades of the 20th Century (Evans, 2002; Falck, 2010; Chandrasena, 2014; 2019, 2020, 2021).

However, not everyone hated weeds, even in the mid-19th Century. Despite the farmers' concern about the *unpredictable* crop losses from pests and weeds, a relatively benign attitude towards weeds also prevailed, at least within some sections of society in North America. For instance, a famous American Poet – James Russell Lowell (1863) wrote:

> *'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...'*

Another influential naturalist, Ralph Waldo Emerson (1979, p. 8), praised weeds in a famous lecture delivered in Boston, USA, in 1878:

> *'What is a weed? A weed is a plant whose virtues have not yet been discovered'.*

Such statements show that sections of American society had no qualms about boldly expressing the positive side of weeds. At this time, the USA was emerging from the traumatic Civil War years (1861-65), which had ravaged much of agriculture in the conflicted South-Eastern States of the country. There were other naturalists also in the latter half of the 19th Century, such as George Perkins Marsh (1867), Gerald McCarthy (1892) and Asa Gray (1879), whose sympathetic views on weeds preceded our ecological understanding of the strengths and capabilities of colonizing taxa.

Weed Science, as a discipline in agriculture, first received significant national recognition in the USA and Europe only in the mid-1940s (Burnside, 1993). The almost simultaneous discovery of herbicides 2,4-D (2,4-dichloro-phenoxy acetic acid) in the USA and MCPA [(4-chloro-2-methyl-phenoxy) acetic acid] in England during the *World War II* years (1941-42), revolutionized the field of selective weed control.

For the first time in history, around 1944, the selective activity of the auxin-mimic herbicides in controlling broad-leaved weeds in grass turf was demonstrated in the USA and U.K. This led to much excitement and the release of the first commercial herbicides (Duke, 2005). More or less, at the same time, the absurd idea of a '*War With Weeds'* took root (Evans, 2002; Falck, 2010; Dwyer, 2011).

This misguided attitude has been a bane of *Weed Science* and has been around for more than 70 years. From that time, this slogan has been like a *mantra*, repeatedly heard at various weed conferences. The war metaphor, a concocted narrative, believes *humans could win a war against weedy enemies*. The primary 'weapons' of war (herbicides) expanded rapidly as many new molecules were discovered and developed as commercial products in the 1950s and '60s decades. *Weed Science*, as a discipline, flourished in those decades (Duke, 2005; Timmons, 2005).

Somewhere along the way, we lost track of what we were dealing with. *Weedy species are a small cohort of the Planet's rich biological diversity*. The species we label 'weeds' are ecologically nothing but 'colonizing plants'. They comprise about 9-10% (about 3000 of 375,000 known plants worldwide) [2]. The taxa originated under a natural environment and in response to newly opened habitats or imposed habitat constraints to 'colonize' the vacant habitats. The evolutionary driver has been the opportunities created by disturbances and the availability of vacant niches. The genetic makeup of these extraordinary plants was formed more than 100 million years before humans walked on the Earth.

Herbicides initially provided highly effective weed control across agriculture and many other areas where weedy taxa posed problems, such as golf courses, infrastructure, public spaces and rights-of-way. These chemicals were considered 'saviours' and not problems. However, within two decades, the overuse of herbicides for weed control in agriculture

[1] William Darlington (1859), a medical doctor from Pennsylvania, was the first American to publish a copious 'Modern-day' volume on weeds. He compared weeds to the Western Plains 'savages' (First Nation Americans) that should be *fully exterminated* just like the European foxes were targeted for eradication in the British Isles!

[2] In 2016, the accepted number of plant species stood at ca. 374,000, of which approximately 308,312 were vascular plants, with 295,383 flowering plants (angiosperms; monocots: 74,273; eudicots: 210,008). Global numbers of smaller plant groups were as follows: algae – ca. 44,000, liverworts – ca. 9,000, hornworts – ca. 225, mosses – ca. 12,700, lycopods – ca. 1,290, ferns – ca.10,560 and gymnosperms – ca. 1,079.

and other situations presented a significant difficulty in the USA, U.K. and Western Europe.

More than six decades ago, ecologists and biologists warned that weeds would most likely evolve resistance to the repeated use of herbicides on the same land (Harper, 1956). The incredible success of herbicides in killing weeds and the profits that could be made by the chemicals led to these warnings being largely unheeded.

It also prompted *Weed Science to be derided as 'Herbicide Science'* (Burnside, 1993; Appleby, 2005). The excessive focus on weed control and herbicides hampered the discipline from broadening an understanding of how people should integrate colonizing species more effectively and profitably into their lives.

Despite those enlightened views on weedy taxa, the opportunities to utilize their strengths were not realized for another 100 years until the latter part of the 20th Century. Water hyacinth [*Pontederia crassipes* Mart.] and other aquatic weeds were the first taxa to be seriously examined for utilization for societal benefits, mainly in the USA and for promotion elsewhere, especially in developing countries (Wolverton and McDonald, 1976; 1979).

My objective in this essay is to explore avenues by which the utilization of colonizing taxa can be promoted, giving their human adversaries a chance to 're-think' and adjust their positions – if that is warranted. Herein, I discuss some ideas, concepts, and a framework that might help shift attitudes on weeds towards a more balanced 'middle path,' a doctrine that humans would do well to embrace.

The 'Boundary Object'

The *Boundary Object* is an analytic concept of 'scientific' objects or entities inhabiting several intersecting and potentially conflicting social worlds. The idea was first explored by Susan Star and James Griesemer (Star and Griesemer, 1989) in a seminal paper published in the *Social Studies on Science* journal. From my viewpoint, the terms '*weeds*' and '*utilization of weeds*' can be both 'boundary objects' because they divide people's opinions by an invisible boundary. Weed Science history knows that disagreements about some weedy taxa can be robust among scientists who deal with them.

Nevertheless, from the original concept, boundary objects can link communities together as they '*allow different groups to collaborate on a common task*' without agreeing on every issue. The 'common task' for which people must 'collaborate' is to understand the beneficial aspects of colonizing species and manage them without causing further damage to fragile ecosystems.

A few definitions and interpretations of a boundary object show this possibility (Figure 1).

> *'A Boundary Object is an entity (**artifact, object, document, vocabulary**) that can help people from different communities build a shared understanding. Various communities will interpret boundary objects differently. Acknowledging these differences enables a shared experience to be formed.*
>
> *'A boundary object **allows coordination without consensus** as they can allow an actor's local understanding to be reframed in the context of a wider collective activity'.*
>
> *'Cross-disciplinary collaborations require negotiation across disciplinary work boundaries, rather than working separately at the edges of the shared boundary'.*
>
> *'Boundary Objects are **learning objects**. This understanding acknowledges their role in 'making meaning' and better communications across diverse social groups'.*
>
> *'Objects which are both plastic enough to adapt to local needs and the constraints of the several parties employing them, yet robust enough to maintain a common identity'.*

How could weed scientists apply the boundary object concept as a *learning object* and a *tool* to improve communications between parties with different worldviews? A better ecological and evolutionary understanding of the species in question would reduce the tensions between those who *despise* weeds and others who *admire* them.

What happens when humans excessively disturb and modify their habitations and natural ecosystems is well known. Ecologists expressed six decades ago that w*eeds are not the cause but a symptom of our inability to and failures in managing our living environment* (Bunting, 1960; Baker, 1965; Baker and Stebbins, 1965).

Weeds show us how plant succession occurs in new habitats after natural or human-caused disturbances. These taxa also highlight the evolutionary forces in Nature through their adaptations (see Baker, 1965). With more than 120 million years of evolution in their genes, weedy taxa are far more successful in every sense as organisms than their human adversaries.

Using the 'boundary object' concept, those who admire weedy taxa could explain their strengths, weaknesses and virtues while asking for sustainable approaches to managing weeds where they may pose problems to humans. These may include preventative, cultural and biological weed control, conservation farming, regenerative agriculture and ecological restoration methods. This side of the debate should also present evidence of the failures of overkill and the results of the overuse of herbicides (water and soil pollution, resistance development in weeds, biodiversity losses and public health issues).

Those with a relatively benign but still adversarial relationship with weeds will undoubtedly and justifiably re-iterate the losses of crop yields, farming profits, and other harmful effects of weeds, including potential habitat degradation and biodiversity losses (largely unproven). Those with hard-nosed attitudes towards weeds (i.e. *Invasion Biologists*) and those who follow such a narrative without challenge will continue to defend their robust actions to protect '*natives*' against '*alien invasions'*.

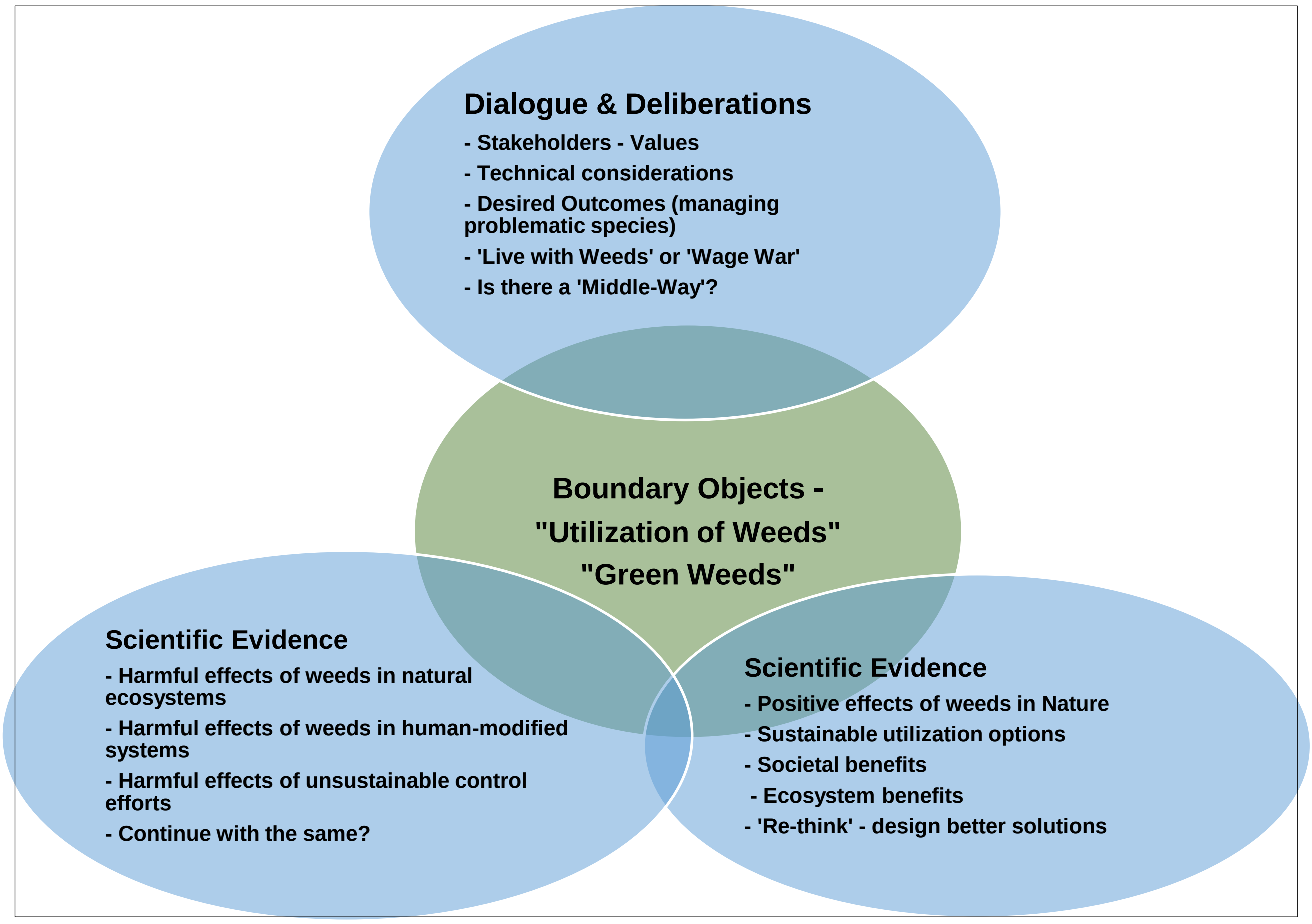

Figure 1 'Utilization of Weeds' as a Boundary Object in facilitating deliberate discussions without agreeing on every issue but aiming for rational discussions and collaboration between different stakeholders

The virulent undertones of this debate hamper the coordination of workable weed management solutions across landscapes. The more balanced position might be a 'middle-way' (Jordan and Davis, 2017) to show the progress of *integrated weed management* (IWM) approaches, which are well-developed. All weed scientists and agriculturists know that IWM focuses more on preventative, cultural and biological weed control methods, which minimize the ecological disturbances caused by other methods, such as the excessive use of mechanical weed control or herbicides.

Are Weeds 'Guilty until proven Innocent'? Not So

E O Wilson's book (1992) popularised the notion that '*invasive species*' are the '*second greatest threat in the world*', following '*habitat loss*'. The contentious idea ignited the emergence of *Invasion Biology* as a subject, expanding the ideas expressed in Charles Elton's book (1958). The simple but fraught ecological process of '*colonization*' by which highly adaptive taxa are established in new areas was misconstrued with a fear-invoking term '*invasion*'.

Despite the lack of consensus (Hall, 2003; Shackelford et al., 2013), many taxa are used as scapegoats for human follies and blamed as

'*Invasive Alien Species*' (IAS) that might engulf our Planet (Mooney et al., 2005; Rejmánek et al., 2005).

Nevertheless, many biologists have challenged the false assumptions in the '*invasions*' and '*native*' versus '*alien*' viewpoints (Davis and Thomson, 2000; 2001; Daehler, 2001; Theodoropoulos, 2003; Davis, 2005; Larson, 2005; Shackelford et al., 2013). These were followed by solid objections by philosophers (Sagoff, 2002) and environmental historians (Chew and Laubichler, 2003; Chew and Caroll, 2011; Dwyer, 2011; Chew, 2015; Guiaşu and Tindale, 2018). Writing to *Nature*, Davis and 18 others (Davis et al., 2011) complained about the nebulous concepts and narratives that blamed introduced species for human follies and objected to using fear-invoking terms in public discourses [3].

Defence against *invasions* became a primary goal of conservation biologists, who claim that the '*impacts*' of IAS present a dire threat to biodiversity. In this narrative, any form of *colonization* of a new location by plants or animals is viewed as a problem (Chew, 2015). Introduced species are accused of driving out the '*natives*' all the time, an unproven claim in many landscapes. The ecological evidence that 'non-native' species seldom compete successfully with 'natives' in relatively undisturbed ecosystems is lost in this debate.

Disagreements about these views hinder the utilization of many species with unique capabilities that can be harnessed to help societies. Regrettably, the ideas were embedded in the *Convention on Biological Diversity* (CBD, 1992) without much challenge. This inhibits people from thinking more positively about colonizing species and the advantages they may offer to society [4]. The absurd assertion that all introduced species should be treated as *'guilty' until proven innocent* took the maligning of weedy taxa to unjustified depths.

To say that: '*all weeds must be guilty until proven innocent*' is a form of populism at its worst. The reversal of the universally accepted concept that everyone is '*innocent until proven guilty*', so clearly enunciated for the public good, is intellectually dishonest. The quicker we stop using such divisive language, the better we will be as a society.

A large number of species, including some 'farmer-friendly' weeds, are listed as IAS, deserving lethal killing for merely occupying human spaces. In the confusion created by the IAS branding, one can excuse the public, scientists and policymakers for being misled. Many have been brainwashed to think that all 'weedy' species are plunderers of our resources, moving across geographical barriers to engulf continents. Changes to such irresponsible typecasting will come with time as attitudes change.

