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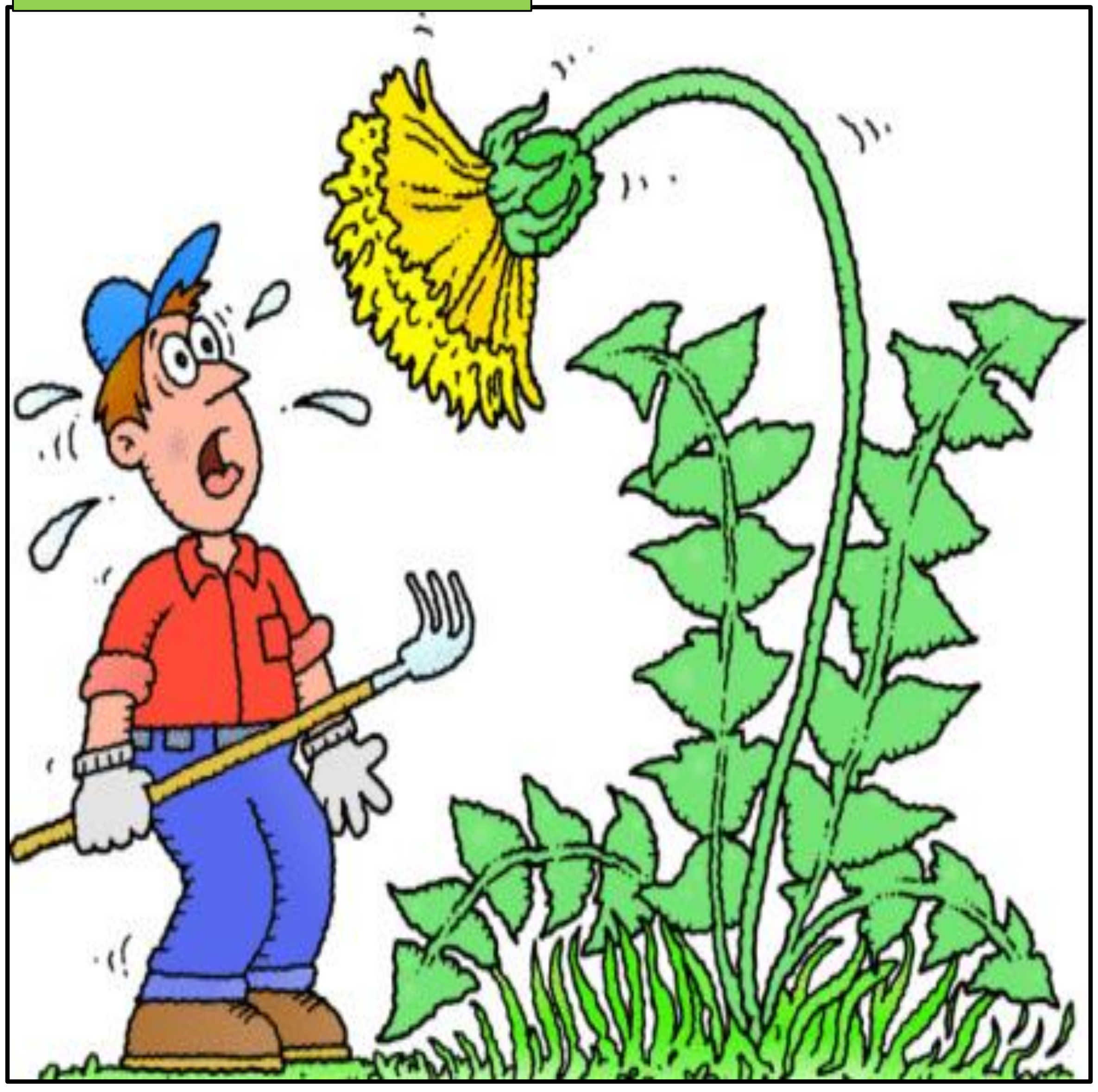
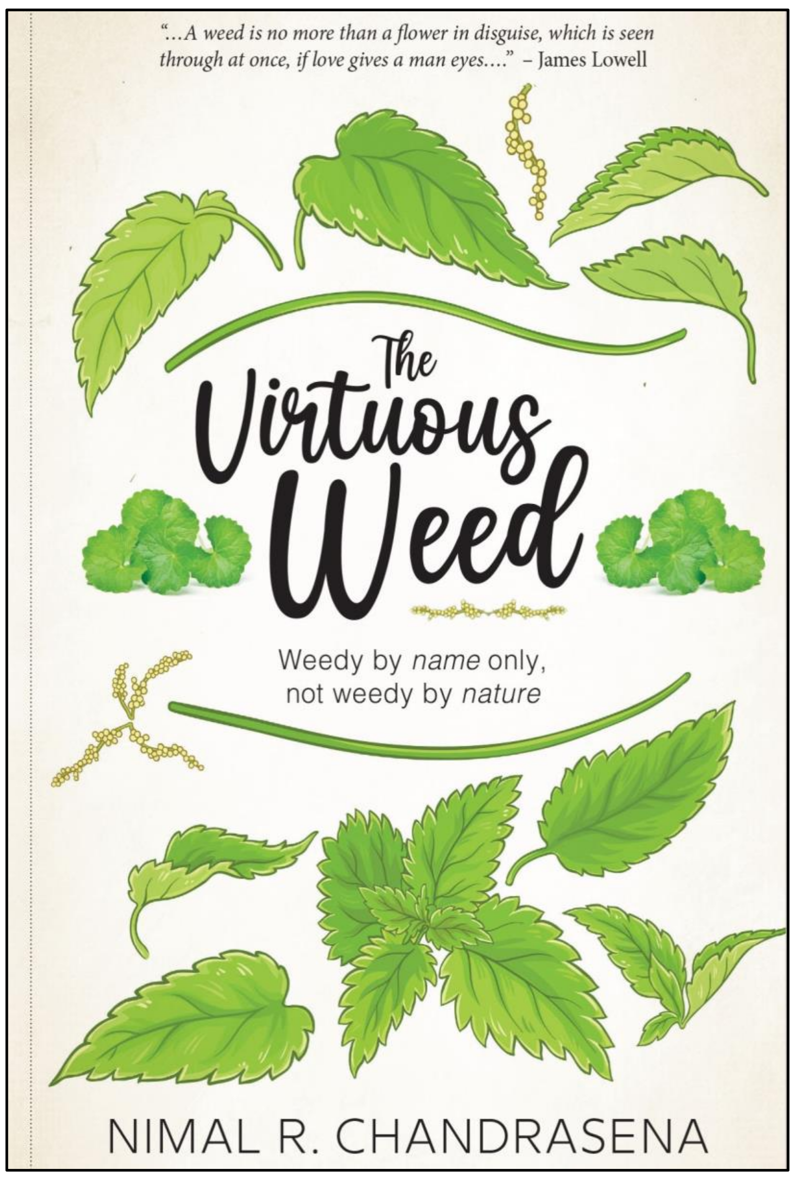
APWSS

Creating Fear



Mixed Messages, 'Invasion Myth' vs. 'Virtuous Weeds'

"Science could help resolve the conflicting views"



Reflecting on the Obstacles to Uses of Colonizing Species ('Weeds') as Bio-resources

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Abstract

Ecology, *Weed Science*, Restoration Ecology Conservation science and related disciplines are now well-developed. These disciplines have the knowledge, capacity and tools, firstly, to recommend the prevention of potentially risky plant introductions; and secondly, to develop methods to eradicate, contain or manage problematic species and reduce any harmful effects, either to food systems, human health, or the environment. However, in all of these 'sciences', the ideas for the *utilization of colonizing taxa* are not well articulated; nor are the opportunities adequately pursued. Why? we may ask.

The utilization of 'weedy' colonizing species for direct human benefits and other practical applications is a much-neglected area within *Weed Science*. It is the result of an inadequate ecological understanding of weeds, which I call 'weed-illiteracy'. Most weed scientists and even some ecologists and conservation 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!

A change in attitude and a shift of focus are required to redress the issue. Weedy taxa have been blamed and 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 urban population growth). Changing our perceptions of colonizing species will allow weed scientists to explore the benefits of a positive relationship with a vast array of such taxa and their unique capabilities. Faced with the uncertainties of a changing climate, not to change our attitude towards weedy species appears another human folly in the making.

Keywords: Colonizing species, weeds, utilization of weeds

'Responsibility' – a Virtue

Unfortunately, most weed scientists are trained from their early careers to fight weeds, not to utilize them. The '*war on weeds'*, is an attitude that has been around for more than 70 years (Evans, 2002; Larson, 2005; Falck, 2010; Davis et al., 2011; Dwyer, 2012). The war metaphor believes *humans could win a war against weedy enemies*. This misguided and unhealthy attitude has been a bane of weed science.

The primary 'weapons' of war (herbicides) were mostly discovered and developed as commercial products in the 1940s and 50s decades. Weed science, as a discipline, was also founded in the 1950s decade. Even in those decades, the slogan '*war with weeds'* has been like a *mantra*, repeatedly heard at various symposia and weed conferences.

After the first synthetic, organic herbicide, 2,4-D was discovered and developed in the late 1940s, many others followed. Herbicides, especially selective chemicals, initially provided highly effective weed control across agriculture and many other areas where colonizing taxa posed problems, such as in the management of golf courses, infrastructure, public spaces and rights-of-way.

Early in the development herbicides were saviours, not problems. However, within two decades, the overuse of herbicides for weed control in agriculture and in other situations presented a major difficulty in the USA, UK and Western Europe.

More than six decades ago, ecologists 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 technological and scientific breakthroughs led to these warnings being largely unheeded.

The echo of the misinformation – that humans can actually 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 even 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 in our possession an arsenal of herbicides. As a result of believing 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, (but not all i.e. Organic agriculture) media stories blare out the sensational message: *All weeds are bad news*. Disappointingly, thousands of weed research articles, even in recognized weed 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 simply 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*' created in people's minds regarding weedy species, presented as '*aliens*' ready to engulf the world.

Given the entrenched view that *weeds are bad news*, most weed scientists, perhaps with some justification, stop short of recommending that these colonizing taxa can actually be useful for societal benefits. 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!*

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

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 huge challenge and the uses and opportunities remain under-explored (Chandrasena, 2008; 2014).

With some species, such as water hyacinth [*Eichhornia crassipes* (Mart.) Solms.] that can be exploited for various uses, and arundo (*Arundo donax* L.) and jatropha (*Jatropha curcas* L.) that can potentially be expanded as a biofuel crop, utilization may present modest but manageable risks. '*Good observers*' do not miss such possibilities [1].

The frameworks and concepts for managing a potential risk posed by a specific species are well-developed within weed science and related disciplines. Given this, as I have previously discussed (Chandrasena, 2014), 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 it is often unnecessary and futile to carry out drastic and lethal action against any widespread species in most habitats.

The resolution of most environmental conflicts lies in the power people have over issues that concern them. The vexed issue of *colonizing taxa,* which are regularly accused of being a 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 a myriad of problems weedy taxa present by their sheer abundance, in specific situations. But solutions can only be found by people themselves, with a sympathetic attitude combined with an enlightened ecological understanding. Developing effective solutions will require balancing the negative effects of colonizing taxa in specific situations with their positive effects, i.e. the values of goods and ecosystem services the taxa provide.

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

[1] Robert Zimdahl, Emeritus Professor of Weed Science at Colorado State University recently stated (*personal communication*, 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*".

as humans face a precarious future under a changing climate. In ethics, *responsibility* is counted as an environmental virtue and often expressed as a good-trait of character. A '*good human being*', with compassion and benevolence, will take responsibility for behaving appropriately towards the environment, including all other species (Thompson, 2011).

Extending from such ideas, both 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 becomes a problem, whether it be in agricultural or non-agricultural settings, we must manage them using well-developed tools and 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.

Zimdahl and Holtzer (2021) have argued that in all our activities, we should worry about the *ethics* of what we do. All of humanity has a moral responsibility to '*do no harm*' to the environment, biodiversity and the planet. In their view, in agriculture, or all other productive endeavours, profits alone must not be the key driver. The environmentally-responsible person will be disposed to acquire the knowledge to achieve this and also 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, but we must allay our fears of the so-called '*Aliens*' or '*Invasive Alien Species*'.

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Should weeds be treated '*guilty, until proven innocent*'? Some people have taken this phrase to unjustified depths, maligning weeds. The view is repeated but hardly questioned in agricultural and related vocational courses in Australia, such as horticulture, landscape ecology or rural development. It is often heard at weed conferences. Thankfully, the false assumptions in this viewpoint have been questioned by many prominent people [20]

The initial objections came from a philosopher - Mark Sagoff (Sagoff, 2002; 2009) and a group of ecologists - Mark Davis and Ken Thompson (Davis, 2005; Davis and Thomson, 2000; 2001), Curtis Daehler (2001) and Brendon Larson (2005). These were followed by strong criticisms by historians - Matthew Chew (Chew and Caroll, 2011; Chew, 2015) and John Dwyer (2012), who expounded the opposite view. Writing to the prestigious *Nature* Magazine, in 2011, Mark Davis and 18 others (Davis et al., 2011) also voiced their strong objection to the nebulous concepts and questionable narratives that blamed introduced species for human follies. Recently, Guiaşu and Tindale (2018) added their voice, objecting strongly against the use of fear-invoking terms in public discourses.

The simple ecological process of '*colonization*' by which some highly adaptive taxa establish in new areas, where opportunities exist, has been misconstrued with a fear-invoking term '*invasion*'. Despite the lack of consensus, over several past decades (Davis and Thompson, 2001; Colautti and MacIssac, 2004; Rejmánek et al., 2005; Davis, 2005), many such species have continued to be branded as '*Invasive Alien Species*' (IAS).

This flawed narrative and disagreement are obstacles to the prospects of the utilization of many species with unique capabilities. The '*native*' versus '*aliens*' debate, which was ignited in the 1990s (Sagoff, 2002; 2009; SCB, 2007; Davis, 2005; Chew, 2015; Shackelford et al., 2013) also continues unabated, often clouding weed-related discourses.

A large number of species, including some humble 'farmer-friendly' weeds have been branded as *IAS* deserving to be punished with death for merely occupying human spaces. The term '*alien*', used correctly, should not disparage species in any sense.

As the pioneer users, who popularized the term (i.e. British botanists - Hewett Cottrell Watson (1847) and Stephen Troyte Dunn (1905) have so clearly explained, it should only apply, if ever, to species '*introduced*' to new areas (Chandrasena, 2021). The terms "*alien*" and "*native*", used by Watson, Dunn and other traditional botanists, along with phyto-geographers in the mid-19th Century, gained *moral force* with the rise of environmentalism, more than a century later (Chew and Caroll, 2011; Chew, 2015).

'Natives' were natural, innocent and untainted by any human association; 'Aliens', like their human enablers, had detrimental "impacts", not effects.

As Larson (2005) and Dwyer (2012) stressed, terms, such as '*alien*', '*feral*', '*invader*' and '*invasion*' are designed to exaggerate and create fear in the public's mind. In my view, 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.

To say that: '*all weeds must be guilty until proven innocent*' is a form of populism at its worst. Unfortunately, despite objections, this trend is still continuing, especially in the USA, Australia, New Zealand and some Western European countries.

The current trend of presenting the negative effect of colonizing taxa as an imminent '*invasion*' is a mess that *Weed Science* would do well to address as a matter of urgency. It has nothing to do with a genuine interest in saving the world from '*invaders*', who, it is alleged, commit crimes against humanity! Disturbingly, in my experience, the claim is hyperbole to get more funding. Ken Thompson (2014) went further and called it 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…".*

These emotive and highly subjective adjectives still continue to thrive within the discipline of *Invasion Biology* (Binggeli, 1994; Chew and Laubichler, 2003; Colautti and MacIssac, 2004). Without a doubt, these powerful terms also influence the public's thinking and prevent positive relationships with weedy taxa.

Defense against "*biological invasions*" became a prominent goal of conservation biologists, who decided, by acclamation, that the '*impacts*' of IAS present a dire threat to biodiversity, thus creating a myth. In this mythology, any form of *colonization* of a new location by plants or animals became viewed as a problem (Chew and Laubichler, 2003).

Historical usage of the terms shows that the concept of '*nativeness*' lacks any 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; Hill and Hadley, 2017). Moreover, there are many global examples, which indicate that not all species introductions to new areas, regions or continents are so dramatically detrimental as claimed by conservationists and the media

My view is that the industrious plant collectors and phyto-geographers of the past, such as Watson (1847) and Dunn (1905), knew more than a century ago that *not all 'introduced' plants can be successful in their new environments*. When moved across geographical barriers and continents only a mere handful can successfully establish on their own without help from humans. Also, only a very few grew in such abundance that they caused problems for humans and natural ecosystems.

Ecology teaches us that given the variety of life cycles, reproductive strategies, and the dispersal means that plants and animals have, many species can indeed move about and spread on their own crossing even geographical boundaries. They would receive some assistance for spread, establishment and eventual '*colonization success*' from natural vectors (such as wind, water, and animals) and also benefit greatly from the relentless disturbances that humans and other animals cause. However, not all species, being moved about by humans or other vectors, can be successful in all types of habitats (Parker et al., 2013).

The combination of two powerful adjectives - '*invasive alien species*' (IAS) - has confused many scientists, including weed researchers and the public. Regrettably, nowadays, one could find large numbers of journal articles using the term IAS interchangeably with weeds. At conferences, symposia, workshops and other fora also the fear-invoking terms IAS, '*alien invaders*' and '*invasion*' are widely used in an *ad hoc* manner with no real understanding.

Statements, such as '*weeds are guilty until proven innocent*' using disparaging adjectives like '*feral*' and '*evil*' in referring to colonizing taxa are not worthy of the people who make them. As with all bad news (or *fake* news), this *untruth* about weeds has travelled farther, faster and deeper, across the globe. In most well-documented cases, the term IAS exaggerates the likely longer-term ecological impacts of organisms in new environments.

In most countries, the IAS lists include some valuable species from which societies can benefit. In the confusion created by the IAS branding, one can excuse the public, scientists and policymakers for being misled. Many have been brainwashed by this narrative 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, but it can be expedited by a better understanding of weedy taxa. *Weed Science, Ecology, Plant Biology and related disciplines have a responsibility to better understand what colonizing taxa really are, their worth for humanity, and what they can offer to our Planet Mother, presently crying in distress.*

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Regardless of our capacity to kill weeds in most situations, by their sheer tenacity, and abundance, colonizing species gives us several messages. The paramount message they give is the *challenge* they pose with the capacity to adapt rapidly to climate change, as well as to the selection pressure applied by humans through the use of herbicides. A relevant question would be - *Despite our 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 does not have a 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 most of the time, get the message wrong.

The echo chambers of negative messages on weeds are largely 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 (Harper and Chandrasena, 2018). Some are convinced that what they do is right and the alternate view - promoting the utilization of weedy taxa for any ecological, environmental or societal benefit - will *go against the grain*.

In Australia, funding has never been available to investigate the positive contributions of colonizing taxa to the environment or to society. All government funding goes towards killing weeds, *presumed as guilty* and harming the environment or human interests. For instance, even the last round of weed research funding, announced in June 2021, sought '*off-the-shelf*', '*farm-ready*' easy fix solutions that hold out 'silver bullet' promises for managing a *priortised* list of taxa (DAFF, 2022). Sadly, this was despite the lack of evidence that these generic solutions have had much of an effect on weed management in Australia (Harper and Chandrasena, 2018).

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 any concern or 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 it be basic (pure) science or applied science, will only come with determined campaigning by concerned citizens seeking better solutions*.

This situation, however, is not unique to Australia. In dealing with weedy taxa, often, governments take a '*we-know-it-all*' attitude, which leads to '*top-down*' enforced approaches. Such an approach fails 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 voice is more powerful than that 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 in the relatively newly-colonized Australian continent is an impediment to exploring the utilization of colonizing taxa as bio-resources. 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 most regional areas of this large and mostly arid continent does not help. Generally, low-density regional communities are too sparse and small to economically utilize the relatively large biomasses of colonizing taxa, which are spread across vast, arid landscapes.

Another powerful reason is the relative affluence of the population, given Australia's rich mining-based economy. Most people are wealthy, deriving income from manufactured goods and services rather than from raw materials in the environment. 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 and nitrogen-fixing ground-covers and trees, or shade trees) or animal farming (i.e. fodder species).

A large portion of the wealthy 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, which creates conflicts with species.

For example, primary producers, large agri-businesses and others- Nursery Industry, and even consumers, often initially experience positive effects from a new plant species. However, when the same colonizing taxa become naturalized over time and then begin to spread, they become the objects of a visceral dislike of the same landowners because of the problems the species may cause.

In Australia, pastoralists derived enormous benefits from N_2-fixing legume trees and leguminous cover crops, which were introduced over a century ago to improve grazing lands and fodder for the animals. 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 strong political constituencies, and their voices drown those of others with opposite views on specific species.