Discussions on weed discourses would do well to jettison the politically evocative terms - '*alien*', '*feral*', '*invaders*' and '*invasions*' and revert back to 'introduced species' (Chandrasena, 2021). The boundary object concept can provide the framework for such a change, allow rational discussions, and work towards collaborations without necessarily agreeing on every aspect of the entity.

Those concerned with the environment must understand that the *Invasion* narrative was designed to create public awareness of the potential risks of introducing species across continents and countries. Undoubtedly, the powerful terms used influence the public's thinking and prevent positive relationships with weedy taxa. Critics (Theodoropoulos, 2003) point out that the *invasion* narrative has nothing to do with a genuine interest in saving the world from *invaders*. The claim appears to be hyperbole to get more funding *for managing such invaders*.

Historical usage of the terms shows that the concept of '*nativeness*' lacks reliable ecological content. It simply means that a species under scrutiny has no *known* history of human-mediated dispersal and may have been a resident of a given bio-geographical area for centuries (Chew and Carroll, 2011; Hall, 2003). Ecologists are responsible for proving that 'non-native species' seldom compete successfully with 'natives' in intact and relatively undisturbed ecosystems.

Human influences, i.e. deforestation, excessive land clearing for urban developments, nutrient enrichment in waterways, unsustainable levels of pastoralism and altered fire regimes, are some of the most significant causes that facilitate the spread of introduced species.

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[3] The '*Native*' versus '*Alien*' debate clouds weed-related discourses. '*Natives*' are implied as natural, innocent and untainted by any human association; '*Aliens*', like their human enablers, are implied to always have detrimental impacts or effects, an unproven claim. The pervasive myth thus created is: *'If a species is not native, it is bad, and the reason it is bad is that it is non-native'.*

[4] Following the first claim, E O Wilson (1997) wrote that: '*Extinction by habitat destruction is like death in an automobile accident: easy to see and assess. Extinction by the invasion of exotic species is like death by disease: gradual, insidious, requiring scientific methods to diagnose'.* Ken Thompson (2014), an ecologists, in his book '*Where Do Camels Belong?*' called such an unproven idea a deliberate lie! "*The assertion that alien species constitute the second greatest global threat to biodiversity has been debunked so often (yet is endlessly repeated) that it no longer deserves the status of a myth and is best described merely as a straightforward lie*…" (Thomson, 2014)

When moved across geographical barriers and continents, only a mere handful can successfully establish themselves without help from humans. Also, only a few grew so much that they caused problems for humans and natural ecosystems. Moreover, many global examples indicate that not all species' introduction to new areas, regions, or continents is so dramatically detrimental, as conservationists and the media prefer to claim.

Ecology teaches us that given the variety of life cycles, reproductive strategies, and the dispersal means that plants and animals have, species can move about and spread on their own, crossing geographical boundaries. Many are assisted by natural vectors (wind, cyclones, water, landslides) to spread, establish, and colonize new areas. They also benefit from the disturbances that humans and other animals cause. However, *not all species, moved about by humans or other vectors, can succeed in all habitats in their new environments* (Watson, 1847; 1870; Dunn, 1905; Parker et al., 2013).

'Green Weeds' as a Boundary Object

How valid is the term 'green weeds' when used as a boundary object? The terms 'green economy', 'green technologies' and 'green living' are already well-entrenched boundary objects in the global environmental discourses. As a result, the term 'green' is no longer ambiguous because it has a definite meaning when used in the proper context.

The term 'green' arose from citizen-driven, environmental movements in the 1960s and '70s. For centuries, people arguably lived more or less in balance with their surroundings. But a burgeoning population and economic booms in industrialized and developed countries put unbearable pressure on the Planet's climate as well as its natural environment and resources, including forests, waterways, soil, animals, and plants. The 'green' movement has now captured the attention of a significant population of ecologically-minded people in almost all countries. Climate change uncertainties have renewed the interest in 'green' and sustainable living, in harmony with the environment and 'eco-friendly' technologies. The scientific basis of 'green' living includes less consumption, less demand, fewer ecological perturbations, renewable energy, and recycling all biological and non-biological resources.

The green movement must also be recognized as a diverse scientific, social, conservation, and political movement that broadly addresses the concerns of environmentalism. It encompasses political parties, organizations, and individual advocates operating on international, national, and local levels. These groups are broadly unified 'across their boundaries' by a desire to protect the Planet's environment and Nature's capital (plants, animals, soil, air and water resources). If not for this common goal, many groups are diverse in philosophies, strategies and actions they champion.

Despite obstacles, the 'green movement' has succeeded in heightening public awareness of environmental issues that cause distress to the Planet and its inhabitants. Its growth reflects widespread social and scientific concerns about the degradation of the Earth's bio-physical environment. Everyone needs to realize that 'Going green' implies changing peoples' awareness about how their behaviour and consumption patterns contribute to unsustainable ecological harm to the Planet.

'Green enlightenment' aims to create or increase ecological awareness (*eco-literacy*) in societies. It seeks to cause lifestyle changes and reduce individuals' and collective societies' ecological footprint. These moves must be seen as in the right direction to save a planet in peril. As discussed below, I find 'green weeds' to be an appropriate adjective that can be readily lined up with well-established global concepts and efforts to improve the Planet's well-being.

Ecosystem Services and Biodiversity

The Millennial Ecosystem Assessment (MEA, 2005) defined *ecosystem services* as the direct and indirect contributions of ecosystems to human well-being, survival and quality of life. The concept of an ecosystem provides a valuable framework for analyzing and acting on the links between people and their environment. Ecosystem services can be categorized into five main types (MEA, 2005):

Provisioning services – these are the products obtained from ecosystems, such as food, fresh water, wood, fibre, spices and medicines.

Regulating services – those defined as the benefits obtained from the regulation of ecosystem processes, such as climate regulation, natural hazard regulation, water purification and waste management, pollination or pest control.

Habitat services highlight the importance of ecosystems in providing habitat for migratory species and in maintaining the viability of gene pools.

Cultural services include non-material benefits that people obtain from ecosystems, such as spiritual enrichment, intellectual development, recreation and aesthetic values.

Evolutionary services including benefits, such as genetic resources that evolve due to selection pressure exerted by humans and nature.

Biodiversity is the source of many ecosystem goods, such as food and genetic resources, and changes in biodiversity can influence the supply of ecosystem services. *Colonizing species are crucial members of global biodiversity and contribute to all of the five types of ecosystem services*.

Sustainable Development Goals

Within the 'greening' ethos, I propose using the term 'green weeds' deliberately as a *semiotic* (a sign) to create an impression of opportunities. Can 'green weeds' be a part of human efforts to save the Planet? The evidence is compelling to say yes. However, weed scientists need to be convinced and encouraged to change their deeply-held views about the harm to human endeavours caused by weedy taxa. As discussed in this essay, 'green weeds' could help in many ways that would reduce the ecological impacts of humans and redress some damage that has already occurred on the Earth.

Historical facts and existing global knowledge illustrate that our weedy colonizers undisputedly contribute heavily to societal development in several critical areas, such as (1) Food and nutritional security and sustainable diets; (2) Sustainable livelihoods; (3) Poverty alleviation, (4) Women's empowerment, and (5) Gender equity.

Nevertheless, given the need to break down barriers and get people to 're-think' their entrenched beliefs and lead them to have a balanced and rational discussion on the contribution weedy species can make to society, frameworks are needed. One important tool on which to base a balanced discussion is the United Nation's *Sustainable Development Goals* (SDGs), which have been updated for 2030 (U.N., 2024).

The latest update encourages signatory countries to pursue with vigour 17 goals (Table 1). Based on widely published information, data, and results over at least seven decades, a vast array of colonizing taxa can contribute significantly to achieving these goals.

At a UN summit in September 2015, 193 countries agreed to work towards the 17 Goals with the aim of improving the lives of all people and the Planet we inhabit. I propose using these Goals as a driver to promote the utilization of weedy taxa and thinking prompts, as shown in Table 1.

To illustrate, I used an arbitrary scoring system from 0-5 to comment on the potential of weedy species to deliver benefits in achieving the UN-declared SDG goals. In this scoring, numerous, palatable edible weeds, which form a part of the diet in most countries, will score high in their potential to end hunger and achieve improved nutrition for societies (SDG Goal 2).

Sustainable diets are diets with low environmental impacts that contribute to food and nutrition security and a healthy life for current and future generations. Medicinal weeds that can be commercially extracted for pharmaceutical benefits need no further elaboration. Most societies also appreciate the dual benefits (nutritional and medicinal) that some taxa provide. Knowledge about such weeds dates back many millennia, well before the Christian Era, and must be an integral part of human society's future development.

The SDG Goal 1 – Ending poverty relies on all forms of employment that can increase peoples' income and living standards. A great many weedy taxa, particularly multi-purpose, fast-growing shrubs and trees, already form the basis of cottage industries. These range from cellulose, fibre, dyes and essential oil extractions to paper and pulp industries. The production of innumerable saleable items by craftspeople and artisans using weed species as raw material is well established.

The products based on weedy species extend from baskets and mats to the globally-popular water hyacinth furniture. In addition to contributing significantly to poverty alleviation, cottage industries empower women (gender equity) and provide life-long learning to children and youth of the future while supporting families, livelihoods and the well-being of societies (SDG Goals 3, 4, 5, 8 and 9).

SDG 6 relates to sustainable management of water resources and sanitation. Colonizers, such as water hyacinth, cattails (*Typha* L. spp.), common reed [*Phragmites australis* (Cav.) Trin. ex Steud.] and many others are crucial components of wastewater treatment systems and constructed wetlands used to extract nutrients from stormwater draining large areas.

Without such resilient species with robust growth and wide ecological amplitudes, pollution reduction in waterways is not achievable. The phytoremediation potential of colonizing aquatic taxa, which is well demonstrated by a large variety of heavy metal accumulators, also falls under this goal. Some of the best examples are given in Appendix 1.

Table 1 Potential Contribution of Colonising Species to Sustainable Development Goals (U.N., 2024) [Score 0-1 = Low; 2-3 = Medium; 3-5= High] [5]

Goal No.	Goal Purpose Contribution	Score	Comments
1	End poverty in all its forms	3-4	Cottage industries, medicinal and edible weeds, food and fodder for livestock
2	End hunger, achieve food security and improve nutrition via sustainable agriculture	4-5	Edible weeds, market gardens, diversified crops, multi-purpose trees
3	Ensure healthy lives and promote well-being for all at all ages	3-4	Those mentioned above, plus Nature-based solutions (NSBs) and education
4	Ensure inclusive and equitable quality education and promote lifelong learning for all	1-2	Nature-based solutions and education
5	Achieve gender equality and empower all women and girls	3-4	Cottage industries, especially crafts
6	Ensure availability and sustainable management of water and sanitation for all	0-1	Water treatment wetlands for water quality improvement
7	Ensure access to affordable, reliable, sustainable, and modern energy for all	3-4	Many biofuel crops and potential taxa are weedy (i.e. high biomass grasses and those that yield oils (such as jatropha and castor-oil).
8	Promote inclusive and sustainable economic growth, productive employment and decent work for everyone	4-5	Small-scale and/or cottage industries, especially handicrafts, based on a large number of weedy raw materials with women's participation.
9	Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation	3-4	Industries such as essential oils, perfumes, dyes and a wide variety of value-added products from weedy species
10	Reduce inequality within and among countries	0-1	No direct effect
11	Make cities and human settlements inclusive, safe, resilient, and sustainable	1-2	Urban greening with fast-growing and resilient species, water-sensitive urban designs and stormwater treatment wetlands
12	Ensure sustainable consumption and production patterns in societies	3-4	Backyard market gardens with edible weeds provide food supplements and raw materials for sustainable consumption and production
13	Urgent action to combat climate change and its impacts (U.N. Convention on Climate Change)	4-5	Resilient landscapes, diversified farming
14	Conserve and sustainably use the oceans, seas, and marine resources for sustainable development	0-1	It may include fish farming and food from Azolla, Lemna, etc.
15	Protect, restore and promote the sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss	4-5	All fast-growing species, including grasses, legume trees and others, restore vegetation via succession processes.
16	Promote peaceful, inclusive societies for sustainable development, with access to justice for all and build effective, accountable institutions.	0-1	No direct effect
17	Strengthen the means of revitalizing the Global Partnership for Sustainable Development.	0-1	No direct effect

U.N. (2024). Take Action on Sustainable Development Goals (**https://www.un.org/sustainabledevelopment/sustainable-development-goals/**).

[5] The UN has been setting global goals since the 1960s as a way to focus attention on the needs of the world's poorer countries. This idea gained prominence with the *Millennium Development Goals* (2000), a set of eight development targets — such as halving extreme poverty and achieving universal primary education by 2015.

SDG 7 aims to promote affordable, reliable, sustainable and 'green' energy for all. This means renewable energy sources, including biofuel crops. Many fast-growing grasses, such as arundo (*Arundo donax* L.) and oil-yielding weeds, such as jatropha (*Jatropha curcas* L.), are at the forefront of contributing to this global goal.

Colonizing species are crucial contributors to SDG 8 (Promoting inclusive and sustainable economic growth and, productive employment and fair work for all) and SDG 9 (Building resilient infrastructure, promoting inclusive and sustainable industrialization and fostering innovation).

Similarly, pioneer species are indispensable components of urban greening, water-sensitive urban designs, urban stormwater treatment wetlands and other Nature-Based-Solutions (NSBs). Resilient, liveable and sustainable cities (SDG 11) cannot be constructed with only slow-growing natives without fast-growing and resilient 'weedy' species.

SDG 12 sets goals to ensure sustainable consumption and production patterns. Cultivating beneficial weed species in backyard market gardens will provide supplementary food, balanced diets, and sustainable raw materials, contributing to lifestyle changes, sustainable consumption and production.

SDG 15 seeks to protect and restore damaged terrestrial ecosystems. Attaining the goal requires action towards sustainable forest management while expanding revegetation of large landscapes to combat desertification. The goal also encourages action to halt and reverse land degradation and prevent biodiversity losses. These objectives are unlikely ever to be attained without selecting and promoting resilient, fast-growing species, including multi-purpose trees from which societies could benefit greatly in the longer term [6].

Can the two Colliding Worldviews be Reconciled?

The essential question we need to answer is how the conflicting worldviews of weedy species can coexist without adversely affecting each other. The boundary object concept allows scientific collaborations without consensus on any aspect. Ultimately, all parties need a way forward to manage the adverse effects of weeds while balancing control efforts with their practical and bioresource values.

A vast knowledge base in *Weed Science* confirms weeds' actual and potential adverse effects on agricultural crops and non-agricultural situations. The adverse effects depend on many factors, including the levels and nature of the disturbances, the specific species and/or the weed community.

Whether the weedy species grow unchecked also determines their success in modifying ecosystems by their sheer abundance and pertinacity. However, not all such species are harmful in all situations. Regrettably, ecological knowledge about plants, animals, microbes and how complex biological systems work on this fragile Earth is not a high priority for most people. As a result, making people understand the virtues of weeds is a considerable challenge.

The uses and opportunities of the species remain under-explored (Jordan and Vatovec, 2004; Chandrasena, 2008; 2014). For some weed scientists, the utilization of weedy taxa seems like an *idealistic position* rather than a realistic and attainable goal. A few, surprisingly, have gone even further, believing that the *utilization of colonizing taxa is the future!*

With some species, such as water hyacinth that can be exploited for innumerable practical uses, as well as arundo and jatropha that can potentially be expanded as biofuel crops, utilization may present modest but manageable risks. Herein, I invoke Colorado State University's Emeritus Professor Robert Zimdahl's thoughts on what a 'good observer' would be (*pers. comm.* Nov 2020):

> *"What we need are good observers. A good observer sees what they are looking for when it is there, does not see what they are looking for when it is not there and sees what they are not looking for when it is there".*

'*Good observers*' and good researchers in Weed Science should not miss possibilities of utilization of weedy taxa. I would also add that all good observers need to *observe as objectively as possible* and have an open mind in acquiring new knowledge. We owe that to Science and our training.