To answer the question of whether we can ever co-exist with weeds, *science is not enough*. Value judgements, societal considerations and democratic decisions are involved, but these should be underpinned by both scientific and non-scientific knowledge and a commitment to Nature [2]. Weed scientists have a *responsibility* to engage more with people working on 'weed policies' or focus on the *social ecology* of weeds.

Armed with scientifically testable ideas, more 'policy-related' research is the only way forward to finding sustainable solutions to managing vast landscapes, agriculture, and soil and water resources. Trade-offs and compromises will have to be made with a commitment to do *no further harm* to the environment. In that regard, the potential for utilization of colonizing species *must* be a serious candidate for funding in the future.

Weed scientists, across the globe, must also take *responsibility* to better understand colonizing taxa before embarking on developing unsustainable and lethal solutions. We must learn lessons from the way weedy taxa rapidly evolved resistance to the continuous use of herbicides (Heap, 2014; 2022).

If our genuine desire is to protect the environment from the ravages allegedly caused by 'colonizing taxa, blamed as the '*second greatest threat to biodiversity*' [3], 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. My view is, in the longer term most weedy species will *co-exist* with the so-called 'natives' without completely displacing the latter or causing irreparable harm.

The idea that the world needs to be 'conserved' or 'restored' is fraught with difficulties, as Matthew Chew (2015) argues so eloquently:

> *"…Evolving as a 'crisis discipline' with a 'call-to-arms' mandate to 'save the world', the Invasion Biology narrative presumes that the earth is 'pristine', as well as rather static and the changes that have occurred or currently happening, could be reversed with direct action. Man's culpability is quite explicit in the conservationists' agenda; however, in the same breadth, most conservation ecologists are ready to blame weeds as a primary cause of biodiversity losses, without much empirical evidence, which is a shame..."*

By writing large numbers of articles on weeds, one should not expect the public to understand weeds or weed-related issues of concern. If researchers really care about how their findings will influence public opinion and government policies, they must redress this '*communication gap*' and '*translational deficit*'. This deficit, obvious in the majority of *weed science* publications, is possibly due to inadequate *ecological literacy*, and often, poorly-selected research topics that have only an academic interest but little practical value to society.

The *translational deficit* regarding the practical applications of specific research findings and scientific insights can only be remedied by balancing scientific evidence with the priorities of societies. Perhaps, weed researchers themselves should better understand colonizing taxa and moderate their

[2] 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.

[3] E O Wilson's 1992 book (Wilson, 1992) 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 had to do something, and it got embedded in the *Convention on Biological Diversity* (CBD, 1992). without much challenge. The repercussions are felt even today, in 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...*"

own views regarding the objects they are dealing with. This will help many researchers not start every article by presuming that all weeds should be controlled, at all costs and that they 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 also have a *responsibility* to form 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 useful resources – for now, and for the future, is not a radical idea or 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 the human hand.

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 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 providing pollen and nectar for bees. They enrich Nature by adding variety, richness, abundance and biological diversity to any landscape.

If we *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* – serious lessons that humans can and should learn. The species are also spotlighting a spectrum of human follies in damaging the very environments that we should be preserving.

Learning from Nature

Instead of demonizing species, we must learn from each other and learn from Nature, as well as from pioneering plants and animals. Our ancestors, notably, *pioneers themselves*, did so admirably. Our existence today is a testament to the adaptability and survival skills of our pioneer ancestors.

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, as well as 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 the 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 to this list soil, air and water pollution, damages caused by the globally-rampant wildlife trade and poaching, and also the environmental pollution caused by the 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…".*(Pascual et al., 2017).

The NCP concept has been developed within the context of the *Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES).* It is proposed as a pluralistic approach, widely applicable to knowledge–based policy initiatives.

The NCP platform recognizes the benefits of embracing the diversity and power relationships across stakeholder groups that hold different values on 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* as a 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 9 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, species and biological traits at an alarming rate, as highlighted at the 1992 *Rio Earth Summit* (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 quite comprehend the complexities of understanding 'causes and effects'. Some people (such as climate change denialists) vehemently 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 it is the poor who will suffer most from inaction by the rich*.

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

As argued by Cardinale et al. (2012) and Hooper et al. (2012), diversity-driven increases in function can boost rates at which nutrients, energy and organic matter flow through an ecosystem, as well as 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 a must 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 in ways that maximise the cycling of energy and nutrients through those ecosystems. Along with all other life forms of plants, pioneer species will fill a variety of roles in ecosystems. Of their very unique nature, they will withstand disturbances and bounce back, responding to environmental changes. Although frugal in the way they consume resources, these highly adaptive species will share those resources with others.

Humans clearly present the greatest threat to biodiversity, of which both people and colonizing 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.

Concluding Comment

Hill and Hadley (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 also change the habitats, which they occupy. 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 damaged ecosystems. *They will survive catastrophes on Earth. We may not.*

Science helps us approach the '*world of weeds*' with both wonder and humility. Scientific ethics call for us to have an honest dialogue with Nature and what we find in life. Science will also help us fight fake news and mis-information and navigate the troubled waters and find a more resilient and reasonable position concerning weedy taxa. What we must all strive for is to '*rethink 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.

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PERSPECTIVE

Sustainable Weed Management Options for Potato (*Solanum tuberosum* L.) Cultivation in Assam

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Abstract

Potato (*Solanum tuberosum* L.) is an economically important tuber crop in Assam, in which weeds can cause productivity losses of up to 80%. This article reviews some effective weed-control techniques for growing potatoes in Assam, developed as part of the "*Potato Knowledge Bank*" of the *International Potato Centre* (CIP). During a potato's vegetative growth, many types of weeds can significantly reduce both yields and tuber quality. Managing weeds, using different methods, is, therefore, a major component of the potato production process. Under most conditions, the critical period of weed competition for potatoes is about 25-30 days from planting.

In potato cultivation, it is important to minimize weeds before the crop emerges using an approach of Integrated Weed Management (IWM). This requires choosing fast-growing, high-yielding potato varieties, planting the crop at the right time and maintaining an ideal plant population in the fields. Added to this list are various cultural practices, which include land preparation, harvesting at the right time, the timing and placement of farmyard manure (FYM) and fertilizers, and the incorporation of green manure crops. Suitable crop rotations can also result in effective weed control in potato fields. The 'stale seed bed' technique is one of the best options for potatoes because it has the potential to reduce human labour and weed management costs. Soil solarization can also be a simple, safe, cost-effective and eco-friendly technology to control weeds.

Chemical weed control is also a significant component of IWM for potatoes. Molecules, such as the soil-applied, photosynthetic inhibitor – Metribuzin, are widely used for this purpose. Rice straw or water hyacinth biomasses could effectively be used as a mulching material to control weeds over conventional modes of cultivation. Potato Production through Zero-Tillage with Paddy Straw Mulch is also a highly effective way to manage weeds in potato fields.

Keywords: potato production, weed management, mulching, zero tillage

Introduction

Potato (*Solanum tuberosum* L.) is one of the important food crops in the world. Among root and tuber crops, potato ranks top, followed by cassava (*Manihot esculenta* Crantz.), sweet potato [*Ipomoea batatas* (L.) Lam.] and many other yams in terms of volumes of global production and consumption. Potato is globally produced in 140 countries (FAOSTAT, 2020) and ranks fourth in production, following wheat (*Triticum aestivum* L.), maize (*Zea mays* L.), and rice (*Oryza sativa* L.).

Potato has been consumed by the Incas in the Andes for about 8,000 years and was brought to Europe by the Spanish in the 16th Century. From a South American origin, potatoes then quickly spread across the globe.

Today potatoes are grown on an estimated 193,000 km^2 of farmland, from China's Yunnan plateau and the sub-tropical lowlands and temperate highlands of India to Java's equatorial highlands and the steppes of Ukraine (FAO, 2009) [1].

Potato is also ranked as the first most important 'non-grain' crop in the world. In 2020, 16.5 million hectares (ha) around the world had been planted with potatoes, with a production of >359 million tons (FAO, 2009; FAOSTAT, 2020). Its importance for global food security was internationally recognized when the UN made "*2008 - the Year of the Potato*" (FAO, 2009) [2].

According to the FAO (2009), "*Food security exists when all people, at all times, have physical, social and economic access to sufficient, safe and nutritious food to meet their dietary needs and food preferences for an active and healthy life.*" Food security, therefore, has four key dimensions: (a) food availability (b) quality and use (c) stability and (d) accessibility to food. The '*humble potato*' is regarded as a high-potential, '*food security crop*' because of its ability to provide a high yield per unit area during a relatively short crop cycle of fewer than 120 days (FAO, 2009).

Potato's production cycle is shorter than those of major cereal crops, such as maize and grain sorghum [*Sorghum bicolor* L.) Moench] (FAO, 2009). Potato, as a food product, is also highly valued because it essentially contains all the nutrients necessary for human nutrition (carbohydrates, proteins, vitamins and minerals) and is so-highly palatable in various preparations (Burgos et al., 2020; Ahmadu et al., 2021). In modern-day food industries, various types of potato products (French fries, potato chips, mashed potatoes, etc.), as well as ready-to-eat products (pasteurized potato) and processed foods (peeled potato in vacuum packaging, etc.), are widely consumed by populations of many countries (Burgos et al., 2020; Ahmadu et al., 2021).

From the 1960s, cultivation of the potato expanded in the developing world. In India and China alone, total production rose from 16 million tonnes in 1960 to 100 million in 2007. In North-Eastern India and Bangladesh, potatoes have become a valuable winter cash crop, while potato farmers in South-East Asia have tapped into the exploding demand for it from food industries. In sub-Saharan Africa, potato is a preferred food in many urban areas, and an important crop in the highlands of Cameroon, Kenya, Malawi and Rwanda (FAO, 2009).

The potato has an extraordinarily rich past, steeped in ancient civilizations (Incas in South America), colonialism (14th to 16th Centuries) and a bright future. While production in Europe – the potato's "second home" for four centuries – is declining, the potato has ample room for expansion in the developing world, where its consumption is less than a quarter of that of developed countries. Today in many mountainous regions of Africa, farmers are shifting from maize to potato, assisted by the FAO with virus-free seed tubers (FAO, 2009).

In the Peruvian Andes, where the potato's journey across the world began, the Government of Peru created in July 2008 a national register of Peruvian native potato varieties, to help conserve the country's rich potato heritage. That genetic diversity, the building blocks of new varieties adapted to the world's evolving needs, will help write future chapters in the story of *Solanum tuberosum* (FAO, 2009).

In India, potato is cultivated on about 2203 ha, producing a national average of 56,173 and 53,575 metric tons (MT) in 2020-21 and 2021-22, respectively (Ministry of Agriculture, 2021-22). As in all countries and regions that grow potatoes (FAO, 2009; FAOSTAT, 2020), potato production in India has also undergone many changes in the way the crop is grown. Research over several decades in both temperate countries and sub-tropical regions, such as North-Western and North-Eastern India, has shown that various factors in the field affect potato's optimal growth and development. These include soil type, climate, water, nutrients and sunlight availability.

Managing weeds, pests and diseases is also critical in potatoes as they are a particularly sensitive crop before their canopy develops (Nelson and Thoreson, 1981; Nelson and Giles, 1989). Weed

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[1] While the Incas called it papa (as do modern-day Latin Americans), the Spaniards called the potato *patata*, confusing it with another New World crop, the sweet potato (known as *batata*). In 1797, the English herbalist *John Gerard* (c. 1545–1612) referred to the sweet potato as "common potatoes", and for many years *Solanum tuberosum* was known as the "Virginia potato" or "Irish potato" before finally displacing batata as the potato (FAO, 2009, p. 17).

[2] The UN's Food and Agriculture Organization (FAO) released *New Light on a Hidden Treasure*, a 144-page illustrated book in 2008, which recorded the achievements of the *International Year of the Potato*. The essential message was that the potato is a vital part of the global food system and will play an ever greater role in strengthening world food security and alleviating poverty. The review also provided the most recent FAO statistics on world potato production and consumption, and profiles of 52 major potato producing countries.

management in potatoes requires an integrated weed management (IWM) approach and also a change in how weeds are perceived. Weeds should be managed in a holistic, intentional and proactive manner.

Understanding the interactions between the potato crop and the weed community is important to discourage weeds; maintain a low weed seed or propagule bank and for sustainable weed management in potato cultivation systems.

This article provides a perspective on sustainable options for weed management in potatoes, based on Indian experiences. At the *International Centre for Potato* (CIP, 2022) [3], the focus was especially on potato cultivation in Assam, a State in north-eastern India (**Figure 1**). Potato is a widely cultivated crop in Assam. It is the second most important crop in all districts of Assam, although the State contributes only a relatively small, 1.41% of the national potato production in India (Ministry of Agriculture, 2021-22).

Recently, the author has been involved in developing a *knowledge Bank* for Potato cultivation in Assam, now available through the CIP (2022). This article reviews some of the existing knowledge about potatoes and their relationship with weeds, with a focus on improving sustainable weed management and increasing potato yields, particularly in Assam but also applicable in other Indian States.

Potato Cultivation in Assam

The State of Assam, in North-Eastern India, is located south of the eastern Himalayas, along the Brahmaputra and Barak River valleys. It extends from 89° 42′ E to 96° E longitude and 24° 8′ N to 28° 2′ N latitude. Assam has an area of 78,438 km^2, which is similar to Ireland or Austria (**Figure 1**). Assam shares borders with Bhutan and Bangladesh and is surrounded by the States of Arunachal Pradesh, Nagaland, Manipur, Mizoram, Tripura and Meghalaya.

[3] The *International Potato Center* (CIP) was founded in 1971 as a research and development organization with a focus on potato, sweet potato and Andean roots and tubers. It delivers innovative science-based solutions to enhance access to affordable nutritious food, foster inclusive sustainable business and employment growth, and drive the climate resilience of root and tuber agri-food systems. Headquartered in Lima, Peru, CIP has a research presence in more than 20 countries in Africa, Asia and Latin America, working with partners, including national and regional research institutes, civil society, academia and the private sector (CIP, 2022).

Together with Assam, these are called India's *Seven Sister States*. The majority of the Assamese population resides in the vast Brahmaputra valley in the north, amidst numerous mountains, streams and rivulets from the nearby hills.

Potato productivity in Assam is between 7-10 tons ha^{-1}, which is very low compared to India's national average of about 23 tons ha^{-1} (Ministry of Agriculture, 2021-22). This significantly lower production output of potatoes in Assam is attributed to low potato seed availability and low seed quality, as well as inadequate scientific knowledge of potato cultivation and pest and disease management.

As a result of low production and the large gap between demand and supply, Assam imports potatoes from neighbouring states, such as West Bengal, Meghalaya, Uttar Pradesh (UP) and Punjab, every year. The *Assam Agri-business and Rural Transform* (APART) is a program established to develop a potato value chain in Assam to benefit farmers including addressing constraints and through farmer support to overcome them. It is carried out with support from the *International Potato Center* (CIP) which provides consultancy services to the Government of Assam.

Assam is ranked 8th in potato production among the Indian States (Ministry of Agriculture, 2021-22) and much effort is underway to increase potato production with options, including improved varieties and cultural practices (CIP, 2022). The major potato-growing districts in Assam are Karbi Anglong, Cachar, Hailakandi, Jorhat, Lakhimpur, Golaghat, Sivasagar, Kamrup, Kokrajhar, Morigaon, Darang, Nagaon, Nalbari, Barpeta, Sonitpur, Majuli, Bongaigaon, Dhemaji and Biswanath Chariyali (**Figure 1**), which account for about 75% of production (CIP, 2022).

In Assam, potato is planted between two paddy cultivation seasons i.e. *Sali* (from June/July–Nov/Dec) and *Boro* (from Nov/Dec to June/July). Therefore, the available time for potato cultivation is only about 70 to 90 days. The region requires varieties that can mature in 80-100 days and can tolerate the potato late-blight disease (caused by the fungal-like oomycete pathogen [*Phytophthora infestans* (Mont.) De Bary] [4].

[4] The Late blight fungus causes sudden plant death and destroys infected potato crops in a matter of days. It attacks the potato foliage, fruit, stems or tubers at all growth stages. Healthy looking potato tubers may also break down in storage due to late blight infection.

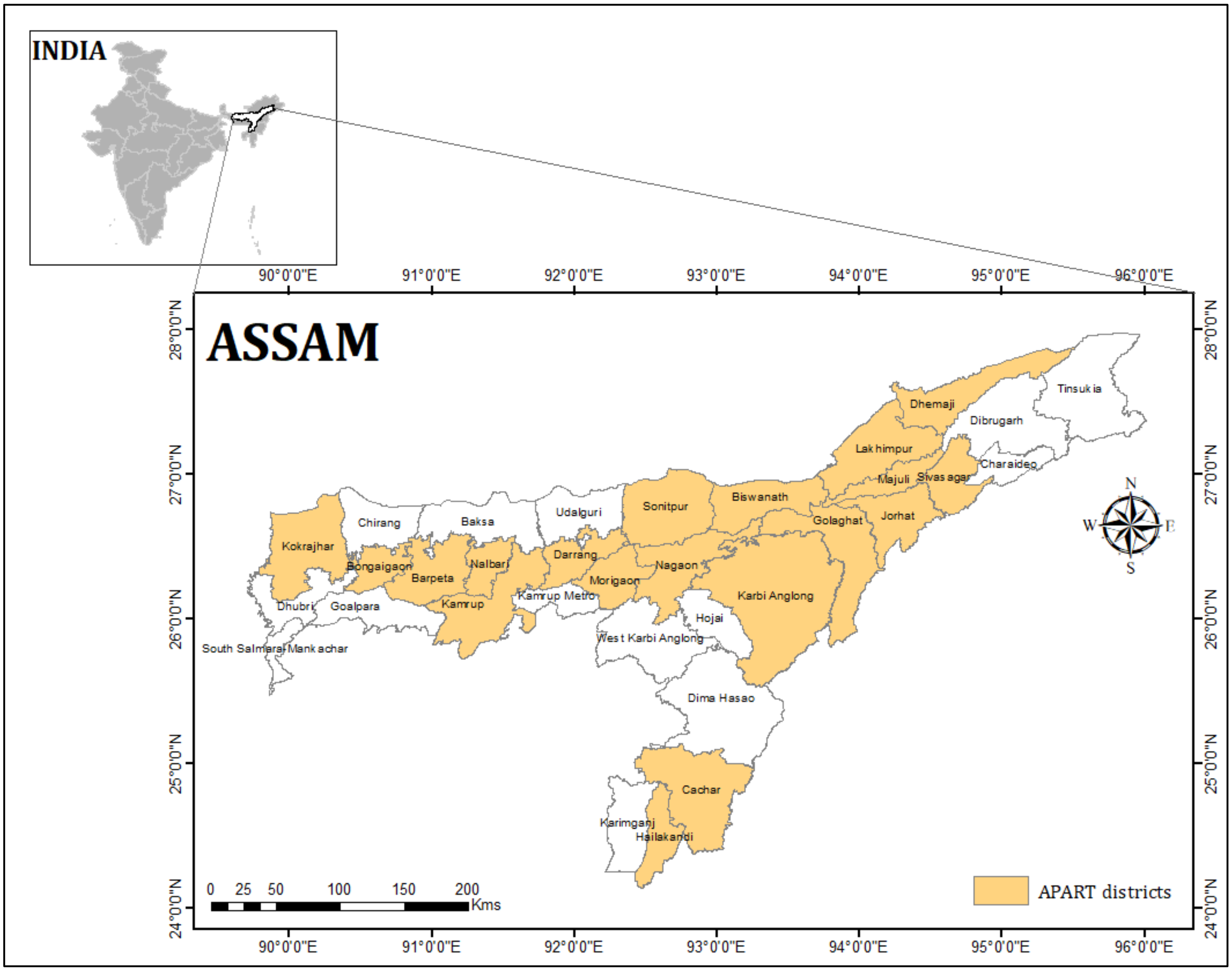

Figure 1 Map showing the location of Assam State in North-Eastern India

The most suitable varieties also need to have the capacity to tolerate drought and also have good keeping quality. The suitable planting time for potatoes is from October to mid-December when night temperatures fall below 20 ^{0}C.

The recommended table-purpose potato varieties and those suitable for processing are summarized in **Table 1**. The most popular varieties for cultivation are selected by farmers according to climatic conditions, market demand and resistance to diseases. **Figure 2** and **Figure 3** show some potato fields in Assam.

As a cool season crop, in Assam, potato is planted when the maximum temperature is less than 30°C. The optimum day/night temperatures for potato growth are 28/12°C. The optimum night temperature in Assam for tuber growth is between 10-15°C. The highest average yields are obtained where the day length is 13-17 hours (CIP, 2022).

Figure 2 A typical potato field – early growth

Figure 3 A potato field with maturing crop growth

Higher soil temperatures adversely affect tuber development, which virtually stops if temperatures rise above 30°C. Sunshine, along with cooler nights, is essential for reducing the spread of potato diseases. While well-drained sandy loam and medium loam soil are best for potato cultivation, soils rich in organic matter with good drainage and aeration are also suitable and can be used.