[6] Some globally-important terrestrial weedy taxa, such as lantana (*Lantana camara* L.), mesquite [*Prosopsis juliflora* (Sw.) DC] and some wattles (*Acacia* L.) species, are often accused of causing biodiversity losses on a regional or local scale.

The basis of this argument is that such species are impossible to manage and should not be introduced to any country or region where they are not present. This argument has validity except that most of the alleged, problematic species are already distributed worldwide. Human introductions were the dominant cause of worldwide spread. The success of the species in establishment across continents is attributable to their strengths as pioneering species. The paradox we have is the compelling evidence of their beneficial ecological roles and values to vulnerable communities and societies living in marginally productive areas.

'Responsibility' – a Virtue

Responsibility is counted as an environmental virtue in ethics and is often expressed as a good character trait. With compassion and benevolence, a 'good human being' will take responsibility for behaving appropriately towards the environment, including all other species (Thompson, 2011).

Extending from such ideas, individuals and a collective society *must* take *responsibility* to obtain an enhanced ecological understanding of the interactions between humans, other species and the environment. This awareness is critical in dealing with colonizing taxa. When and where the excessive growth of a weedy species or a community becomes a problem, whether in agricultural or non-agricultural settings, we must manage them using well-developed tools, tactics, and strategic approaches. We must also do so without harming the environment or other organisms that rely on the colonizing taxa. This is being good environmental stewards.

The echo of the misinformation – that humans can win a war against weeds - reverberated through the discipline in the 1960s, '70s and '80s decades. The message was heard loud and clear by public officials, land managers and volunteers, who enthusiastically joined the 'forces' against weeds. More ecological understanding and common sense should have alerted ecologists, weed scientists and environmental scientists that it is foolish to believe in such a myth just because we have an arsenal of herbicides in our possession. As a result of accepting the pervasive myth, most weed scientists have become wary of evaluating the ecological roles that weedy taxa play in Nature and exploring the opportunities to integrate them into our lives.

These days, most media stories blare out the sensational message: *All weeds are bad news*. Disappointingly, thousands of weed research articles, even in recognized weed science journals, also give the same negative message. Many weed scientists are still too busy '*battling*' the evolving weedy taxa to think about concepts and practical applications of utilization that weedy taxa offer.

A major obstacle is the shallowness of the discourse and prevailing '*weed-illiteracy*'. Ideas regarding '*beneficial*' or '*tolerable*' weeds run contrary to killing weeds. Any ideas about utilization are thwarted by the '*fear*' in people's minds regarding weedy species, presented as '*aliens*' ready to engulf the world [7].

Hiding the positive attributes of the accused is part of this story of misinformation. The ease with which proponents spread falsehoods about colonizing taxa inhibits a better relationship with them. *Our societies are poorer for this mistake*.

The frameworks and concepts for managing a potential risk posed by a specific species are well-developed within Weed Science and related scientific disciplines. Given this, we have a moral responsibility to change our attitude towards colonizing taxa so that suitably targeted action to manage them can be taken on a *case-by-case* basis, *where, when and if required*. The experience of ecological restoration projects is that taking drastic and lethal action against any widespread species in most habitats is often unnecessary and futile.

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Devine-Wright et al. (2022) recently argued: '*The learnings from Social Sciences prove that placing people at the centre of solving the problems they have created is essential*'. Additionally, actions by individuals and society are crucial, as humans face a precarious future under a changing climate.

The resolution of most environmental conflicts lies in people's power over issues that concern them. The vexed issue of *colonizing taxa,* which are accused of being a constant problem in agricultural land, home gardens, public spaces or nature reserves, falls into this category.

There can be no doubt that sustainable solutions need to be found for problems that weedy taxa may create by their sheer abundance in specific situations. However, people can only find lasting solutions with a sympathetic attitude and enlightened ecological understanding. Developing practical solutions will require balancing the harmful effects of colonizing taxa with their positive effects, previously discussed.

Zimdahl and Holtzer (2021) have argued that in all our activities, we should worry about the *ethics* of what we do. Humanity has a moral responsibility to '*do no harm*' to the environment, biodiversity and the Planet. In their view, profits alone must not be the

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[7] E O Wilson's 1992 book popularized the flawed notion that 'invasive species' including weeds, are the '*second greatest threat in the world*', following '*habitat loss*'. The idea was attractive to some who got embedded in the *Convention on Biological Diversity* (CBD, 1992). without much challenge. The repercussions are that it inhibited people to think more positively about colonizing species and the advantages they may offer to society (Chew, 2015). Since the first claim, E O Wilson (1997) has written that "…*Extinction by habitat destruction is like death in an automobile accident: easy to see and assess. Extinction by the invasion of exotic species is like death by disease: gradual, insidious, requiring scientific methods to diagnose...*"

critical driver in agriculture or all other productive endeavours. The *environmentally responsible* person will be disposed to acquire the knowledge to achieve and execute that know-how.

It is also important to note that, as climate change adaptations show, *science and technology alone cannot solve complex societal problems*. All our actions should be undertaken with an eye on protecting the Earth and sharing resources with billions of other animals and plants. A priority must be to conserve what *Mother Earth* has endowed us with. However, we must allay our fears of the so-called '*Aliens*' or '*Invasive Alien Species*'.

Regardless of our capacity to kill weeds in most situations, by their sheer tenacity and abundance, pioneering species give us several messages. The paramount message they give is their capacity to adapt rapidly to climate change and to any other selection pressures humans may apply on them. *Despite our undoubted ingenuity, do humans have that adaptive capacity? The answer is no.*

Notwithstanding the inconveniences weeds may cause humans, they will always be there, now and in the future, as part of the Earth's rich biodiversity. *We should be thankful that these pioneer species exist and are unlikely to go extinct.* The time is upon us to enter into a peaceful co-existence with colonizing taxa and learn how to live with them.

Contrary to the alarmists' view, colonizing taxa *will not take over the world*. It should hardly be necessary to point out that *the Earth has no feral future!* The distortions of what science has taught us are driven by the feeding frenzy of the twenty-four-hour news cycles. Sensational messages consume us day-in-day-out. Science writers, looking for attention-grabbing stories, put their own spin and often get the message wrong.

The echo chambers of negative messages on weeds are primarily designed to obtain more funding to manage the *invasion* threats. But they skew our thinking, make people feel powerless, and often debilitate our rational thought processes concerning the true Nature and virtues of colonizing species. Public servants who deal with policies on weeds and natural resources, feeling the need to protect their jobs, prefer not to be too vocal in support of weedy taxa and their uses. Some convince themselves that what they do is correct, and the alternate view - promoting the utilization of weeds for any ecological or societal benefit - will *go against the grain*.

Since the mid-1990s, substantial weed research funding has been spent in Australia, unimaginatively, to 'manage', more or less, the same list of species, with limited success. The absence of funding for exploring potential uses of colonizing taxa in such calls for research reflects how the discourses have been hijacked by the more powerful (negative) voices. *Use-inspired*, *utilization research funding, whether basic (pure) science or applied science, will only come with determined campaigning by concerned citizens, researchers, scholars and academics, who seek better solutions*.

In dealing with weedy taxa, governments often take a '*we-know-it-all*' attitude, which leads to '*top-down*' enforced approaches. Such approaches fail because it does not adequately foster collaborations and community-based weed management. The availability of funding for on-ground weed management is also influenced by privileged stakeholder groups whose voices are more powerful than those of environmental groups and advocates of conservationist agendas.

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Compared to countries with diverse and mature cultures, the European mindset on weeds is an impediment to exploring the utilization of colonizing taxa as bio-resources in Australia. The fear of weeds, stealing resources from crops and drawing energy out of human endeavours is deeply ingrained in the population. Unfortunately, the knowledge of the extensive use of weeds as biological resources within Australia or by other traditional cultures extending to nearby Oceania has not penetrated deeply into the society's worldview.

The low population density in the large Australian continent does not help. Generally, low-density regional communities are too small to economically utilize the large biomasses of colonizing taxa, spread across vast and mostly arid landscapes. Another powerful reason is the relative affluence of the population, given Australia's mining-based economy. Most people are wealthy, deriving income from manufactured goods and services rather than from biological resources.

The affluence creates little incentive for people to utilize natural resources for their livelihoods. This is especially true for plant resources unless that use is directly related to profitable pastoralism (i.e. fast-growing grasses as fodder, and N-fixing ground-covers or shade trees).

A large portion of wealthy Australians also have no reason to develop sympathetic attitudes toward Nature, which they believe is there to be exploited. *In this social milieu, weedy taxa are cast aside as unimportant, or worse still, to be killed off at every opportunity*. The disconnect between sectors in the community and the environment is also a contributory factor that creates conflicts with species.

In Australia, pastoralists derived enormous benefits from N_2-fixing legume trees and leguminous cover crops, introduced over a Century ago to improve grazing lands and animal fodder. But it did not take long for the same farmers to despise these species as they spread across vast, arid rangelands. Although the judgements of wealthy landowners and pastoralists with vested interests are flawed, they form solid political constituencies, and their voices drown opposite views on specific species.

Science is not enough to answer whether we can ever coexist with weeds. Value judgements, societal considerations and democratic decisions are involved. These should be underpinned by scientific and non-scientific knowledge and a commitment to Nature. Non-scientific knowledge comes from traditional knowledge, as well as the personal experiences, intuition, logic, and authority of individuals in a society.

Scientific knowledge, on the other hand, relies on hypothesis-testing and research findings obtained by following the scientific method. Weed scientists are responsible for engaging more with people working on 'weed policies' or focusing on the *social ecology* of weeds. Weed scientists across the globe must also take responsibility for a better understanding of colonizing taxa before embarking on developing unsustainable and lethal solutions. We must learn lessons from how weedy taxa rapidly evolved resistance to the continuous use of herbicides (Heap, 2022).

If our genuine desire is to protect the Planet's environment from the ravages allegedly caused by 'colonizing taxa, blamed as the '*second greatest threat to biodiversity*' [8], we must find more funding to prove this claim more convincingly. We also need better measures and ecological data to inform our understanding of the effects of colonizing species across varied landscapes and time scales. In the long term, most weedy species will *coexist* with the so-called 'natives' without completely displacing the latter or causing irreparable harm.

By writing many articles on weeds, one should not expect the public to understand weeds or weed-related issues of concern. Suppose researchers care about how their findings influence public opinion and government policies. In that case, they must redress this '*communication gap*' and '*translational deficit*'. This deficit, evident in many *Weed Science* articles, is possibly due to inadequate *ecological literacy* and, often, poorly selected research topics with only an academic interest but little practical value to society.

The *translational deficit* regarding the practical applications of specific research findings and insights can only be remedied by balancing scientific evidence with societies' priorities. Perhaps weed researchers should better understand weedy taxa and moderate their views regarding the objects they are dealing with. This will help many researchers not start every article saying that all weeds should be controlled at all costs and that weeds are among the greatest threats to the Planet's biological diversity.

Only cross-disciplinary research, integrating weed research with other disciplines, including *Social Science* and *Ethnobotany*, will allow weed scientists to better appreciate the values of weedy taxa. Weed scientists must realize that they are also responsible for forming hypotheses regarding the potential uses of colonizing taxa that can be carefully tested. Presenting a convincing research agenda is the only way to attract funding from governments or civil societies and change the discourses to favour these resourceful taxa.

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The prevailing *minority view* that weeds are not the enemy of humans, not liabilities, but are valuable resources – for now and for the future, is not a radical idea. Nor is it a misleading notion. Although the message is somewhat muted in the discourses, most people, farmers, biologists, and even politicians who care for the environment will have to agree.

Colonizing taxa have clearly staked claims on disturbed habitats over large landscapes, which are increasing around human habitations. This is inevitable as the vast human population disturbs the Planet's natural ecosystems. Hardly any areas on the Planet now exist untouched by human hands.

The sheer abundance and persistence of many weedy taxa get our attention. They meet our wrath because they will not yield to control easily. These experiences often cloud our judgements, and in this

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At that time, the idea went through without much challenge. The repercussions, felt even today, are that it inhibited people to think more positively about colonizing species and the advantages they may offer to society (Chew, 2015).

Since the first claim, E O Wilson (1997) has written that "…*Extinction by habitat destruction is like death in an automobile accident: easy to see and assess. Extinction by the invasion of exotic species is like death by disease: gradual, insidious, requiring scientific methods to diagnose...*"

confusion, it is easy to overlook the redeeming values of colonizing species. They provide vegetative cover over barren areas, stabilizing soil, anchoring nutrient cycles, producing food for animals and humans, and pollen and nectar for bees. They enrich Nature by adding variety, richness, abundance and biological diversity to any landscape.

Let's listen carefully and also observe carefully. We will hear the silent story that weedy, pioneering species tell us – *of their resilience in the face of adversity and capacity to adapt* – profound lessons humans can and should learn. The species also spotlight a spectrum of human follies in damaging the environments we should preserve.

Learning from Nature

Instead of demonizing species, we must learn from each other, Nature, and pioneering plants and animals. Our ancestors, *pioneers themselves*, did so admirably. Our existence today is a testament to our pioneer ancestors' adaptability and survival skills. Unfortunately, survival is now precarious for many human cultures and societies across the globe.

As climate change poses the greatest threat to humankind's survival, our future existence as a species depends on how well we integrate with Nature's wonders and the challenges the natural world throws at us. Humility, combined with a fundamental understanding that we are merely a species passing through a specific period in the Planet's life, would be a definite advantage as we continue our struggles to survive on Earth.

We must also do our best to mitigate human impacts on the environment. Some of the most destructive human activities include the excessive use of fossil fuels (related to global warming), over-exploitation of natural resources (such as caused by mining for oil, gas and minerals), habitat destruction, large-scale deforestation, expanding animal farming, monocultures and other forms of unsustainable agriculture. One must add soil, air, and water pollution, damages caused by the globally rampant wildlife trade and poaching, and pollution caused by human waste created by a burgeoning population.

An emerging idea – of *Nature's Contributions to People* (NCP) – was recently highlighted by Pascual and co-workers (2017). It is a conceptual framework that fits the world of colonizing taxa and how we may strive to create a sustainable future for the present and future generations. As the authors explain:

> *"…Nature's contributions to a good quality of life are often perceived and valued by people in starkly different and often conflicting ways. People perceive and judge reality, truth, and knowledge in ways that may differ from the mainstream scientific lens…"*
>
> *"…Hence, it is critical to acknowledge that the diversity of values of nature and its contributions to people's good quality of life are associated with different cultural and institutional contexts and are hard to compare on the same yardstick…".*

The NCP concept is a pluralistic approach, applicable to knowledge-based policy initiatives. The NCP platform recognizes the benefits of embracing diversity and power relationships across stakeholder groups with different values regarding human-nature relationships. Resonating with the term *Ecosystem Services*, the NCP concept includes all of the positive benefits and occasionally negative contributions, losses, or detriments that people obtain from Nature (*anthropocentric values*). It also captures a *non-anthropocentric* value centred on something other than human beings.

These values can be *non-instrumental* (e.g. a value ascribed to the existence of a specific species for their own sake) or *instrumental* to non-human ends (for example, the instrumental value a particular habitat type may have for a species that is well-adapted to it).

Other knowledge systems, such as '*Nature's Gifts*', prevalent in many indigenous and traditional cultures, are recognized within the NCP concept. In a sympathetic worldview, colonizing taxa, which are accused of causing adverse effects on biodiversity and people, fall within the milieu of NCP and are most certainly '*Nature's Gifts*'. *A flexible mind will allow us to seek clarification on this viewpoint*.