Slightly acidic soils (pH 5.5-6.5) are ideal for growing potatoes. The incidence of common scabs in Assam tends to be less of a problem where soil pH is below 5.4 for susceptible varieties. The common scab of potatoes is a soil-borne disease, widespread in the world, caused by the bacteria-like organism *Streptomyces scabies* Lambert and Loria. The bacterium attacks both potato tubers and stems.

Table 1 Potato Cultivation in Assam – A summary

Potato cultivation area: 103,812 ha 14.74% of the total area under horticultural crops of the State			Assam occupies a geographical area of 7.8 million ha of which the total cropped area is 4.0 million ha. However, only 5.4% of the gross cultivated area is irrigated. Assam's average farming land holdings are very small; only 0.63 ha, compared to India's National average of 1.10 ha. Farm families in Assam: about 27.5 lakhs of which small and marginal farm families account for 85.3%
Popular Cultivars #	**Duration**	**Production Tons ha^{-1}**	**Characteristics**
Kufri Surya (T)	80-90	25-30	Heat tolerance, blight tolerance, very good keeping quality
Kufri Pukhraj (T)	70-80	35-40	Poor blight resistance, early bulking, high yield
Kufri Jyoti (T)	80-90	25-30	Blight tolerance, good keeping quality
Kufri Himalini (T)	80-90	25-30	Blight tolerance, good keeping quality, high yield
Kufri Khyati (T)	70-80	30-35	Poor blight tolerance, and early bulking. high yield
Kufri Lima (T)	80-90	25-30	Blight and heat tolerance, good keeping quality
Kufri Mohan (T)	70-80	35-40	Moderately blight resistance, early bulking
Kufri Karan (T)	80-90	25-30	Blight and virus tolerance, good keeping quality
Yusi Maap (T)	80-90	25-30	Blight, drought and virus tolerance, good keeping quality
Kufri Chipsona-3 (P)	90-100	25-30	Blight tolerance, good keeping quality, high dray matter
Lady Rosetta (P)	90-100	25-30	Blight susceptible, good keeping quality, high dry matter
Atlantic (Pvt) (P)	90-100	25-30	Blight susceptible, good keeping quality, high dry matter
Taurus (Pvt) (P)	90-100	25-30	Blight susceptible, good keeping quality, high dry matter
Columba (Pvt) (T)	80-90	25-30	Blight susceptible, good keeping quality, early bulking

Source: Potato "Knowledge Bank" (CIP, 2022); T – Table varieties; P – Processing varieties

A common practice is to lower the soil pH to be in the range of 5.0 to 5.4 to manage the common scab disease. Harvesting potatoes at soil temperature >20°C is known to increase the risk of microbial rotting, especially of damaged tubers (CIP, 2022).

A well-pulverized seedbed is required for good tuberization of potatoes. In Assam, the common field bed preparation involves the use of a mould-board plough, followed by two to three cross harrowings, using a disc harrow rotavator (**Figure 4**) or cultivator to plough the fields up to 20-25 cm. One or two plankings are also used to level the surface. Most farmers use a rotavator one week before potato planting to further loosen the soil (CIP, 2022).

Figure 4 Loosening the soil by using a rotavator one week before potato planting

In fallow lands, newly converted to potato, green manuring with Indian hemp (*Crotalaria juncea* L.) or yellow pea bush [*Sesbania cannabina* (Retz.) Pers; syn. *Sesbania aculeata* (Willd.) Pers.] is undertaken during the rainy season. These species “fix” nitrogen through root nodules. A dry biomass of 4-5 tons ha^{-1} of the legumes can add 80−100 kg N ha^{-1} to the fields. When buried about one month before potato planting, the decomposing green manure reduces pest and disease incidence and also improves soil fertility and the soil’s water-holding capacity (CIP, 2022).

Potato is also cultivated under the cover of plastic sheets (Pszczółkowski et al., 2020; Mohaniya et al., 2020), or polythene film in various countries, particularly in Western and Eastern Europe, to provide the plants with appropriate thermal and humidity conditions and reduce the risk of spring frost damage. This practice is common in other Indian States (Mohaniya et al., 2020; Gupta et al., 2020) but not common in Assam because of the costs involved in purchasing plastic sheets.

Losses caused by Weeds in Potato

Crops and weeds compete for space, light, water, nutrients, and other resources during the growing season (Zimdahl, 1980; 1987). The competitiveness of a weed community depends on the species' composition, time of emergence and abundance. Yield losses are usually high when weeds emerge earlier or at the same time as the crop and are minimized if they emerge later than the crop. Prevailing environmental conditions also influence the outcome of weed-crop interactions (Zimdahl, 1980).

Weed infestations are one of the most important limiting factors in the production of potatoes in Assam. In potatoes, weed infestations are favoured by a wide row spacing, a long period from planting to plant emergence, the potato’s slow initial growth and the use of organic manures and mineral fertilization (CIP, 2022). As a consequence, many cultural practices and influential factors need to be modified to obtain better potato yields and profits for farmers.

When abundant, broad-leaf weeds (dicotyledons), grasses and sedges (monocotyledons) can deplete the resources available for the potato crop. Some may also interfere with potato growth by releasing allelochemicals or by harbouring harmful insects and pathogens. Apart from affecting yields, weeds reduce the quality, size and weight of potato tubers (Nelson and Thoreson, 1981; Atiq et al., 2009; Azadbakht et al., 2017; Soren et al., 2018; Gugała et al., 2018; Barbaś et al., 2020; Yadav et al., 2021).

The Critical Period of Weed Competition in potato

The critical period of weed competition is approximately 1/3rd of the duration of most crops, including potatoes. The severity of yield loss depends on weed infestation, duration of infestation and climatic conditions, which affect the growth of both weeds and crops (Zimdahl, 1980; 1987).

The critical period of weed competition is the shortest time during the crop’s growth when weeding results in the highest economic returns. The crop yield level obtained by weeding during this period is almost similar to that obtained by the full season weed-free conditions. It is also the period of crop growth when the crop must be kept weed-free to prevent yield loss due to weed interference (Zimdahl, 1987).

Bleasedale (1965), in an early article, explained how the early growth of weeds affects potato growth and yields. In India, Mani et al. (1968) reported potato yield losses of 25-35% and Saghir and Markoullis (1974) reported a 58% yield loss when weeds competed for the full season with potatoes. In their studies, early-season weed presence was not detrimental unless weeds remained in the plots past 6-9 weeks after potato planting.

Zimdahl (1980) pointed out that these results disagreed with those reported from Java, Indonesia, by Everaarts and Satsyati (1977) who found that if potatoes were kept weed-free for the first four weeks after planting, they experienced no yield losses. In the Java study, under zero weed control, the yield loss in potatoes was 22% compared with 'weed-free' plots (Everaarts and Satsyati, 1977).

Different potato varieties can compete effectively with annual broad-leaf weeds in particular and their competitive ability correlated with early emergence, rapid early growth and maintenance of a dense leaf canopy throughout the growing period. However, it is well-known that, as a crop, potato does not possess vigorous early competitiveness.

In some early studies, Baziramakenga and Leroax (1994) found that to achieve 90% of the highest possible potato tuber yield, the maximum time permitted for weeds to grow after potato emergence was 15 days. They also found that the same level of tuber yield could be obtained if the crop was kept free of weeds from its emergence until 23–68 days.

Baziramakenga and Leroax (1994) also showed that perennial quackgrass [*Elytrigia repens* (L.) Nevski], at a density of 25 stems m^{-2}, caused a 10% potato tuber yield reduction in Quebec, Canada. The studies of Ciuberkis et al. (2007) in Lithuania found that the 20 cm potato height was the most important stage affecting potato yield loss due to weed competition. Potato yield losses were minimized when weeds were removed before potatoes reached 20 cm or were kept clean from this point forward. The results indicated that the critical weed-free period when weed competition was detrimental to yield started from planting and lasted until 25 days after flowering.

Research in India and Assam has shown that in most situations, the critical period of weed competition for potatoes is 25-30 days from planting (CIP, 2022). However, the global literature indicates that, broadly, the potato crop should remain weed-free for up to 40-50 days depending upon the farming situation, which can vary widely. Delayed weeding until late stages could result in irreversible damage due to weed competition. Therefore, effective weed control is crucially important to obtaining high tuber yield.

Potato plants tend to drop between ridges after 65-70 days of planting as the crop matures and at this stage, the second flushes of weeds thrive. These may not cause significant damage to tuber productivity but play a role in increasing the soil's weed seed bank while hindering harvesting the crop (Singh et al., 2018b). Nelson and Giles (1989) also pointed out the importance of not neglecting the weed flora that must be controlled to reduce the intensity of competition in future crops in the fields used for potatoes.

Major Weeds of Potato fields and Yield Losses

As with most other crops, weeds compete with crop plants for nutrients, soil moisture, space and sunlight. Weeds also serve as an alternate host for several insect pests and diseases. Weed competition can reduce potato quality, affecting tuber size, weight and quantity (Ahmadu et al., 2021). Weeds also interfere with mechanical harvest options in potatoes (Singh et al., 2018b).

Uncontrolled weed growth can reduce tuber yield by about 18-82% depending on the types of weeds, their abundance and the duration of the competition (Singh et al., 2002; Ciuberkis et al., 2007, Kumar et al., 2009; Soren et al., 2018; Ahmadu et al., 2021). In recent studies in Ludhiana, North-West India, Shafique and Kaur (2021) reported that uncontrolled weed growth resulted in 50% potato yield losses.

Weeds interfere with harvest, causing more potatoes to be left in the field and increasing mechanical injury. In some early studies in the USA, Nelson and Thoreson (1981) reported that if annual weeds and perennial weeds compete with potatoes all season, each 10% increase in dry weed biomass could cause a decrease of up to 12% in tuber yield.

According to Azadbakht et al. (2017), Soren et al. (2018) and Barbaś et al. (2020), potato yield losses due to weed infestation in Europe are estimated to be 10% to 70%. These estimates are highly variable and include losses resulting from direct competition with weeds, as well as the host role of weeds relating to diseases and pests, harvest difficulties, mechanical damage and deterioration of the quality of the harvested potato. Caldiz et al. (2016) reported even higher losses, up to 95% potato tuber yield reduction, depending upon the potato variety, the infesting weed species and the crop-weed competition period.

In India, 10% potato yield losses due to weeds in potatoes were estimated to result in production losses of INR 40 million (CPRI, 2021). The wider row spacing, frequent irrigation, and use of organic manures and fertilizers favour the early emergence of weeds before potato tubers germinate, causing yield losses by 40-65% or even more in some cases (Singh et al., 2002; Mohaniya et al., 2020; CIP, 2022).

In studies at India's *Directorate of Weed Research* (DWR) in Jabalpur, Madhya Pradesh (MP), Chethan et al. (2019) reported that the potato plots were heavily infested with burr clover (*Medicago denticulata* Willd.), followed by wild oat (*Avena fatua* L.), toothed docks (*Rumex dentatus* L.), sowthistle (*Sonchus* L.

sp.), figleaf goosefoot (*Chenopodium ficifolium* Sm.), lamb's quarters (*Chenopodium album* L.) and small canary grass (*Phalaris minor* Retz.). In potato trials at Gwalior (MP) in India, Gupta et al. (2020) reported purple nutsedge (*Cyperus rotundus* L.), lamb's quarters and small canary grass as the major weeds (38%, 25% and 18%, respectively of the flora) while several other annual and perennial grasses and broad-leaf weeds formed the remainder. Working at *ICAR-Central Potato Research Station* (1740 m above mean sea level), based at Shillong, Meghalaya, in Northern India, Yadav et al. (2021) reported a similarly mixed weed flora comprising common broad-leaf weeds and grasses, as well as sedges (i.e. *Cyperus cyperiodes* (L.) Kuntz).

In Assam, Baruah and Sarma (1994) reported a total of 33 weed species in potato fields belonging to different families. Lamb's quarters, carpet grass [*Axonopus compressus* (Sw.) Beauv.] and Bermuda grass [*Cynodon dactylon* (L.) Pers.] were the dominant weeds. **Table 2** gives the most predominant weed species found in potato crops in Assam, which can appear in the fields before potato emerges. Sedge weeds were less prevalent in Assam compared to other Indian States (CIP, 2022).

Table 2 Important weeds associated with potato in Assam

Common name	Scientific name	Family
Grasses		
Carabao grass	*Paspalum conjugatum* P.J. Bergius	Poaceae
Barnyard millet/Barnyard grass	*Echinochloa crusgalli* (L.) P. Beauv.	Poaceae
Bermuda grass	*Cynodon dactylon* (L.) Pers.	Poaceae
Rice grass	*Leersia hexandra* Sw.	Poaceae
Glenwood grass	*Sacciolepis indica* (L.) Chase	Poaceae
Swamp millet	*Isachne globosa* (Thunb.) Kuntze	Poaceae
Torpedo grass	*Panicum repens* L.	Poaceae
Indian goosegrass	*Eleusine indica* (L.) Gaertn.	Poaceae
Broad-leaf weeds		
Giant sensitive weed	*Mimosa diplotricha var. Innermis* C. Wright	Fabaceae
Giant sensitive weed	*Mimosa pudica* L.	Fabaceae
Shiny bush	*Peperomia pellucida* (L.) Kunth	Piperaceae
Sisso spinach/Joyweed	*Alternanthera sessilis* (L.) DC	Amaranthaceae
Jersey cudweed	*Pseudognaphalium luteoalbum* L.	Asteraceae
Floss flower	*Ageratum houstonianum* Mill.	Asteraceae
Indian-field cress	*Rorippa indica* (L.) Hiern	Brassicaceae
Lamb's quarters/fathen	*Chenopodium album* L.	Amaranthaceae
Common knotweed	*Polygonum plebieum* R.Br.	Polygonaceae
Winged false button weed	*Spermacoce alata* Aubl.	Rubiaceae
Spreading dayflower	*Commelina diffusa* Burm.f.	Commelinaceae
Chocolate weed	*Melochia corchorifolia* L.	Malvaceae

Weed species growing in potato fields can also harbour plant pathogens, although information on this aspect is lacking from Assam and also, more broadly from India. Nevertheless, reporting from Cameroon, Fontem and Olanya (2003) recorded the potato late blight pathogen *Phytophthora infestans* on some common weeds in potato fields, such as *Polygonum alatum* (D. Don) Buch.-Ham. ex Spreng. [renamed, *Persicaria nepalensis* (Meisn.) H. Gross], purple morning-glory [*Ipomoea purpurea* (L.) Roth] and sowthistle (*Sonchus oleraceus* L.).

The pathogen of potato bacterial wilt, *Ralstonia solanacearum* Smith, was also found on Billy goat weed (*Ageratum conyzoides* L.), green amaranth (*Amaranthus viridis* L.) and seed-under-leaf (*Phyllanthus niruri* L.) growing in and around potato fields (Fontem and Olanya, 2003).

Weed Management Methods in Potato

The production process of potatoes comprises 'best practice' cultivation and weed management. The methods most commonly used are well-documented from temperate and sub-tropical countries, with some local differences (Atiq et al., 2009; Azadbakht et al., 2017; Chethan et al., 2019; Barbaś et al., 2020).

Research over decades has shown that the main objective of managing weeds in potatoes should be to decrease weed abundance to below the economic threshold level with minimum damage to the crop and its growing environment. The literature shows that cultural practices, including a well-planned crop rotation, planting cover crops, sanitation practices, optimum row spacings and timing of planting are important aspects of managing weeds in potatoes. Multiple, well-timed shallow cultivations, either by using simple implements or mechanically operated ploughs, can eliminate many early-season weeds during land preparation. Once emerged, some potato varieties grow fast and produce a canopy, which can suppress weeds (CIP, 2022).

Our surveys indicate that, as with most crops, the choice of effective weed control strategies for potatoes in Assam is influenced by the severity of predicted weeds and their abundance in cultivation areas. Nevertheless, how Assamese farmers manage weeds and the methods they use are influenced by their socio-economic conditions and local constraints of related agricultural enterprises.

The following sections describe the weed control methods deployed in Assam in potato production and include various cultural practices, as well as mechanical and chemical control, aiming to reduce yield losses due to weeds.

Cultural Weed Control Methods

Potato varieties and Seeding rate

Weeds in potatoes can be suppressed during the initial phases of potato growth by way of crop competition. This requires fast-growing and high-yielding varieties, timely planting, higher seed rate and maintaining the optimum plant population in the fields (Boydston and Vaughn, 2002; CIP, 2022). Cultivars that emerge fast after planting and grow fast to develop a strong canopy, can either suppress weeds or tolerate weed competition. This is an important component of an Integrated Weed Management (IWM) system for potatoes. Cultivar tolerance of weed competition is directly related to emergence timing and canopy closure during the early season.

Such cultivars would reduce the reliance on herbicides for weed control in potatoes. Nevertheless, crop competitive ability has not been a focus of potato plant breeding efforts, or indeed in many other vegetable crops. As a result, the competitive ability of some new potato cultivars has decreased over time (Colquhoun et al., 2009). Our surveys have also found that the impetus to adopt cultivar competitiveness against weeds, as a management tactic in potatoes has been minimal, in India and elsewhere. A possible reason is the success of pre-emergent, soil-applied herbicides in reducing weed populations.

In Assam, farmers conduct timely management of cultivation - from land preparation to harvesting – as a component of 'best practices' to suppress weeds and also minimize crop-weed competition. If seeding rates are insufficient, an optimum potato crop population cannot be achieved, which leads to heavy weed infestations, and the emergence of species that are difficult to manage. However, weeds emerging from under a fast-growing crop canopy are generally weak and do not always reduce tuber productivity.

Typically, virus-free, healthy, 35-45 mm (B) grade size, sprouted seed tubers are planted and the seeding rate depends on seed size and planting geometry when using inter-row distances of 60 cm and seed-to-seed distances of 20 cm (**Figure 5** and **Figure 6**). The preferred seed weight of full or cut tubers with 2-3 sprouting 'eyes' for seeding is 35 gm (i.e. approximately, 83,000 tubers per ha). Potato crops are usually planted 8-12 cm deep, on ridges (45-60 cm apart) or on loose soil and flatter surfaces, in shallow furrows (CIP, 2022).

Field preparation

The importance of tillage using cultivators and harrows, and seedbed preparation with raised beds ('hilling'), in growing potatoes successfully, has been long established (Nelson and Giles, 1989; Boydston and Vaughn, (2002). However, excessive cultivation can increase soil erosion, especially in hilly areas, increase soil compaction, and bring weed seeds to the soil surface (Nelson and Giles, 1989). Some planting failures in Assam are due to poor tuber sprouting or lack of germination caused by an incorrect planting depth and poor seed bed preparation.

Figure 5 A proper planting geometry (planting distance) of a potato field in Assam

Figure 6 Sprouted seed tubers

A well-pulverized seedbed is important for good initial germination of seed potato and the tuberization of potato as the crop matures. In Assam, deep ploughing of the field up to 20-25 cm is optimal and can be achieved by using a mould-board plough, followed by two or three cross harrowings, using a disc-harrow cultivator. One or two plankings are also needed to make the surface smooth and level.

The final soil preparation is done by a rotavator a week before potato planting. These primary and secondary operations help in destroying existing weeds and preventing others from germination. Pre-plant tillage operations for making a proper soil tilth will also accelerate the potato's faster emergence, giving it a competitive advantage (CPRI, 2021).

Generally, the potato crop is raised in a wider planting geometry. The method of hand-broadcasting manures and fertilizers is common in small and marginal farms in Assam. It is not advantageous because it encourages weed growth all over the field. Further, frequent irrigation also benefits the early and faster-emerging weeds (CPRI, 2021).

A common practice in Assam is the application of well-decomposed farmyard manure (FYM) at a rate of 20-25 tonnes ha^{-1}, combined with N-P-K fertilizer at the rate of 125-100-125 kg ha^{-1}, placed in bands 5-6 cm below the seed tubers. These placements ensure that the nutrient inputs remain in the potato's root zone, allowing the crop to utilize the nutrition more effectively and speed up its vegetative growth.

Crop rotation

Crop rotation has been a long-standing method in cropping, especially to reduce pests and diseases and the build-up of weed populations in cropping fields, as well as to replenish soil nutrients, such as nitrogen. If the same crop is grown year after year, there is a greater chance that a particular weed species or a weed community will begin to dominate in that field.

Diversified crop rotations can prevent such weed flora changes by varying planting dates and the length of the growing season and by the weed control practices associated with each crop. A diversified crop rotation is also the basis of preventing many soil-borne pests and pathogens from developing into levels that can harm a crop.

For Assam, at least a two-year crop rotation is generally recommended as a '*Potato-Mung-Paddy'* rotation, in which the rice is transplanted. This rotation can be implemented on suitable fields that can be irrigated for the rice. An alternative is a green manure crop (sun hemp, dhaincha) rotated to smother weeds and add nutrients for a succeeding potato crop.