Conservation of biodiversity

I sometimes wonder how many people actually appreciate that the most unique feature of the Earth is its biological life, and the most amazing feature of life on Earth is its biological diversity. Innovative messaging and a greater emphasis on '*ecological literacy*' are required in discourses to hammer this message to some sections of society.

Approximately nine million types of plants, animals, protists and fungi inhabit the Earth. So, too, do more than eight billion people. Human actions have been continually dismantling the Earth's ecosystems, eliminating genes and biological traits of these species at an alarming rate (Hooper et al., 2012; Cardinale et al., 2012).

Most people push global biodiversity losses and their link to human activities to the margins of their consciousness because they cannot comprehend the complexities of understanding 'causes and effects'. Some people (such as climate change denialists) refute the linkages altogether, mainly for their own benefit.

There is still a great deal of money to be made by continuing destructive activities, such as large-scale logging of the tropical forests in Borneo or the Amazon and relentless extraction of oil and gas in the fossil fuel industry. Despite the overwhelming evidence (IPCC, 2022), it is too risky for many parties to accept that climate change is occurring. *And the poor will suffer most from inaction by the rich*.

Nevertheless, a clear message emerging from ecological studies is that increased biodiversity often leads to more significant and less variable levels of ecosystem functioning. That means that the richer the biodiversity, the lesser the threat of the extinction of plant and animal species.

Cardinale et al. (2012) and Hooper et al. (2012) argued that diversity-driven increases in function can boost rates at which nutrients, energy and organic matter flow through an ecosystem and increase their overall multi-functionality and stability. Therefore, in the conservation efforts of global species and ecosystems, maintaining high levels of overall biodiversity across landscapes is necessary to even reduce the extinction risks of specific species.

As critical components of biodiversity in any bio-geographical area, assemblages of pioneer taxa would collectively exploit the resources of particular environments to maximize the cycling of energy and nutrients through those ecosystems. Along with all other life forms of plants, pioneer species will fill various ecosystem roles. Of their very unique Nature, they will withstand disturbances and bounce back, responding to environmental changes. Although frugal in how they consume resources, these highly adaptive species will share them.

Concluding Comments

I have argued in this paper that *Weed Science* will continue to under-perform if our discipline does not consider that weeds may, in many situations, provide positive ecosystem services for the Planet and societal benefits, not just disservices (Marshall et al., 2003; Jordan and Vatovec, 2004; Altieri et al., 2015; Chandrasena, 2019). Therefore, weeds are not plants that should *necessarily* be killed all the time with herbicides or any other method. This point has emerged strongly in recent discourses on ecosystem services and disservices (Vaz et al., 2018; Tebboth et al., 2020; Guo et al., 2022).

I, therefore, encourage weed scientists in India and elsewhere to look beyond the paddock in researching weedy taxa for their values and usefulness in future societies. Those who are in cropping systems research and agriculture must look for opportunities to live with weedy species and focus on *nature-friendly farming, conservation farming* and *regenerative agriculture* systems.

As Altieri et al. (2015) showed, the pollination benefits alone of maintaining weedy taxa in agricultural landscapes is enormous. Besides, weedy taxa and their genes enrich the biological diversity of landscapes which they occupy. Can people ever imagine a world without colonizing species?

At all times, we must use IWM approaches to tackle and manage those problematic species in the field and be aware that this might take more than a few seasons. None of the above ideas is new. Many countries have adopted ways by which they could use weedy taxa and the bioresources they provide to the maximum. However, in our Asian-Pacific region, weed biodiversity and utilization are topics are yet to become front and centre of weed discourses.

Hill and Hadly (2017) recently wrote: '*As the world stumbles deeper into the Anthropocene, the novel biogeographic dynamics (globalization, mass disturbance, and climate change) will progressively warp habitats*'. Under such disturbances, colonizing taxa will thrive and change their habitats.

However, I must emphasize that *weedy species are no more alien or villainous than we humans have been*. With or without humans on the Planet, colonizing species will play vital roles in stabilizing the Earth's ecosystems. *They will also survive future catastrophes on Earth. We may not.*

Countering mis-information about weedy taxa requires the following: (1) recognition of the seriousness of the problem and (2) refuting the claims that weeds are bad news all the news with evidence-based scientific findings. Science helps us approach the '*world of weeds*' with wonder and humility. Scientific ethics call for us to have an honest dialogue with Nature.

Science will also help us fight fake news and mis-information, navigate the troubled waters, and find a more resilient and reasonable position concerning weedy taxa. We must all strive to '*re-think Nature*' (Hill. and Hadly, 2018) and attempt to find the '*middle ground*' in the discourses (Shackelford et al., 2013) instead of blaming colonizing taxa for human follies.

Science, as a human enterprise, often moves too slowly, as Thomas Kuhn (1962) said. Science is also largely conservative in the sense that changes in ideas and directions occur only after the cumulative accumulation of sufficiently robust evidence, which might take a long period. Science also suffers from prejudices, sentiments and conventions, as it is a human endeavour.

Concerning the broad aspect of *utilization of the powers and strengths of weedy taxa*, I believe that we have reached a point that the evidence cannot be ignored any more. We are all aware that scientists spend too much time taking long periods and small steps towards working out solutions to a problem. Weed researchers are no exception to this. Introspection and profound reflections on the subject matter are critical to formulate new hypotheses and test their validity. However, when there is a large volume of evidence to support changing a paradigm, scientists should not hesitate for too long.

I believe colonizing taxa, labelled intruders in human-modified landscapes, have suffered enough. This "fixed" pessimistic worldview of colonizing species has led us to a crisis point of relentless warfare against them. This unsustainable, negative attitude must change to a new paradigm of 'living with weeds', which is not radical. Positive appreciation of weeds has also existed around human-plant interactions for millennia.

With their remarkable botanical and ecological attributes (Baker, 1965), weedy taxa generate 'threshold' situations for us – moments when the factors that cause environmental degradation are, for a time, reversed. We can take advantage of these moments. Weeds can turn the plant world and enhance the biodiversity of landscapes around them and make a genuine dialogue with all that is 'still wild' possible. This suggestion (claim) can be scientifically investigated, which will help understand their critical ecological roles better.

I encourage weed researchers all over the world to urgently re-focus attention on understanding the ecology and biology of weeds a great deal more. Weed scientists should also redouble their efforts to combat misinformation about weeds and seek a collaborative co-existence.

Egocentric humans might argue that humans can devise ways to survive without the natural world and that we need not depend on it for our existence. *But is that world we want to live in?*

People will find no joy in a world without the rich diversity of flora and fauna, including colonizing species that share the Planet with us. Weed Science, in my view, should also be taught at various levels, to foster a deeper appreciation of our natural world and the critical role weedy species play in it.

A change in attitude towards misunderstood weedy taxa can be expedited by focusing on their utilization and economic values and *what they can offer to our Planet mother, who is presently in distress*. In that sense, what I have sought to highlight in this essay is not necessarily a need for a 'paradigm shift' in Weed Science (in the sense of Thomas Kuhn, 1962) but simply a re-focusing and an objective re-appraisal of weedy taxa that can assist both human societies and the distressed Planet.

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PERSPECTIVE

The Future of Weed Science

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Abstract

Agricultural scientists, farmers, ranchers and the agriculture industry remain confident of their basic faith in the possibility of continued increasing production through the intelligent use of ever more efficient agricultural technology and research. Increasing production has been and remains the accepted way to achieve the moral obligation of feeding a growing population. Given that weeds are an obstacle to increasing food production, but not necessarily the only one, managing weeds in an integrated way is an important factor to consider in global agriculture. In this essay, I pose a number of questions concerning agriculture's moral justifications and ethics, as concerns of widespread human impacts and environmental harm of agriculture are felt, along with public fear of technology and food quality standards.

Keywords: Ecology, Ethics, Agricultural ethics, Integrated Weed Management, Herbicides, Pesticides, History, Island Empire, Values, Weeds

Introduction

We can, of course, be deceived in many ways.

We can be deceived by believing what is not true, but we certainly are also deceived by not believing what is true.

…………………….Kierkegaard - *Works of Love*.

I have chosen to begin with a topic that does not immediately relate to climate and weed management but, in my view, affects global food security. Those familiar with my writing will not be surprised that my topic is agricultural ethics (Zimdahl and Holtzer, 2018; Zimdahl, 2018; 2022). Nevertheless, it is a philosophical reflection on the future of weed science and agriculture. My presentation is a challenge to you. My comments on the future directions of weed research and technology will follow a consideration of what agricultural ethics is.

Agriculture Ethics

Universities routinely include ethical study in the curriculum for medicine, law, business, and the environment. Agriculture, the essential human activity and the most widespread of human interactions with the environment, does not. The agricultural science curriculum lacks consideration and study of the effects of agriculture on society and the environment. Ethics has not been institutionalized in Colleges of Agriculture, agricultural professional organizations, or the agribusiness industry. That is not to say there are no professional ethical standards.

[1] Zimdahl, R. L. (2024). The Future of Weed Science. *Indian Journal of Weed Science*, 56(4): 323-333.

Many assume agriculture has an adequate ethical foundation. The assumption is not questioned. There has been too little investigation and too little critical thinking about the lack of and need for an ethical foundation.

Agriculture has scientific challenges: achieving sustainability, maintaining production, pesticide and antibiotic resistance, invasive species, loss of biodiversity, biotech/GMOs, and pollution. Those involved in agriculture believe that the development and use of more energy-dependent technology is always good and that more will be better. It will address the need for production, address the problems caused by the unintended consequences of present technology, and alleviate public concern.

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 what we do is desirable. Although all involved in agriculture know what they are doing, they should think about what they may be undoing.

The moral imperative is to produce food and fibre to benefit all humanity. Production is what must be sustained. Agriculture's producers, suppliers, and researchers, regardless of their employer, should ask if production is a sufficient criterion for judging the consequences of all agricultural activities. *Does increasing production justify everything agriculture does? Does it achieve sustainable production practices? Does the quest to increase production solve or even address agriculture's moral dilemmas?*

Agricultural scientists have assumed that as long as their research and the resultant technology increased food production and availability, they and the end users were somehow exempt from negotiating the moral bargain that is the foundation of the modern democratic state (Thompson, 1989).

It is unquestionably a moral good to feed people. Therefore, it is assumed that anyone who questions agriculture's morality or the results of its technology simply doesn't understand the importance of what is done and how it is done. It is assumed that agricultural practitioners are technically capable and that the good results of their technology will make them morally astute.

When those involved in agriculture claim credit for improving production and keeping food costs low, they must also accept society's right to hold them responsible for problems often regarded as externalities. They need to ask and be prepared to respond to what has not been asked often enough. *What could go wrong? What has gone wrong? What are the appropriate responses?*

We live in a post-industrial, information-age society. No one will ever live in a post-agricultural society. Continuing to justify all agricultural activities and technology by the necessity of achieving the moral obligation and production challenge of feeding a growing world population has not been and will not be a sufficient defense for agriculture's negative environmental and human effects. We are disturbing and changing the climate and our planet's ecosystems at a pace and scope never seen in human history (Friedman, 2016).

What is the problem? Feeding the 11 billion expected to be on the planet at the end of this century is undeniably a good thing. *Is it a production problem?* Of course, it is. But enough food is produced now to feed the global population.

Nevertheless about 810+ million people still go hungry every day. After steadily declining for a decade, world hunger is on the rise, affecting 1 of 9 of the world's people. From 2019 to 2020, the number of undernourished people grew by 150 million, a crisis driven largely by conflict, climate change, and the COVID-19 pandemic.

In spite of the abundance of food, people are hungry in many countries because of inadequate food distribution, inadequate infrastructure that delays or prevents food distribution, food storage waste, waste by consumers, government policies, and poverty. *More production will not solve the hunger problem* (Sen, 1999).

It is obvious citizens of democratic societies are becoming increasingly 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 initiate and participate in a dialogue that leads to social consensus about the effects of agriculture's technology, its risks, and reasonable solutions. In the past, most risk was borne by users of the technology. Now there is widespread concern 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 explain their positions and understand those of their fellow citizens. All involved in agriculture and those who enjoy abundant societies must recognize they are dealing with how we ought to live.

Agriculture practice, research, and teaching involve scientific and ethical values. 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.

People throughout the world have rational concerns about the ethical dimensions of agriculture and our food system that go beyond the central need to feed humanity. Each of agriculture's multiple responsibilities includes an ethical dimension. These include:

- Achieving sustainability, resolving pollution of water and soil while assuring the availability of surface and groundwater.
- Stopping harming other species, cruelty to animals and habitat destruction.
- Stopping exploitation and inhumane treatment of farm labour, stopping the loss of small farms and rural communities.
- Considering the power of corporate farming and its lack of transparency, stopping the harmful treatment of animals.
- Addressing public concern about biotechnology and genetically modified organisms (GMOs),
- Stopping the losses of crop genetic diversity and addressing public concern about the nutritional value of foods provided by the food system.

These are not just scientific problems. We should not expect scientists alone to solve them. Leaders of the agricultural enterprise should work together with others to identify, discuss, and address them. Collective action is required to achieve morally good goals. Agriculture will gain little if it wins the production battle and loses the moral battle.

Agricultural education has given too much emphasis on what to think rather than how to think. Universities have traditionally been places where different opinions were welcomed and encouraged. The present trend toward specifying what controversial topics may or may not be welcome is disturbing. It stands in sharp contrast to the role of teaching - to lead out - to educate. Encouraging students and the general public to be aware of and discuss difficult, controversial issues is an important role of education and those who teach.

There are 1459 universities in the world with agricultural faculties. Forty US universities (Weed Science Society of America, 2023) and 78 international universities have departments of weed science (Ahmad et al., 2023). Only six US universities have a course on agricultural ethics. The worldwide agricultural curriculum lacks courses that focus on general ethical principles and their application to agricultural issues.

It is my view the lack of university courses on agricultural ethics in the USA is because the faculty who teach, plan the curriculum, and advise undergraduate and graduate students do not regard studying the ethical values of agriculture as important preparation for agricultural professionals.

When I was a student I was never advised to enrol in a class in philosophy, and I suggest my professors and their mentors were not advised. The present faculty is also not interested in or does not care to cooperate with a colleague in the Department of Philosophy to create a class on agricultural ethics and encourage students to enrol.

Such classes will be a recognition of the need to acknowledge and discuss agriculture's ethical dimensions. Agriculture has (Zimdahl and Holtzer, 2016) problems that have focused attention on production and profit, while education and practice have ignored agriculture's human and ethical dilemmas (Damasio, 1994).

Professors, Department heads, and Deans of colleges of agriculture who have not chosen to address agriculture's ethical dilemmas are contributing to the problems. There is a clash between the environmental and human harm of modern agricultural production and the values held by the general society and those who practice agriculture. Ignoring value conflicts and societal concerns will lead to a loss of public support and trust in agriculture.

Our technology may outweigh our character. We hold at the level of our training - our education. We risk becoming moral people in an immoral profession (Niebuhr, 1932). "*He who knows only his side of the case knows little of that*"(Mill, 1859). We must begin to interact and listen to people who don't share our beliefs and who confront us with evidence and counter arguments (Haidt, 2022).

What we resist pursues us. What we accept transforms us. We are a mass audience consuming the same content while looking in a mirror reflecting the view we have (Haidt 2022). My experience has shown students may be more willing than the faculty to question and explore outside the agricultural curriculum

When the morally good goal of feeding a growing world population bumps up against the morally good goal of protecting the environment, one is confronted with value questions that science is not designed to answer. When the environment's natural objects are valued only in terms of their worth to humans, they can be legally destroyed or modified.

I offer a few examples of what we have and are doing. We cut down original forests, till the prairies, irrigate deserts, dam and pollute streams, overgraze hillsides, flood the valleys, and prevent forest fires. We have changed the climate and acidified the oceans. Little, if any, attention is paid to the inevitable environmental consequences: ocean hypoxic areas, soil erosion, melting ice, species extinction, and invasive species. Our predatory self-interest dominates our environmental concern.

As Kolbert (2022) correctly noted – '*It seems normal to send in the bulldozers, chainsaws, and backhoes to cut down the trees, fill the wetlands, and "develop" the land'*.

Until something or someone receives a right granted by law or public pressure, we often see the environment as something for our use. The objection that streams and forests cannot speak has been addressed. Neither corporations, States, estates, infants, incompetents, municipalities, nor universities can speak. These entities are amply represented - some might say overrepresented - in the courts.

We make decisions on behalf of and in the purported interest of others every day. The other creatures (e.g., soil microorganisms, pollinating insects), whose wants are far less verifiable, may be more important. They are more metaphysical (the fundamental nature of reality) in conception than the wants of rivers, rocks (Nash, 1977), trees (Stone, 1972) and the human benefits from and obligation to them.

Is it possible for human intelligence to increase the range of benevolent impulses and encourage us to consider the needs and rights of other humans in addition to the things to which we are bound by organic and physical relationships? Can we transcend our own interests to grant rights to the interests of our fellow humans and the creatures in the environment? If agriculture's practitioners continue to ignore agriculture's moral dilemmas because we must produce they may lose the right to determine agriculture's future and jeopardize our chances of surviving on this planet (Berry, 1977).

Suppose we fail to institutionalize the study of the ethics of agriculture. In that case, we will not learn how to ask and discuss moral questions. We should not continue to defend only the interests of agriculture when there are obviously unjust effects on the interests of the planet and our social communities. Human ingenuity has increased the treasures nature provides for the satisfaction of human needs; it will never be sufficient to satisfy all human wants.

Predictions of the future for weed science and agriculture are always tempting, often successful, and usually hazardous. If all parts of the agricultural enterprise, including professors, farmer/rancher producers, agribusiness firms, food processors, and sellers, do not begin to recognize and address agriculture's ethical dilemmas, three unwelcome outcomes may follow:

- Firstly, agriculture practitioners may find their arguments and justification for their technology and production practices ignored.
- Secondly, public unease and dissatisfaction with known and perceived effects of agricultural technology (e.g. pesticides, cruelty to animals, farm labour, and food quality) will result in increasing societal unrest and pressure for political action. Decisions on how agriculture can be practiced and how land is to be treated will be made by society and the government.
- Thirdly, The increasing concentration of food production in the hands of agribusiness companies will continue. Small farms, farmers, and rural communities will continue to gradually disappear.

Agriculture is a capital-intensive, high-tech business. Rather than wait to see if appropriate levels of sustainability and resilience can be achieved by the present capital, chemical, and energy-intensive system, agricultural people could begin to learn how to impose ethical standards on themselves. Because agriculture is a diverse, widespread enterprise, reaching an agreement will be difficult but not impossible.

Recognizing the possible undesirable outcomes and choosing to act wisely will help maintain the essential industry. I challenge you to consider some hard questions that will affect your future: *What does it mean to live well? What matters? What needs and values do you live by?. What needs and values ought you live by?*

The Future of Weed Science

Now, I turn to comments on the future of weed science. It is not another challenge, but I hope my comments make you think. Weed science, although young among the agricultural sciences, has an enviable, rich, productive history and will continue to contribute to agriculture, other disciplines, and food production. Weed control was a necessity recognized by farmers who had been controlling weeds long before herbicides were invented.

Herbicides changed the way control was done, but not its fundamental purpose —to improve the yield of desirable species. The chemical energy of herbicides replaced human, animal, and mechanical energy. No other method of weed control was as efficient at reducing the need for labour or as selective. People with hoes could distinguish weeds from crops and weed selectively.

Mechanical and cultural methods, while effective, were not selective enough. Herbicides enabled prevention, reduced weed populations, and selectively removed weeds from crops. Weed control in the world's developed countries now depends on herbicides. This situation will prevail well into the 21st century.

A Problems

Seven important problems (below) have and may continue to hinder the progress of weed science.

1. The assumption that anyone can control weeds is made by those who do not understand the complexity of agriculture or weed management. Marshall (2010) reinforced this assumption with the misconception that weed science is easy and, more importantly, has all the answers to weed problems, which it does not. Environmental and production demands will require significant adjustments in weed management and agricultural practice.
2. Although weeds have been and will continue to be components of agriculture and the environment, they lack the attention, appeal, and urgency of sudden infestations of other pests.
3. Weed science lacks foundational hypotheses "linked to established bodies of ecological and evolutionary theory to provide deeper theoretical justification, a broader vision, and increased collaboration across diverse disciplines" (Ward et al., 2014).
4. There is a lack of people and research funds (Davis et al., 2009). Research on weed biology, ecology, seed dormancy, and other problems leading to basic understanding rather than immediate control is done by too few scientists. Publicly funded interdisciplinary agricultural research has lacked adequate funding and, it seems, will remain so for decades.
5. Underlying all agricultural issues, there is always an unexamined ethical position (Zimdahl, 2022). Thompson (1995) pointed out there is only one imperative to produce as much as possible, regardless of the environmental/ecological costs and perhaps even if it is not profitable. Agricultural people cannot escape responsibility for societal views of its effect on the environment, other species, and themselves. Agriculture's views on ethical issues have not been and should be examined.
6. All in agriculture know farming is crucial to all economies (Economist, 2022) and important to the welfare of all. The public in most societies is certain food is important but is abysmally unaware of the complex processes and people who provide their food.
7. Climate change and lack of appropriate weed control practices will affect farmer's ability to produce. Modern agricultural technology developed country farmers rely on is beyond the reach of poor farmers in the developing world. More than 90% of farmland in Africa has no irrigation, 1/3 of the world's people, and 60% of Africans do not receive warnings of impending natural disasters or routine weather forecasts. Agriculture's admirable goal of feeding an expanding world population in a warmer, dryer climate would benefit from expanding its horizons beyond developed country farmers.

A few conflicting claims illustrate some future challenges for weed science.

1. Moss (2008) charged the overall direction of weed research was wrong. There was too much emphasis on scientific effect at the expense of practical application. Moss argued weed science was weed technology. He suggested his colleagues lacked an awareness of the complexities and resources needed to translate research results into actions for farmers.
2. Ward et al. (2014) claimed two broad aims have been driving weed science research: improved weed management and improved understanding of weed biology and ecology. Research has developed a very high level of repetitiveness, a preponderance of purely descriptive studies, and has failed to clearly articulate novel hypotheses linked to established bodies of ecological and evolutionary theory. Although Ward et al. (2014) noted studies of weed management remain important, they urged weed scientists to recognize the benefits of deeper theoretical justification, a broader vision, and increased collaboration across diverse disciplines (especially ecology). One might conclude weed science research has not been as good (weeds, like the poor, are still with us) as many colleagues think it has been.
3. Swanton (2022) accused weed science of being primarily reactive. Scientists responded to current needs and worked to solve on-farm problems. He recommended that the discipline make long-term thinking automatic and common instead of rare. Long-term thinking is required because weed science, a sub-discipline of agriculture, must begin to answer complex questions regarding cropping systems and environmental challenges.
4. The Editor-in-Chief of Weed Research (Marshall, 2019) introduced "the post-herbicide era of weed science". He argued this was "increasingly prescient as herbicides continue to face the ever-increasing legislative restrictions and the challenge of evolved resistance. They are key influences on the practice of intensive agriculture, whose success is intimately linked to the heart of the planetary crises: climate

change, global warming, loss of biodiversity, environmental harm, etc.

5. Buhler (2006; 2017) argued weed scientists must develop integrated cropping systems and weed control strategies in a comprehensive, environmentally and economically viable system. This approach would "help reduce economic effects and improve weed control practices." Herbicides will continue to be an essential part of integrated cropping systems.
6. Westwood et al. (2018) claimed weed science was at a "critical juncture" because decades of chemical control have dramatically increased herbicide-resistant weed populations. The problems were critical because there were few new herbicides, new modes of action, and no economically acceptable alternative to herbicides in large acreage crops. They suggested new modes of action could be discovered using genetic engineering, computing power, automation, employment of artificial intelligence and machine vision to improve weed management.
7. Gould (2002) portrayed the situation well by contrasting "immediate and practical" with "distant and deep" issues. Immediate and practical issues are about potent and unanticipated effects (e.g. herbicide resistance). Distant and deep issues include legislative, ethical, aesthetic and practical consequences of altering agriculture's fundamental geometry and permitting scientists in the developed world to change the way agriculture is and ought to be practised. He advocated proper development and use while giving adequate, proper consideration to human and environmental health, agricultural progress, and sustainability.

In this review, I deal with thoughts about the future weed science research, but not in terms of what will be accomplished. It is conjecture, not prophecy. It might be best conceived as a proposal of what ought to be done. It may not be what will be done because research does not always follow a straight path, and other developments may change what is desirable and possible. For example, environmental legislation mandating reduced herbicide use could rapidly change the way agriculture is practised.

A description of research needs is a safer prophetic stance. It describes what could be done rather than describing what the situation will be several years hence. This approach, of course, reduces the possibility the prophet may be wrong.

B Research Needs

Dependence on herbicides for weed control is equivalent to treating the symptoms of a disease without actually curing the disease. Agriculture would be far better served if weed scientists learned how to control weed seed dormancy and seed germination so weeds could be prevented rather than controlled after they appear. No one knows enough about weed seed dormancy, and much research remains to be done to reach the prevention goal.

Throughout this essay, the emphasis will be on the two major goals put forth by Ward et al. (2014):

1. Discussion and debate of appropriate goals and the pathways necessary to achieve the goals;
2. Rediscovery of the ability to pose critical research questions designed to advance the theoretical underpinnings of weed science.

Weed science began when herbicides (e.g., 2,4-D) made control possible without studying much about weeds. Those who controlled had to know what weeds were to be controlled and where they were growing. That is, control was not blind. There are objects to be controlled, and they are known. But, with herbicides, it has not been necessary to know much more about weeds.

In general, herbicide development has neither exploited weak points in a plant's life cycle nor used specific physiological knowledge for control purposes. The safest approach has been to aim for complete control of weeds in a crop. As knowledge grows, scientists find some plants may be beneficial and should not be controlled (Chandrasena, 2023).

A series of projects could be developed to study the regulation of seed and bud dormancy of perennial weeds and the development and life of reproductive propagules (Wyse, 1992). Population genetics and modelling of crop-weed systems will contribute to improved weed management.

C Weed Ecology

Important insights on the future role of weed ecology are found in two recent papers - Neve et al. (2018; 35 authors) and MacLaren et al. (2020; six authors). Both papers support the increasingly dominant claim that the present weed management system is unsustainable because of its many negative effects and dependence on chemical, capital, and petroleum energy.

Both papers strongly advocate combining multiple known weed management techniques in a new integrated weed management system. The creation of an integrated system based on agroecological approaches will require multi-disciplinary - trans-disciplinary participation. A host of other authors (Buhler, 2006; 2017; Young, 2012; 2020; Jordan et al., 2016; Young et al., 2017; Swanton and Valente, 2018; MacLaren et al., 2020) have also advocated strongly for the incorporation of weed ecology into integrated weed management systems.

MacLaren et al. (2020) argue that "new herbicides, gene editing, and seed destructors do not address needed systemic challenges and are unlikely to provide sustainable solutions".

Neve et al. (2018) advocate a better understanding of weed evolution, climate change, weed invasiveness" and, perhaps the greatest challenge, "*disciplinary challenges for weed science*". Neve et al. (2018) advocate as a solution, the "*integration of agro-ecological weed management with socio-economic and technological approaches*".

The scientific system that helped create these problems accepts credit but resists accepting blame for negative effects, therein is part of the tragedy. It is an example of the agricultural mindset and justifies Mayer and Mayer's (1974) conclusion – "the system is unsustainable". Their second claim - the integration and isolation of the system have led to what they call – "*The Island Empire*". Agriculture is a vast, wealthy, powerful intellectual and institutional island. The Land-Grant system created Colleges of agriculture and allowed agriculture's isolation within the university and from mainstream American life.

Mayer and Mayer (1974) accused agricultural colleges of being separated from the university, mainstream scientific thought, and national discussions about social policy. Agriculture does not ask for and only reluctantly receives outside criticism. They said: "Those who practice agriculture must move off their 'island".

Much of the basic information required to develop computer-based models of weed-crop systems and available control techniques has come and will continue to be derived from weed biology and ecology research. What plants compete for and when competition is most severe between crops and weeds is known in sufficient detail to be useful in the development of weed-management systems.

The still-used (Dawson, 1965) period threshold concept of weed competition affirms that weed competition is nearly always time-dependent. Seedling weeds at crop emergence are less detrimental than those emerging later. This principle led to the timely use of herbicides and other techniques for weed management. Some crop cultivars are more competitive and this needs to be considered in developing integrated weed management systems. It is a basis for cooperative work with plant breeders.

Weed populations change with time, and reasons are beginning to be understood. A major challenge presently dominating weed research is the appearance of herbicide resistance, often after only a few years of use in one field. Active research is coupled with the development of techniques to combat it. When resistance occurs, it does not lead to totally unmanageable weed populations because other weed-control techniques (e.g., cultivation, crop rotation) and other herbicides are available.

Understanding why populations change, and management of population shifts is important to the development of successful, sustainable weed management. However, as Harker et al. (2012) note, the best way to reduce selection pressure for herbicide resistance is to reduce herbicide use, although the dominant weed-management programs continue to advocate herbicide use.

Even casual observers of the world of weeds will recognize weed problems have changed (see Van Wychen, 2016; 2020; 2022; Fernandez-Quintanilla et al., 2007). Some of the most difficult weeds in most crops today were not important 10 or 20 years ago. This is evidence weed scientists have developed successful solutions to some weed problems. It is also true that many common weeds (e.g., pigweeds, lambsquarters, velvetleaf, Canada thistle, cheatgrass) have been targets of control programs for many years. Thus, we have simultaneous evidence of success and continuing problems.

It is also evidence that nature abhors empty niches. When successful control efforts have reduced the population of a species, they inevitably leave space unoccupied and resources unused. Other species move into empty niches created by successful weed control.

Solutions to this dilemma take two forms. The first solution is to reduce the attractiveness of the niche. Farmers typically overprovide for crops. Fertilizer placement and precise rate recommendations have reduced surplus nutrients, but nitrogen runoff due to excessive application is a significant problem with notable externalities. Whole fields are irrigated, and light cannot be controlled. If water could be placed (e.g., drip irrigation) as precisely as fertilizer and only as much was provided, the attractiveness of the niche and the success of potential invaders could be reduced = preventive weed management.

The second approach has elements of prevention. Some of the important problem weeds of the next decade are already in fields or lurking on the edges. If they were identified and their weedy potential determined, weed scientists, cooperating with ecologists (see MacLaren et al., 2020), could try to predict those most likely to be successful invaders. They could be managed before the invasion. Invasive plant management is now a major area of weed science research, as indicated by the 2008 launch of the Weed Science Society of America's journal *Invasive Plant Science and Management*.

Basic biological-ecological knowledge is essential to either approach. Without it, weed scientists may be doomed to endure the Red Queen effect (a character in Lewis Carroll's classic book *Through the Looking Glass* - 1871). The Red Queen tells Alice, "In this place, it takes all the running you can do to keep in the same place". Weeds and their control, especially with herbicides, seem to be evolving at about the same rate. In trying, and often succeeding, to eliminate weeds from fields, weed scientists have created, in a sense, better, more ecologically successful weeds while accepting herbicide's negative environmental effects.