Stale seedbed

A stale seedbed is one where the initial one or two flushes of weeds are destroyed before planting a crop. This is achieved by soaking a well-prepared field with irrigation or rain and allowing weeds to germinate. At this stage, shallow tillage or non-residual herbicides, such as paraquat or glyphosate could control flushes of young weed seedlings, which allows potatoes to germinate in an almost weed-free environment. The stale seedbed is seen as an '*eco-friendly*' method for weed control as it kills weeds before the planting of the crop. It also depletes the weed seed bank in the surface layer of the soil (Senthilkumar et al., 2019).

Soil Solarization

Soil solarization is a method that uses solar energy for the destruction of weed seeds. In this method, the soil temperature is further raised by 5–10ºC by covering a pre-soaked fallow field with a thin transparent plastic sheet. The plastic sheet reduces the long-wave 'back' radiation from the soil and prevents energy loss by hindering moisture evaporation. Solarization of soil has been reported to manage weeds and control nematodes, soil-borne diseases and insects (Singh et al., 2018).

'Earthing up' and Mulching

'Earthing-up' is essential in potato cultivation to keep the soil loose, control weeds, and for firming up the ridges to prevent exposure of the growing tubers. The first earthing-up is usually done when the plants are about 15-25 cm high with a small canopy (25-30 days after planting). In Assam, earthing-up is done by using hand tools like Khurpa and spades.

Hoeing, bullock-drawn mould-board plough or tractor-drawn two- or four-row ridges can also be used for earthing-up. Sometimes, a second earthing-up is done to cover up the tubers more effectively, two weeks after the first. Fertilization with a split dose of N is also done simultaneously while earthing-up. Delaying these cultivation operations beyond 30 days after planting runs the risk of damaging the developing potato roots, foliage and stolons (CIP, 2022).

Plant-based mulches

Mulch, placed on the soil surface, protects the soil. It also physically prevents weed seed germination. Decomposing plant mulches also release inhibitory compounds, which can kill weed seeds (Mahmood et al., 2002; Teasdale and Mohler, 2008; Barman et al., 2009; Razzaque and Ali, 2009; Bhullar et al., 2015).

Working in India, Gupta et al. (2020) showed that dried or green crop residues - straw from rice or other cereals- can be effective in potatoes, against annual weeds and even some perennial grasses and sedges. Other researchers (Shafique and Kaur, 2021; Liu et al., 2023) have reported that plant-based mulches are most effective in potatoes when they are used in combination with herbicides. Plant-based mulches reduce the surface soil temperature and also prevent moisture loss from the soil surfaces, which helps potato growth (Sadawarti et al., 2013; Pulox et al., 2016; Azadbakht et al., 2017; Sarangi et al., 2018).

To effectively control weeds from germinating and prevent weed seedling establishment, the mulch covering should be sufficiently thick (about 15-20 cm thick). Paddy straw, applied at about 10-12 tons ha^{-1} (4-5 kg of rice straw/m^2), provides a cover of a 15-20 cm thick layer. For mulching one *bigha* of the zero-tillage potato crop, rice straw from three bighas can be used. Potato plants come out of the rice straw in 15-20 days and rapidly grow to cover the entire available area. Weed growth is practically nil due to the thick rice mulch (Brijesh Kumar et al., 2022).

Added advantages of using straw mulches are that when they slowly decompose, they add organic matter to the soil, increasing both nutrients and the soil's water-holding capacity. The growth of soil microbes is also greatly stimulated by decomposing plant residues used as mulches. Bhullar et al. (2015) and Shafique and Kaur (2021) reported improved weed control with the application of rice straw mulch at the sowing time at 6 tonnes ha^{-1} of potatoes.

Water hyacinth [*Eichhornia crassipes* (Mart.) Solms] is ranked among the top-ten weeds worldwide. Water hyacinth multiplies fast and due to its negative impacts, it is popularly known as the '*Beautiful Blue Devil*'. Its vast growth and coverage of water surfaces adversely affect navigation, fishing, recreational usage of water bodies, and hydropower generation. Manual harvesting and some forms of mechanical removal are the most common method of control of water hyacinth, especially in developing countries.

In Assam, water hyacinth is abundant in almost every water body, extending from large lakes to household ponds in rural areas. For a long time, water hyacinth was considered only as waste, which is cleaned up from waterways and left to decompose, unused. In recent decades, however, dried water hyacinth biomass has become popular as mulch that can be used in potato cultivation, as well as growing other vegetable crops. However, to be most economically viable, the utilization of water hyacinth mulch needs to occur near the source of origin.

The adoption of dried water hyacinth mulch, under rainfed conditions, increases potato tuber yields. Water hyacinth mulch can be applied to cover the entire field after planting tubers under the flatbed method (**Figure 7** and **Figure 8**). The skin of the tubers may turn green due to exposure to sunlight or shrinkage of mulching materials on drying. Tubers become unsuitable for consumption upon greening. However, this undesirable effect may be reduced by applying the mulch in furrows just after planting tubers, immediately followed by a light soil cover. Such practices also reduce rodent damage to tubers considerably (AAU, 2019; CIP, 2022).

In studies conducted at the DWR, in Jabalpur (Barman et al., 2008), both rice straw and water hyacinth mulches controlled weeds well throughout the growing period of potatoes. In the presence of mulches, there was no additional benefit from herbicides (Metribuzin at 0.25 or 0.5 kg ha^{-1}) in terms of weed control or tuber yield. Moreover, there was a 40% increase in potato yield in plots mulched with water hyacinth, compared with rice straw. In Bangladesh, Razzaque and Ali (2009) also confirmed that different potato varieties differed in their responses to rice straw and water hyacinth mulches under no-till conditions. However, higher tuber yields were recorded under the water hyacinth mulch treatments.

Figure 7 A water hyacinth-mulched field after planting of potato

Figure 8 Emergence of the potato crop in water hyacinth mulching after one month

Plastic Mulches

Mulching with black plastic has been shown to improve potato stem number, plant height, and yield (Bharati et al., 2020). Black plastic mulches were reported to have increased soil temperature, reduced weed competition, improved nutrient uptake, and improved soil moisture regimes, which resulted in more large-sized tubers being produced (Ibarra-Jiménez et al., 2011).

Compared to black and white plastic mulch, silver plastic mulch had a greater PAR (photosynthetically active radiation) reflectance, and such increased PAR reflection by silver plastic mulches lowered root zone temperature, resulting in optimum soil temperature and reducing water loss (Amare and Desta, 2021). Plants grown under black plastic mulch retained the highest soil temperature but showed a marginal difference only in yield compared with control plants (Ibarra-Jiménez et al., 2011).

Among the various mulching materials tested, films of silver on black plastic and black plastic have been the most effective in increasing tuber yields (Aryal et al., 2023). Research in China (Li et al., 2018) showed that mulching with black plastic film is an effective practice for winter potato production. It increased the soil temperature and was more suitable for potato emergence and tuber bulk in winter potato production. Mulching has a positive effect on microclimates and maintains a better growing environment, which is imperative for increasing potato yields.

Herbicides

Chemical weed control is a significant component of weed management in potatoes and has a long history dating back to the 1960s and 70s in the USA and other developed countries (Nelson and Giles, 1989; Ackley et al., 1996; Robinson, et al., 1996; Renner and Powell, 1998; Caldiz et al., 2016). Herbicides act much quicker against weeds in potato and present an advantage because potato is a relatively short-duration crop.

Herbicides in potatoes can be applied over large areas in a short time with minimal labour costs (Baranowska et al., 2016; Gugała et al., 2018; Barbaś and Sawicka, 2020; Yadav et al., 2021). Many soil-applied herbicides, such as EPTC, linuron, metolachlor, metribuzin and rimsulfuron have long been used in potato cultivation in the USA and elsewhere (Bellinder et al., 2000; Yadav et al., 2021).

Metribuzin has long been a standard component of pre-emergence (PRE) and post-emergence (POST) weed management programs in potatoes because it is effective on many broadleaf weeds and grasses (Friesen and Wall, 1986; Ackley et al. 1996; Robinson et al., 1996; Wilson et al., 2002). However, heavy reliance on metribuzin in potato cultivation in the USA shifted weed species to those that are metribuzin-tolerant within a few decades, resulting in inadequate weed control in potato cultivation.

Following this, in an important study in the USA, Renner and Powell (1998) showed how the major weeds in potatoes can be well managed with PRE and POST applications of rimsulfuron, metribuzin, and mixtures of rimsulfuron plus metribuzin. PRE applications of rimsulfuron at 27 g a.i. ha^{-1} and POST applications at 18 g a.i. ha^{-1} controlled barnyard grass [*Echinochloa crus-galli* (L.) Beauv.], redroot pigweed (*Amaranthus retroflexus* L.), and wild buckwheat

(*Polygonum convolvulus* L.). Common lamb's quarter (*Chenopodium album* L.) was controlled by PRE or POST applications of metribuzin or a tank mixture of 18 a.i. ha^{-1} rimsulfuron plus 140 a.i. ha^{-1} of metribuzin. The variety '*Russet Burbank*' potato was relatively tolerant to all of the herbicides and the mixtures, and potato yield was not reduced compared to the hand-weeded control (Renner and Powell, 1998).

In other studies in the USA, Tonks. and Eberlein (2001) showed that the sulfonylurea- rimsulfuron rates of 9, 18, 26, or 35 g ai ha^{-1} achieved effective weed control with little potato injury (less than 5% across all rimsulfuron rates) when applied post-emergence, in combination with various adjuvants- i.e. nonionic surfactant (NIS), crop oil concentrate (COC), methylated seed oil (MSO), or silicone-polyether copolymer (SIL). In general, a host of common weeds were controlled by 75-93% and tuber yields increased with better weed control (Tonks. and Eberlein, 2001).

In the USA, past research has shown that cultivation alone may reduce weed competition with potatoes but may also result in tuber damage, as well as reduced harvesting efficiency from increased weed presence at harvest. Given the sensitivity of potato varieties, the use of PRE applications of metribuzin and POST applications of rimsulfuron, either alone or in combination with other soil-applied herbicides, has now become almost standard practice.

In combination with timely cultivations, applications of PRE and POST herbicides are an essential component of growing potatoes profitably in the USA, especially if the fields are infested with difficult-to-control weeds, such as yellow nutsedge (*Cyperus esculentus* L.) and a wide spectrum of broadleaf weeds and grasses (Bailey et al., 2001; 2002).

In related studies, Wilson et al. (2002) showed that sulfentrazone and flumioxazin were selective and safe when applied to many potato varieties and controlled many weeds common in potato fields in the USA. They also reported evidence that both herbicides were much more effective than metribuzin and could also be used in combination with other chemistries (such as metolachlor) to provide a broader spectrum of weed control (Wilson et al., 2002).