A difficult and central issue for weed science is understanding the nature of weeds: What makes a weed a weed? How can weeds consistently come out ahead when matched up against the finest commercial varieties plant breeders have developed? Weeds persist, they spread, and they out-compete crop plants, reducing yields when left uncontrolled. Weeds are not conscious, but they seem to be clever. The nature of the competitive ability weeds possess seems an interesting target for research and an appropriate target for analysis through the generation of mutants.

Goethe's "The Sorcerer's Apprentice", Mary Shelley's "Frankenstein", and, more recently, Michael Crichton's "Jurassic Park" reinforce the often inchoate fear of intelligent, rational concern about a powerful form of life manufactured with good intentions but excessive hubris, which might one day slip out of control (Specter, 2016).

The 1950s gave us catchy phrases that still resonate—*Better Living Through Chemistry and Atoms For Peace*. We don't hear similar things now. Chernobyl/Fukushima nuclear reactors, Agent Orange, space shuttle crashes, thalidomide, ozone destruction, pesticides in food, and climate change dominate the public's thoughts. Scientists clearly solve problems, yet, in the public's view, untoward problems continue to occur.

These well-known problems, combined with human drug disasters, have made people suspicious of the efficacy and trustworthiness of science and scientists (Lemonick, 2006). It is in this context public doubts about genetic modification of anything are raised and must be addressed. Weed scientists and others involved with GM technology often think they could educate/tell people about what they do (William et al., 2001).

Education is important, but careful listening followed by a conversation among equals may be better, especially at a time when science has made mistakes and is regarded with well-founded suspicion. Weed scientists should not regard themselves as the only acceptable arbiters of how developments in their science should be created and used. Because of public perceptions of greed, a bit of arrogance on the part of developers and a misunderstanding of science, many people view genetic modification as a hazard, not salvation, and reject it (Specter, 2016).

D Education

A review of some published articles on the future of weed science reveals few comments on the role of education. Research and appeals for more funding (Davis et al. 2009) dominate. There is at least one undergraduate weed science class at all US Land Grant universities and several others required of undergraduate and graduate students. The absence of discussion of what students ought to know among those who teach is disturbing.

Surely, the education of the next generation of weed scientists with "innovative and diverse teaching practices", advocated by Chauhan et al. (2017), is as important to the collective future of weed science as biotechnology, invasive species, and new herbicides. If it is, why isn't education closer to the top of the future agenda? We must integrate weed management and education.

E Other Challenges

A. Scientific

Several other research areas should be considered when planning weed science's future. They include:

- The value, advantages, and disadvantages of monoculture agriculture.
- The role of companion cropping and regular inclusion of cover crops in weed management? Can weeds be cover crops? (See Young, 2020).
- The long-term effects of soil erosion after regular ploughing and cultivation? One effect is all too apparent in the brown colour of many country rivers (Logan, 1995; Montgomery, 2007).
- The future and influence of perennial crops.

Weed scientists were not too concerned with long-term effects when the science was developing. Weeds decreased crop yield — a detrimental long-term effect. The vision did not extend much farther because solving the weed problem was a sufficient challenge. Any technology used for enough time has demonstrable environmental and social effects.

A longer-term view will help reveal these effects and compel their consideration before widespread use is achieved.

- Weed scientists must begin to work more closely with economists who ask, what does it cost and what is it worth? What is it worth to do the work to develop a more competitive cultivar, deplete the soil seed bank and achieve assurance of 80% or 100% weed control?
- What will it be worth to be able to predict weed problems? No one knows, but the answers are important to IWM systems.
- How will nanotechnology affect weed science? Nano integrates biological material with synthetic materials to build new molecular structures. Synthetic biology goes beyond moving existing genes to creating new ones programmed to perform specific tasks. It operates at the nanoscale (one billionth of a meter = 10−9m) of living and non-living parts. It has enormous potential for good and harm (Shand and Wetter, 2006).

Weed scientists are aware of the scientific research opportunities and challenges. There are equally important, although less discussed, social and moral challenges. The primary goal of agricultural scientists has been to develop technologies that enable achieving the maximum yield of a few crops in the world's developed (rich) countries. It is a good goal, but one must ask if it is the right goal (Kirschenmann, 2012; Zimdahl, 2022).

Is it more important than enabling the poor of the world to feed themselves? Can the seemingly unending task of discovering new technologies to maximize yields lead to a sustainable agricultural system to feed 9 billion or more people? Is maintaining rural communities a proper goal for agricultural science, or is that someone else's task?

Should achieving maximum yield and profit always take precedence over preserving the environment? Liu et al. (2015) found cultural practices with negative effects on global food production. "It is crucial for agricultural sustainability to increase crop yields and simultaneously decrease environmental impacts of agricultural intensification".

B. Sustainability

Achieving sustainable agriculture is a goal all agricultural scientists share. Even a cursory review of current writing on agriculture reveals achieving sustainability has obtained the generally revered status of motherhood with one important difference.

There is little debate about what motherhood is or its worth and goodness. The difference is in spite of the nearly universal adulation of agricultural sustainability, *there is little agreement on its nature, what is to be sustained, or how it is to be accomplished* (Zimdahl, 2022, p. 135).

Production is and always will be important, but it is not possible to create sustainable agriculture without a sustainable culture. The reverse is also true (LeVasseur, 2010). It is impossible to have a serious, comprehensive discussion of sustainable agriculture without including community and culture (Holthaus, 2009). Within the agricultural community achieving sustainability is viewed as mainly or wholly technical in nature. It requires different farming methods and the adoption of alternative technologies (Morgan and Peters, 2006), which will be significantly aided by advances in biotechnology.

This view ignores the moral, educational, and political tasks that must be considered. In Morgan and Peters' view (2006), it requires a commitment to "philosophical principles that depart from the utilitarian premises of industrial agriculture". It is a demanding task that requires new thinking and a change in attitude toward the earth. It requires us to cease attempting to achieve dominion over the earth and achieve humility and reverence before the world (Berry, 2002).

The majority of the mainstream agricultural community does not agree with Liu et al. (2015). The dominant view has been supporting crop intensification is the best route to feed 9 billion people and protect the environment. But there is no room for complacency, especially that invoked by some biotechnology advocates (Fischer et al., 2014).

Finally, a caution. Those engaged in agriculture and its sub-discipline, weed science, possess a definite but unexamined moral confidence or certainty about the correctness of what they do. The basis of moral confidence is not obvious to those who have it or to the public. Agriculture's unexamined moral confidence is potentially harmful. It is necessary for all engaged in agriculture to analyze what it is about their science and their society that inhibits or limits their science.

All should strive to nourish and strengthen the beneficial aspects and change those that are not. To do this, agricultural people must be confident to study themselves, their science, and its institutions, and be dedicated to the task of modifying the goals of both (Zimdahl, 2022).

Agriculture's Human Dimension

Doohan et al. (2010) claim that "the human dimension of weed management is most evident when farmers make decisions contrary to science-based recommendations". Agricultural scientists and many levels of administration may be aware their recommendations are often ignored but usually do not ask why because such questions are beyond their area of expertise. Scientists do science, leading to science-based recommendations. When recommendations are ignored, the reasons could be economic (too expensive), stubbornness, lack of trust, and different perceptions of risk and benefit.

Doohan et al. (2010) argue that farmers exhibit an inverse relationship between perceived risk and benefit. If any technology is regarded as beneficial, it is automatically perceived as low risk, which, of course, is not true. Ignoring farmers' reasons is perilous for agriculture's future.

Agricultural scientists have contributed to increasing crop production over several decades. Pesticides have been the primary control technique (Fernandez-Cornejo et al., 2014). Because of their efficacy and ease of use, there has been over-reliance on them at the expense of other control methods (Blackshaw et al., 2008).

If the only or primary goal of weed science is to increase production, the quest for better herbicides must continue. If the goal is sustainable weed management in a sustainable environment and society, other control techniques must be investigated and integrated. Research on non-herbicide weed management must show low or no risk of crop failure and reduced profit. The goal should be the development of successful weed-management systems with minimal or no effect on the flora and fauna of soil, water, or air and no adverse effects on people or other creatures.

Scientists and others engaged in agriculture are not, by nature or choice, politicians. Failure or inability to consider we live in a political world and are affected by it is a prescription for disappointment or disaster. Political considerations affect our daily life. A major political accomplishment in many countries is cheap food, especially in urban areas. It affects the way we practice agriculture and manage weeds. If the government removed itself from agricultural policy-making and markets, cheap food might disappear.

Given the agricultural and environmental history, concern about environmental pollution from agriculture is a fairly recent political development. It wasn't too long ago that pesticide use in agriculture meant prosperity and progress rather than human harm, environmental pollution, and lack of corporate responsibility. For example, a study commissioned by the American Farm Bureau, an organization noted for its defense of agriculture (King, 1991), showed only 15% of the American public was in favour of abolishing pesticide use in agriculture. However, 66% of those surveyed thought pesticide use should be limited in the future, and 38% thought farmers were using more pesticides than they had in the past.

Such information and concern have political meaning and consequences. About 70% of US agricultural produce harbours some trace of pesticides (Gross, 2019). Such challenges are often dismissed by the agricultural community because they are regarded as biased, irrelevant and lacking supporting scientific evidence.

An example is in the Consumer Reports article by Roberts (2024). The findings are ignored or dismissed by those who wilfully ignore the effects of criticism on political action. Political acts change many things, and agriculture has to recognize and work in a political milieu or suffer the consequences of regulation by those who do.

Conclusion

The American author and farmer Wendell Berry (1981b) has written often and eloquently about problems facing American agriculture and their solutions. He advocates solving for pattern: "To the problems of farming, then, as to other problems of our time, there appear to be three kinds of solutions."

The first solution causes a ramifying series of new problems. The only limitation of the new problems is they "arise beyond the purview of the expertise that produced the solution". Those who are burdened by the new problems are not those who devised solutions for the old problems. This kind of solution shifts the burden away from those who created the problem.

The second solution is one that immediately worsens the problem it is intended to solve. These are often quick-fix solutions that, within weed science, take the form of questions such as - what herbicide will kill the weed? Adopting this kind of problem-solving leads to the need for more quick-fix solutions. Everyone who has tried to fix something is familiar with this kind of solution. What was tried first didn't work, and some studies (perhaps, little knowledge) revealed that loosening another bolt or screw would do it. Alas, loosening that screw was the wrong thing to do because it loosened other things, and suddenly parts were everywhere and neither the source of each part nor a way to fit them back together was known.

The third, most desirable solution creates a ramifying series of solutions. These solutions make and keep things whole. For Berry (1981b), a good solution is one that acts constructively on the larger pattern of which it is a part. It is not destructive of the immediate pattern or the whole. Good solutions solve for the whole system, not for a single goal or purpose.

Those who create the next generation of integrated, sustainable agricultural production systems for simple and complex problems will do well to remember Berry's admonition as they search for solutions. One must know the whole system and devise solutions that create more solutions to maintain the pattern and improve the system. Agriculture's inevitable problems should be viewed as a good family physician views patients — in family, not just individual terms. It is the entire system, not just the current problem, that must be managed.

Contributing to the elimination of hunger in the world is a proper goal for weed science. It is a goal consistent with the Millennium Goals of the UN (Sachs, 2005, pp. 211–212). Two of the goals are relevant to agriculture and worthy of attention. These large-scale goals include:

- Eradicating extreme poverty and reducing hunger by half and
- Ensuring environmental sustainability.

Although progress has been made, neither goal has been achieved. In his Recollected Essays, Berry (1981a, p. 98) writes eloquently about a vision of the future shared by those who want to create alternative futures, including alternative, improved, sustainable agricultural systems. His words are a good place to end thoughts about the future. Readers may determine if I have reached beyond my knowledge and ability.

We have lived by the assumption that what was good for us would be good for the world. We have been wrong. We must change our lives so that it will be possible to live by the contrary assumption that what is good for the world will be good for us. And that requires that we make the effort to know the world and to learn what is good for it. We must learn to cooperate in its processes and to yield to its limits.

But even more important, we must learn to acknowledge that the creation is full of mystery; we will never clearly understand it. We must abandon arrogance and stand in awe. We must recover the sense of the majesty of the creation and the ability to be worshipful in its presence. For it is only on the condition of humility and reverence before the world that our species will be able to remain in it. Berry's challenge is clear - Change requires more than the contemplation of fixed verities. It must move beyond reproducing the qualities of the science to which we have devoted our careers.

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Table 1. Examples of Knowledge Required to Develop Improved Weed-Management Systems and Decision Aid Models. Adapted from Buhler, D. D., Hartzler, R. G., Forcella, F. (1997). Implications of weed seed bank dynamics to weed management. Weed Science, 45, 329–336.

Management Goal	Research Need
Management Decision Aid Model	• Relationship of the size of the weed seed bank to the final weed population • Emergent rate of individual species • Determination of economic optimum thresholds for control • Interaction of management practice and weed seed production • Effect of weed density on control
Prediction of seedling emergence	• Mechanism of dormancy • Determination of interactions of environmental conditions • Seed germination and dormancy
Effect of Management	• Effect of crop rotations on weed seed bank size • Effect of living and dead mulches • Rate of seed predation and decay • Rate of seed mortality • Light requirements for seed germination • Role of tillage and cultural practices
New Herbicides and Biopesticides	• Discovery of new Modes of Action (MOAs) • Genetic engineering and new options for manipulating herbicide selectivity • Creation of entirely novel approaches to weed management
Artificial Intelligence	• Computing power and automation • Use of machine vision and global positioning systems

ORIGINAL RESEARCH

Rice flatsedge (*Cyperus iria* L.) is Resistant to the Auxinic Herbicide 2-methyl-4-chlorophenoxyacetic acid (MCPA)

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Abstract

This study assessed the potential resistance build-up in rice flatsedge (*Cyperus iria* L.), a dominant sedge weed in paddy fields of Sri Lanka, to MCPA (2-methyl-4-chlorophenoxyacetic acid; WSSA/HRAC Group 4). Mature seeds of *C. iria* were collected from susceptible (S) and suspected-resistant (R) biotypes in five districts of the Northern Province of Sri Lanka. Experiments were conducted in a completely randomized design with five replicates. A knapsack sprayer fitted with a flat-fan nozzle was used to spray MCPA on *C. iria* seedlings at the three-leaf stage at ten dosages ranging from 25% (0.54 kg a.i. ha-1) to 300% (3.24 kg a.i. ha-1) of the recommended dose (1.08 kg a.i. ha-1), with a water-only control. Seedling survival % was estimated at ten days after treatment.

The seed germination of MCPA-S and MCPA-R biotypes of *C. iria* did not significantly differ across districts (P>0.05). Probit analysis and ED50 values calculated using log-logistic model-fitting showed that *C. iria* has developed resistance against MCPA (Resistance Index ranging from 1.59 to 1.62), with no significant difference among districts (P>0.05). Auxin-mimicking Florpyrauxifen-benzyl effectively controlled the MCPA-R biotype with no indication of cross-resistance.

The other four herbicides, namely, Bispyribac sodium, Carfentrazone ethyl, Pretilachlor + Pyribenzoxim and Fenoxaprop-p-ethyl + Ethoxysulfuron, did not effectively control MCPA-R and MCPA-S biotypes. However, multiple resistance in *C. iria* cannot be ruled out. Interestingly, MCPA at the recommended dosage also showed relatively poor control of MCPA-S biotypes, indicating the need to revisit the herbicide recommendation against the sedge weed in paddy fields.

Keywords: *Cyperus iria*, herbicide resistance, MCPA, paddy fields, Sri Lanka

Introduction

The input-intensification in agriculture, including herbicides, has progressively increased herbicide-resistant weeds (Heap and Duke, 2018; Hulme, 2023), thus limiting crop productivity and production worldwide. It has become one of the significant challenges in the sustainable development of agronomic practices. Rice is the main staple for Asians, and the annual crop yield loss due to weed infestation is about 15–21% (Karim *et al*., 2004). In the Sri Lankan context, a 20-40% loss in rice yields was reported due to weed infestation (Herath Banda *et al.,* 1998; Amarasinghe and Marambe, 1998). The weed diversity is the highest in the family Poaceae, with at least 70 species, followed by Cyperaceae, with more than 55 species (Rao *et al*., 2017).

Herbicide use has become the most effective practice in weed management (De Prado *et al.*, 2004; Travlos et al., 2017). However, the shift in weed flora (Marambe, 2002) development of herbicide resistance (De Prado *et al*., 2000; Marambe and Amarasinghe, 2002; Preston and Powles, 2002; Travlos and Chachalis, 2010; Travlos *et al*., 2018) and other environmental concerns (Balderrama-Carmona, 2020) are some of the adverse effects of continuous and misuse of herbicides.

The number of resistant biotypes of weeds is increasing alarmingly in many cropping situations (Duary, 2008; Travlos *et al.,* 2020). The evolution of herbicide resistance in weeds has increased the cost of chemical control measures (Kniss *et al*., 2022), thus affecting the cost of production of crops in addition to various other challenges.

Rice flatsedge (*Cyperus iria* L.), an annual herbaceous sedge (Family Cyperaceae), is among the most troublesome weeds in rice fields in Sri Lanka, India, Pakistan and the Philippines (Awan *et al*., 2022). The weed *is listed* as one of the weeds of national significance in direct-seeded rice cultivation in Sri Lanka (Rao *et al*., 2017).

The extensive use of the direct seeding method of rice (DSR) has resulted in *C. iria* becoming a notorious weed in rice fields (Azmi and Baki, 2002), with a 64% reduction in paddy yield when the weed infests the whole crop duration (Dhammu and Sandhu, 2002). In Sri Lanka, about 7-10% yield loss was recorded in paddy in the Northern Province due to *C. iria* infestation (PDOA, 2020). Sedge weeds, especially the smaller-statured ones, are known to be susceptible to the herbicide MCPA (2-methyl-4-chlorophenoxyacetic acid; WSSA/HRAC 4), which is an auxinic, selective herbicide. MCPA is among the most extensively used herbicides in paddy in Sri Lanka and has been used since the 1960s (Bandara *et al*., 2017; Dissanayake *et al*., 2019; Piyasiri *et al*., 2022).

Based on the field observations, Abeysekera *et al*. (2017) speculated a potential resistance build-up in *C. iria* and Dirty Dora (*C. difformis* L.) in paddy fields against MCPA. Our discussions with experienced paddy farmers, research officers, and agricultural instructors of the Provincial Department of Agriculture and field surveys conducted in 2018-2021, especially in the Northern Province of Sri Lanka, also supported the hypothesis that *C. iria* might have developed resistance to the continuous use of MCPA.

The preliminary surveys also revealed that the farmers in different districts in the Northern Province have been using MCPA at variable dosages, not following the recommendation made by the Department of Agriculture (DOA, 2019).

Further investigations on the regional differences in potential resistance development in *C. iria* in paddy fields to MCPA are warranted as no such scientific evidence is available. Hence, we conducted the study reported herein to detect whether *C. iria* biotypes have already developed resistance to MCPA, quantify the resistance level, and suggest alternate treatments to control such resistant biotypes in rice agriculture in Sri Lanka.

Materials and Methods

The experimental sites were in the five districts of the Northern Province of Sri Lanka, namely Jaffna, Kilinochchi, Mannar, Mullaitivu and Vavuniya. Paddy fields infested with weeds were selected from five districts (Figure 1) based on farmer surveys at those locations where high densities of the *C. iria* had been previously reported (i.e. ≥ 20 *C. iria* plants /m^2).

The main criterion for paddy field selection was the continuous use of the popular sedge-control herbicide MCPA (CAS number 94-74-6] for more than five years in the paddy fields (two cultivating seasons per year) for weed control. The *C. iria* plants in paddy fields, where the herbicide MCPA of 600 g L^{-1} SL (Soluble Concentrate) formulation was applied at the recommended rate (1.08 kg of a.i. ha^{-1}; DOA, 2019) but could not successfully control the weed in the past two years (including the current season) were considered as the suspected resistant (MCPA-R) populations (biotypes).

The *C. iria* populations in paddy fields in each district, where MCPA has continuously controlled the weed, including the current season, were considered susceptible (MCPA-S) biotypes.

Seed Collection

Mature seeds from suspected MCPA-S and MCPA-R biotypes were collected separately from at least five paddy fields per district belonging to several farmers. **Figure 2** illustrates the status of paddy fields where heavy infestation of *C. iria* was observed. Twenty-five mature inflorescences from MCPA-R biotypes of *C. iria* were collected randomly from selected paddy fields that the researchers suspected to have developed resistance to MCPA based on continuous field surveys.

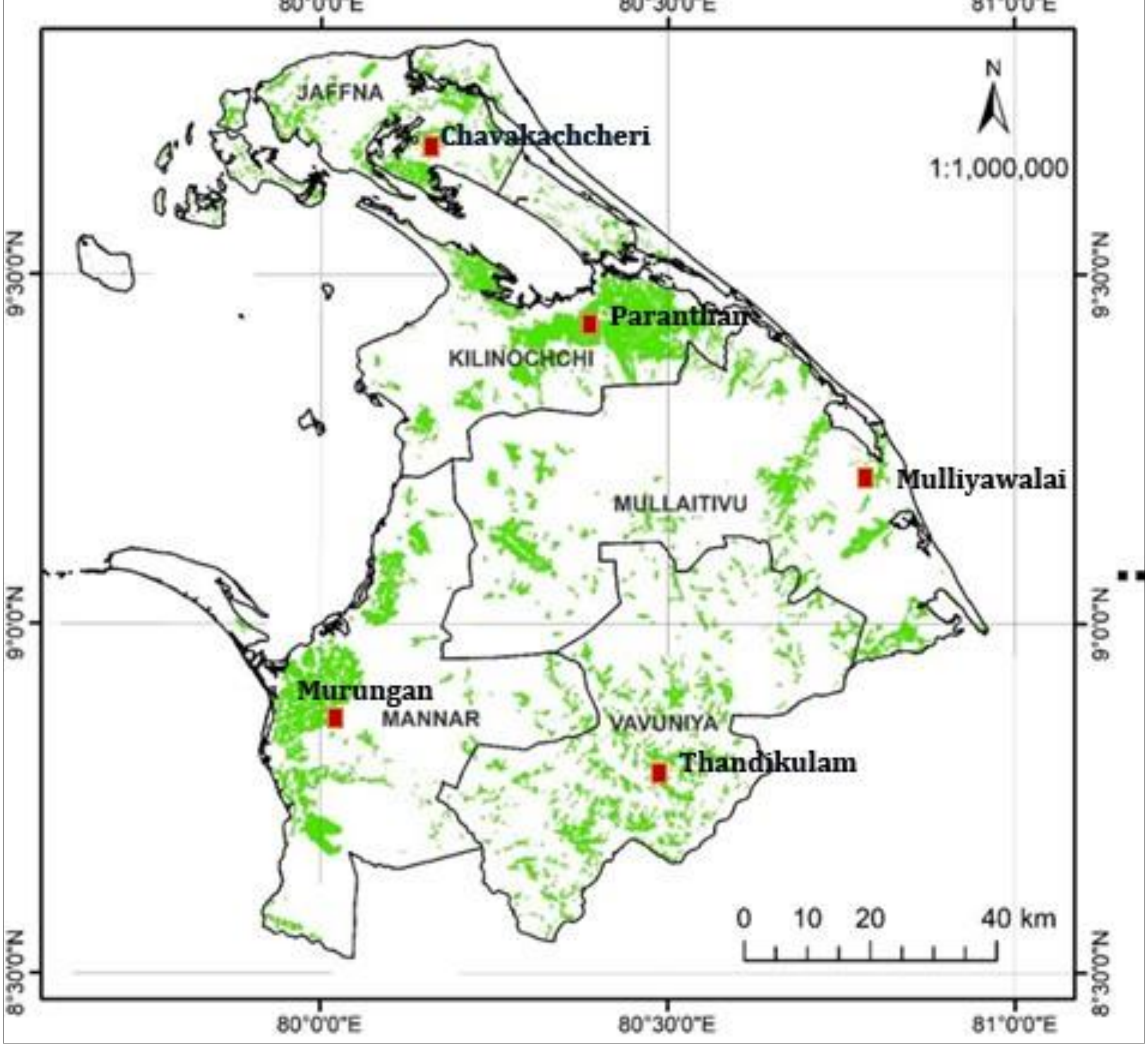

Figure 1. Locations of the paddy fields in five districts in the Northern Province of Sri Lanka from where seeds of the suspected MCPA-resistant *C. iria* biotypes were collected

Figure 2. (A) Paddy fields infested with *Cyperus iria* in the Northern Province of Sri Lanka; (B) Mature inflorescence of *C. iria*

More than 50 inflorescences were collected from several locations in each district, and composite samples were prepared for each district separately as MCPA-S biotypes. The samples were then transported to the laboratory; mature seeds were manually extracted separately and preserved in plastic containers unde

r refrigerated conditions (4 °C) until further use. The study comprised two experiments. The first experiment investigated the potential development of resistance to the commonly used herbicide MCPA. The second experiment explored the potential of alternate herbicides to control the resistant biotypes of *C. iria* in paddy fields.

Seed Germination

Fifty seeds of MCPA-S and suspected MCPA-R biotypes of *C. iria* were placed on Petri dishes laid with Whatman No. 1 filter paper at 27/16 °C day/night room temperature. The Petri dishes with seeds were covered with Aluminium foil to simulate seed burial under natural conditions. The germination rate was recorded for ten days. The Petri dishes were moistened once every 48 hours until the end of the experiment.

Experimental Conditions

Plastic containers (25 cm length x 22.5 cm width x 19 cm height) were used for the experiment conducted in a plant house at the Faculty of Agriculture, University of Jaffna, Kilinochchi, Sri Lanka. The representative paddy soil samples collected from each district were used to grow MCPA-R and MCPA-S biotypes of *C. iria* collected from the respective district. The containers were filled with paddy soil to a height of 15 cm.

Fifty mature seeds harvested from MCPA-S and MCPA-R biotypes from each district were planted in rows in separate containers. The soil was moistened continuously using a hand sprayer. All weeds emerging, excluding the planted *C. iria*, were carefully removed from the pots with minimum disturbance to the soil.

Treatment Regimes

The experiment comprised 11 treatments based on the different rates of application of MCPA (600 g L^{-1} SL formulation); T1: No herbicide application (water-only control), T2: 25% of the recommended dosage (0.27 kg a.i. ha^{-1}), T3: 50% of the recommended dosage (0.54 kg a.i ha^{-1}), T4: 75% of the recommended dosage (0.81 kg a.i ha^{-1}), T5: Recommended dosage (1.08 kg a.i ha^{-1}), T6: 125% of the recommended dosage (1.35 kg a.i ha^{-1}), T7: 150% of the recommended dosage (1.62 kg a.i ha^{-1}), T8: 175% of the recommended dosage (1.89 kg a.i ha^{-1}), T9: 200% of the recommended dosage (2.16 kg a.i ha^{-1}), T10: 250% of the recommended dosage (2.7 kg a.i ha^{-1}), and T11: 300% of the recommended dosage (3.24 kg a.i ha^{-1}).

Each treatment was replicated five times and laid down in a complete randomized design. Herbicide treatments were applied at the 3-leaf stage *of C. iria*. Plastic pots were moved into an open space and placed evenly before spraying the herbicide.

The treatments were imposed separately for S and R biotypes, ensuring no cross-contamination. A lever-operated 16 L Knapsack sprayer equipped with a flat-fan nozzle was used, with a nozzle deliverer rate of 576 mL min^{-1} to cover the whole area of the open space. The spray volume was 320 L ha^{-1}.

Alternative Herbicides to Control *C. iria*

Tray experiments were conducted under the same plant house conditions using weed seeds collected from the five districts to identify alternative control measures for the MCPA-R weeds. The trays used in the first experiment were also used, and soil was filled to 15 cm height using the same paddy to grow the MCPA-S and MCPA-R biotypes. Fifty seeds of each of the MCPA-S and MCPA-R biotypes were planted in each container separately. Five alternate herbicides, which are also recommended and used by the farmers in the province to control sedge and broadleaf weeds, were evaluated for their efficiency in controlling *C. iria* (Table 1).

Of the five herbicides, one was an auxin-mimic, as in the case of MCPA. The herbicides were applied using the same method adopted in the previous experiment. The herbicide rates were derived from recommendations of DOA (2019). The experiment was conducted in a completely randomized design with five replicates. The application method and equipment used were the same as previously reported in this paper.

Table 1 Alternate herbicides used in the experiment

No.	Herbicide and Formulation	Mode of Action	Recommended dose of commercial product
H1	Bispyribac sodium (100 g a.i. L-1) EC	Acetolactate synthase (ALS) inhibitor	225 L ha-1
H2	Carfentrazone ethyl (240 g a.i. L-1) EC	Protoporphyrin oxidase (PPO) inhibitor	90 L ha-1
H3	Pretilachlor (300 g a.i. L-1) + Pyribenzoxim (20 g a.i. L-1) EC	Very long chain fatty acid and ALS inhibitor	1.25 L ha-1
H4	Fenoxaprop-p-ethyl (69 g a.i. L-1) + Ethoxysulfuron (20 g a.i. L-1) OD	Acetyl-CoA Carboxylase (ACCase) + ALS inhibitor	0.5 Lha-1
H5	Florpyrauxifen-benzyl (25 g a.i. L-1) EC	Auxin-mimic	1.2 L ha-1

Measurements and Statistical Analysis

The number of seedlings killed and survived ten days after each treatment was counted. Data are presented as % of seedlings that survived in each treatment. The Chi-Square test (p=0.05) was conducted to test the association between the resistance build-up and seed germination.

The resistance development was assessed using the dose-response curves from probit analysis (NCSS Statistical Software, Chapter 575). A log-logistic model was fitted to estimate the ED50 (effective dosage to kill 50% of the population of a given biotype). The Resistance Index (RI) was calculated using Equation 1 as given in Pilho *et al.* (2009).

Resistance Index (RI) =

$$\frac{ED_{50}\text{ of the Resistant Population}}{ED_{50}\text{ of Susceptible Population}}\;\ldots\ldots\ldots$$

Results

Seed Germination (%) of MCPA-S and MCPA-R *C. iria* biotypes

A similar germination % (Figure 2) among the districts was observed in MCPA-S and MCPA-R within each district. Among the districts, MCPA-S ($\chi^2_{df=4}$ = 1.034; p=0.90) and MCPA-R ($\chi^2_{df=4}$ = 2.19; p=0.69) showed no significant differences in the germination pattern of the *C. iria* seeds collected.

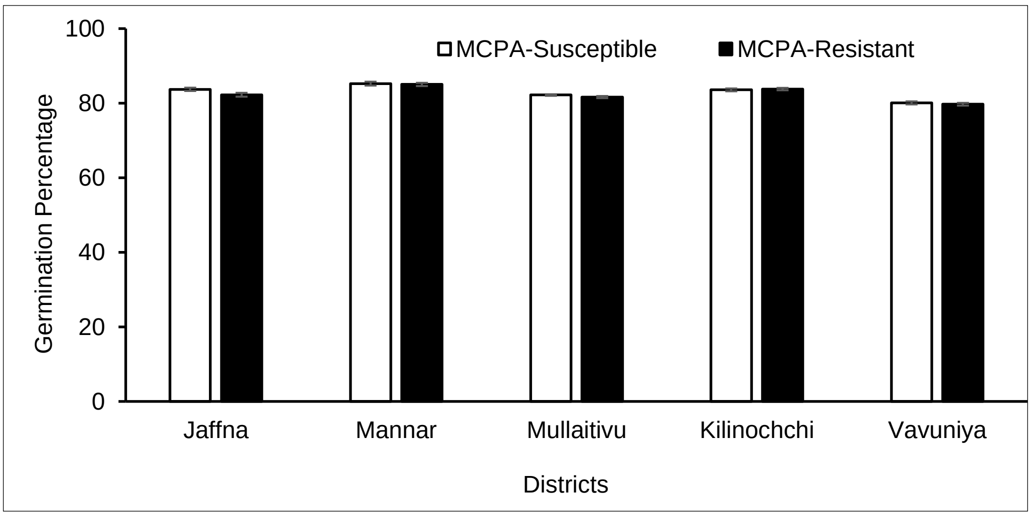

Figure 2. Seed germination % of MCPA-S and MCPA-R biotypes collected from different districts in Sri Lanka. Vertical lines are the Standard Errors of Means (N=5).

Resistance Build-Up in *C. iria* populations to MCPA

Based on the parallel and non-parallel model fitting, the non-parallel dose-response curves were selected to explain the results, as the responses showed a genetic (G) x environment (E) interaction. Inverse Sigmoidal dose-response curves of *C. iria* seedlings exposed to different concentrations of MCPA indicated a strong relationship between increased MCPA concentrations and mortality rates (Figure 3). The herbicide controlled the weeds effectively (100% control) at a 25% higher dosage than the recommended (Figure 3). According to the ED50 values, the MCPA-R biotype had an RI of 1.59-1.62 in all five districts, indicating resistance build-up compared to the MCPA-S biotype (Table 2).

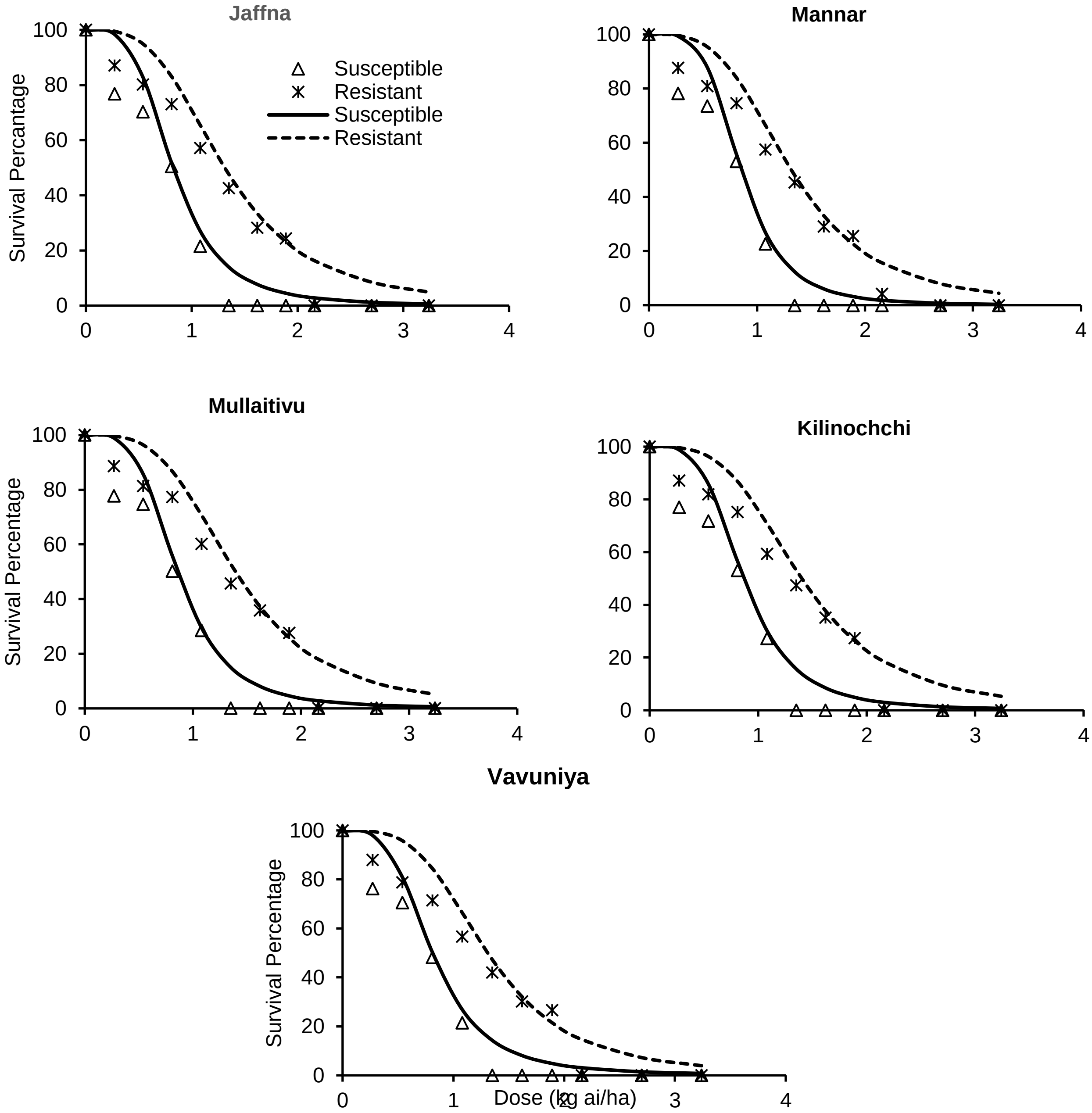

Figure 3. Non-parallel dose-response curves of susceptible and resistant biotypes of *C. iria* from five districts in the Northern Province to MCPA, using the log-logistic model. Lines are response curves predicted from non-linear regression. Symbols represent the mean survival rate of five replicates.

Table 2. ED_{50} values of MCPA-S and MCPA-R biotypes and Resistance Index (RI) of *C. iria* in five districts of Sri Lanka

Districts	ED50 Values for MCPA-S Biotype	ED50 Values for MCPA-R Biotype	RI Index
Jaffna	0.82	1.3	1.59
Mannar	0.84	1.34	1.62
Mullaitivu	0.9	1.44	1.6
Kilinochchi	0.9	1.44	1.6
Vavuniya	0.85	1.35	1.59

ED_{50} = herbicide dosage required to kill 50% of the weed population, R = resistant biotype; S = susceptible biotype, RI = Resistance Index

The ED50 values for MCPA-S biotype ranged from 0.82 to 0.9 kg a.i. ha^{-1} and that for MCPA-R biotype raged from 1.59 to 1.62 kg a.i. ha^{-1}. The results of the present study also showed that even the MCPA-S biotypes identified by the farming community were not effectively controlled by the recommended dosage of MCPA (1.08 kg a.i. ha^{-1}).

The Effectiveness of Alternative Herbicides to Control MCPA-Resistant *C. iria*

None of the five alternative herbicides tested provided satisfactory control of *C. Iria*, irrespective of whether the biotypes were MCPA-S or MCPA-R (Figure 4). Notably, all MCPA-R biotypes were collected from the five districts of the Northern Province of Sri Lanka. Although the differences were statistically insignificant, the resistant biotypes showed a marginally better survival rate than the susceptible biotypes (P>0.05).

Discussion and Conclusions

Differences in seed germination rates have been observed among the herbicide-resistant and susceptible weed biotypes (Alcocer-Ruthling et al., 1992; Torres-Cgarcia et al., 2015). However, similar to the results observed in our study, Shaeffer et al. (2021) also reported identical germination patterns in the two biotypes, suggesting that the germination behaviour of herbicide-susceptible and resistant weed biotypes would vary depending on conditions encountered in the ecosystems.

The results clearly showed G x E interactions among the biotypes of *C. iria* biotypes collected from the five districts in the Northern Province for both MCPA-S and MCPA-R biotypes, even when the herbicide was used at the recommended dosage.

Our preliminary analysis has confirmed that, though the extent of farmer fields varied significantly, there was only a marginal variability in the use of other agricultural inputs, such as fertilizer in the study sites and that all paddy farmers used herbicides for weed control in paddy fields (data not shown). Though it was difficult to estimate the actual dosages of MCPA applied to the paddy fields by individual farmers in five different districts, it is still reasonable to conclude that several biotypes of *C. iria* in the study sites are resistant to the herbicide MCPA.

The number of weed species resistant to synthetic auxin herbicides mimicking indole-3-acetic acid (IAA) is relatively low, considering their long-term use globally (Busi *et al.,* 2018). Of the 570 cases reported as herbicide resistant (Heap, 2024), 44 were related to synthetic auxin-type herbicides, while 14 weeds were reported as resistant to MCPA with no records on *Cyperus* spp.

We did not study the resistance mechanism to MCPA in *C. iria* biotypes. However, the differences in the rate of translocation and metabolism of the MCPA among plant populations are considered as a possible mechanism of evolution of resistance to the herbicide in weeds (Singh *et al.* 2023), where the resistant biotypes might have translocated lesser amounts of MCPA while they metabolized the herbicide more rapidly.

Weinberg *et* al. (2006) reported the involvement of more than one genetic locus with additive effects in the absorption, translocation and metabolism of MCPA in the roots of the resistant populations. The MCPA resistance in wild radishes is controlled by a single gene, where resistant plants rapidly translocated more 14C-MCPA to roots than the susceptible plants, resulting in its exudation from the plant (Jugulam *et al.,* 2013).

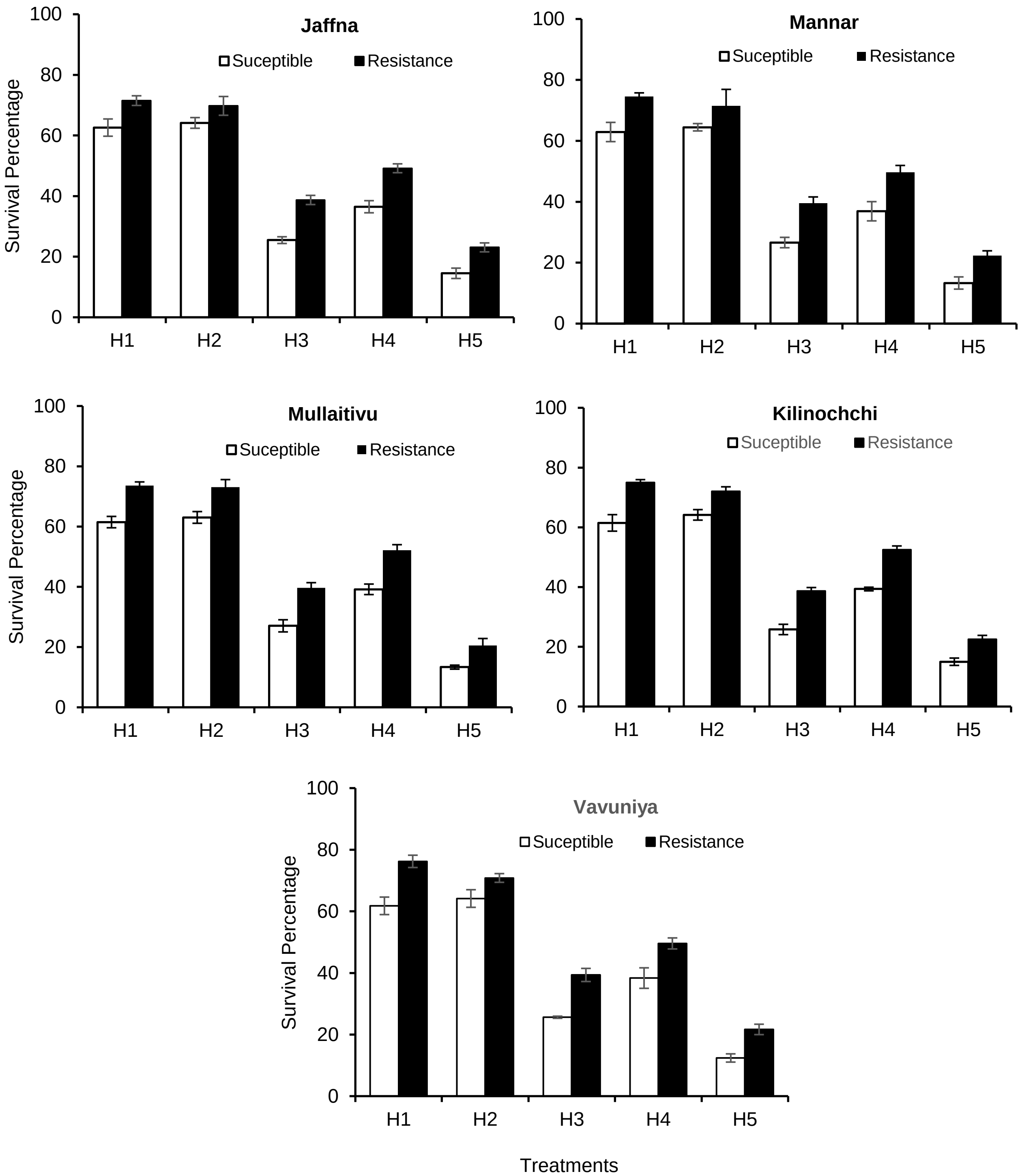

Figure 4. The survival rate of MCPA- Susceptible (S) and Resistant (R) populations of *C. iria* when treated with alternate herbicides (H1 = Bispyribac sodium, H2: Carfentrazone ethyl, H3 = Pretilachlor + Pyribenzoxim, H4 = Fenoxaprop-p-ethyl + Ethoxysulfuron, and H5 = Florpyrauxifen-benzyl. The vertical line on each bar represents the standard error (SE; n=5). Refer to Table 1 for the recommended dosages.

Moreover, Jasieniuk *et al.* (1996) reported that herbicide-resistant populations could be the source of resistant alleles for the nearby susceptible populations, thus aggravating the problem of herbicide-resistant weeds in crop cultivation.

The phytotoxic effects of MCPA on nursery tea plants (Sayanthan *et al.*, 2021) and rice (Bandara *et al*., 2017) are well established. The recommended dosage of MCPA to control sedges and broad leaf weeds applied 20-21 days after planting paddy has affected the paddy plant itself (Shibayama, 1980; Bandara *et al.,* 2017). However, it is essential to note that early application or higher dosages of MCPA would be detrimental to paddy plants despite the sedge weed control observed in this study.

Further, Jayasiri *et al.* (2022) reported a high environmental impact score of 7.4 and a high variability of EIQ-FUR for MCPA. Hence, the study reveals the importance of revisiting the recommendations to control sedge weeds such as *C. iria* in paddy cultivation in Sri Lanka.

The results of the present study also revealed the poor control of *C. iria* by the alternate herbicides with different modes of action, with a marginal increase of survival by the MCPA-R biotypes compared to the MCPA-S biotypes of the weed.

Multiple resistance could occur in weeds owing to the co-evolution of multiple mechanisms in either target site, non-target site resistance, or a combination (Torra *et al.*, 2019).

This study did not investigate the resistance mechanisms or assess the development of multiple resistance in MCPA-R biotypes of *C. iria*. However, these aspects warrant further studies. Tarvlos (2012) reported that the degree of selection pressure will determine the levels and patterns of herbicide resistance and the development of cross-resistance to multiple herbicides.

Cyperus iria, a major sedge weed species in the lowland paddy fields in the Northern Province of Sri Lanka, has developed resistance to MCPA, most likely due to the herbicide’s long application history.

To prevent the dominance of MCPA-resistant *C. iria* in paddy fields and avoid the development of cross- or multiple resistance to herbicides, rotational use of alternate herbicides or non-herbicide control measures should be encouraged. Continuous programmes aimed at farmer education on the impending threat of herbicide-resistant weeds in paddy fields are recommended.

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