In parts of Europe (Poland), potato production relies heavily on mechanical weed control combined with various combinations of herbicides. Barbas and Sawicka (2020) showed that PRE applications of Metribuzin (0.5-1.0 kg ha^{-1}), PRE and POST applications of the sulfonyl-urea herbicide Rimsulfuron or similar, and POST applications of the selective grass-killer Fluazifop for controlling grasses, were highly effective. Herbicides could increase the potato yield by as much as 60% and Metribuzin alone stood out as being the most effective, resulting in yield increases of up to 50% (Barbas and Sawicka (2020).

Globally, the list of both PRE and POST herbicides approved for use in potatoes is quite extensive (**Table 3**). In India, too, herbicides to manage weeds in potatoes have become popular because of their ease, economic benefit and effective control of the weeds (Kumar et al., 1998; Mishra et al., 2002; Singh et al., 2007; Choudhury et al., 2016; Sondhia, 2018; Chethan et al., 2019; Yadav et al., 2021; Chaudhary et al., 2022; Chandel et al., 2022).

A few PRE, pre-plant incorporated (PPI) or POST herbicides are registered for potatoes in India. Choudhury et al. (2016) and Chaudhary et al. (2022) showed that the commonest ones used in India include Metribuzin, 2,4-D amine, Prometryne and Paraquat. Others, used occasionally in some States are Pendimethalin, Fluchloralin and Oxyfluorfen.

In some Indian States, research is focused on PRE applications of Prometryne (1.0 kg ha^{-1}) with a half-rate of Metribuzin (0.5 kg ha^{-1}), which gives the control of a broad range of weeds without affecting tuber yields (Chaudhary et al. (2022).

Paraquat use, as a 'knock-down', non-selective, contact-action herbicide is common in many crops in India, including potatoes. This is partly because it is more affordable to farmers and the fast-acting effects on weeds are visible within hours of application (Chandel et al., 2022).

However, Metribuzin 70% WP, at 0.5-1.0 kg/ha, applied in 500 L of water, as a pre-plant and early PRE application, has long been the principal herbicide used to control both mono- and dicotyledonous weeds in potatoes in India (Choudhury et al., 2016). In other countries, where paraquat is banned, diquat (Reglone ®) is used as a substitute. Although under certain conditions, metribuzin damages some potato varieties, under Indian conditions, and in Assam, PRE application of metribuzin 70% WP at the rate 0.75 kg a.i. $ha\text{-}^{1}$ or 100 g/big ha (1 Big ha=13.37.80 m^2) in moist soil effectively controls a range of broadleaf weeds and suppresses the growth of many types of grasses. Chethan et al. (2019) recently reported that the application of Metribuzin at 0.75 kg/ha as PE effectively controlled most weeds and reduced the weed densities to 2.43 and 2.04 weeds/m^2. The corresponding reduction in the weed dry biomasses were 1.35 and 1.64 g/m^2 respectively at 25 and 55 DAP with a resultant and increased potato tuber yield.

Table 3 Herbicide commonly used for Potato – India and Other Countries*

Herbicide (Trade Name)	Application and Herbicide Mode of Action (MOA)	Usage
Alachlor (Lasso ®) #	PRE applications, 1.0 kg/ha applied in 500 L/ha; Lipid synthesis (long-chain fatty acids) inhibitor.	Global and in some Indian States
Clomazone (Command ®)	Soil applied or PRE before potato emerges for annual broad-leaf weeds; pigment synthesis inhibitor.	Australia, New Zealand, Europe
EPTC (Eptam ®)	Pre-plant incorporated; 1-2 kg/ha; Lipid synthesis inhibitor.	Global
Fluazifop-butyl (Fusilade ®)	Post-emergence, selective grass control; lipid synthesis inhibitor [acetyl CoA (ACCase) enzyme inhibitor].	USA, Europe
Fluchloralin (Basalin ®)	Pre-plant incorporated; 1.0 kg/ha; a dinitro-aniline group herbicide, disruptor of microtubule assembly	Global, including India
Flumioxazin (Chateau ®,Valor ®)	cell membrane disruptor and Inhibitor of protoporphyrinogen oxidase (PPO) enzyme.	USA
Methabenzthiazuron (Tribunil ®)	PRE applications of 2.5-3.0 kg/ha in 340-450 L of water before potatoes emerge; photosystem-II inhibitor.	Global and in some Indian States
Metolachlor (Dual ®; Magnum ®)	Lipid synthesis (long-chain fatty acids) inhibitor.	Global and in some Indian States
Metribuzin (Sencor ®)	Most commonly used as PRE (1.0 kg/ha in 500 L/ha); also used as POST interrow application; photosystem-II inhibitor.	Global, including India and Assam
Oxadiazon (Ronstar ®)	0.75 kg ha^{-1}; Inhibitor of protoporphyrinogen oxidase (PPO) enzyme.	Global and in some Indian States
Oxyfluorfen (Goal ®; Rout ®)	PRE applications of 100-200 g $ha^{-1;}$ Inhibitor of protoporphyrinogen oxidase (PPO) enzyme.	Global and in some Indian States
Paraquat dichloride # (Gramoxone ®, Ozone ®)	Bi-pyridinium; Non-selective, contact herbicide, Pre-plant or interrow applications; fast-acting photosynthesis inhibitor.	Global, including India
Pendimethalin (Stomp ®)	PRE applications, 1.8 kg/ha applied in 500 L/ha; a dinitro-aniline group herbicide, disruptor of microtubule assembly.	Global, including India
Prometryne (Gesagard ®; Bandit ®)	PRE applications of 1.0 kg ha^{-1}; a triazine herbicide, causes Inhibition of photosynthesis at photosystem II.	Global, including India
Trifluralin (Treflan ®) #	PRE applications of 1.0 kg ha^{-1}; a dinitro-aniline herbicide, disruptor of microtubule assembly in cells; often applied in mixture with metribuzin for broad-spectrum weed control.	Global, including India
2,4-D Amine	Phenoxy acid herbicide; Mostly PRE but occasionally used as POST inter-row applications before potato emerges.	Global, including India
Diquat (Reglone ®) #	Bi-pyridinium; Non-selective, contact herbicide, Pre-plant or interrow applications; fast-acting photosynthesis inhibitor.	USA, Australia, New Zealand, Europe
Rimsulfuron (Titus ®, Matrix ®; Resolve ®	PRE or POST applications; amino acid synthesis inhibitor [acetolactate synthase (ALS) enzyme inhibitor].	USA, Australia, New Zealand, Europe
Sulfosulfuron (Apyros ®)	PRE or POST applications; amino acid synthesis inhibitor [acetolactate synthase (ALS) enzyme inhibitor].	USA
Sulfentrazone (Spartan ®)	Soil-applied to control broad-leaf weeds and sedges; cell membrane disruptor.	USA

*Sources: (1) India (**http://agropedia.iitk.ac.in/content/chemical-weed-control-potato-crop**); (2) Mishra et al., 2002; Singh et al., 2007; Choudhury et al., 2016; Sondhia, 2018; Chandel et al., 2022); (3) Europe: Barbas and Sawicka, 2020; ** Only metribuzin is used in Assam, mainly because of the cost, which is INR 1500/ha.

*** All POST applications use adjuvants, such as Crop Oil concentrates (COC) or methylated seed oil (MSO), or silicone-polyether copolymer (SIL); # Paraquat and Alachlor are banned in India; Trifluralin is limited to uses in wheat only; the bans and prohibitions have come into effect since 31 December 2020 (Choudhury et al., 2016). Diquat is preferred to paraquat in some countries.

Adding to these findings, working at *ICAR-Central Potato Research Station* (1740 m above mean sea level), based at Shillong, Meghalaya, in Uttar Pradesh (UP), Yadav et al. (2021) recently confirmed that the most effective weed control was obtained by a combination of hand-weeding with a PRE or POST (at 10% potato emergence) application of Metribuzin (0.75 kg ha^{-1}). and a second POST application of Metribuzin, at the same rate, at 10% of potato emergence. The effectiveness of the treatments gave high potato tuber yields (about 20 tons ha^{-1}) and an income of INR 176,000 ha^{-1}.

Although the use of herbicides is quite limited in Assam, significant amounts of herbicides are used in other States of India, as indicated by literature (Choudhury et al., 2016; Chaudhary et al., 2022). In Assam, only Metribuzin is recommended as PRE applications at 1.0 kg ha-1 applied in 400-500 L ha-1 of water. Metribuzin costs INR 1500 per ha and for most farmers, this is considered affordable relative to the profits from potatoes. In potato cultivation trials at Jabalpur, Sondhia (2002) reported that metribuzin applied at 0.85 and 1.20 kg ha^{-1} persisted up to the harvest time in black soil and also noted that under Indian conditions, metribuzin remained active in the soil for even up to 100 days (Sondhia, 2018).

Colquhoun et al. (2009) noted that site-specific weed management has limited application in potatoes, which have traditionally relied heavily on preemptive herbicide applications to control weeds during the period when the crop is not competitive. However, an overall reduction in herbicide use can be achieved by developing cultivar-specific management strategies. These can combine herbicide use with competitive characteristics, such as rapid emergence and early growth rate and canopy closure. In Assam, it is particularly important to adopt reduced herbicide strategies that should be based on (1) competitive cultivars, (2) a combination of banded PRE herbicides and cultivation, and (3) selective POST herbicides.

Presently, there is not much data on herbicide-resistant weeds in potatoes in Assam. This is because herbicide use is rather limited. However, as herbicides are commonly used in potatoes in other Indian States, there is awareness of the need to prevent herbicide-resistant weeds from developing in potato fields. In other countries, this is done by crop rotations and by using different herbicide mixtures and combinations and changing the regimes of herbicides approved for potatoes. Other methods include applying herbicides to weeds when they are young and most sensitive; applying non-selective herbicides (such as paraquat, diquat or glyphosate), before potato emerges, at rates that guarantee a complete kill.

IWM and Conservation Agriculture (CA) Practices

Conservation Agriculture (CA) is popular in India, as a means of reducing herbicide use and other high-energy inputs for agriculture. CA aims to minimize soil disturbances and retain healthy soil, allowing crop intensification at the same time (Das et al., 2018). Competitive crop varieties are of vital importance in CA, although in potatoes and many other crops, breeding for CA-responsive, specific varieties are yet to make much headway (Das et al., 2018).

With CA approaches, mono- and double-cropping systems are now changing to double- and triple-cropping systems, through Zero-Tillage (ZT) with paddy straw mulch use in potato production in Assam. The practices were introduced for the first time in seven Districts of Assam in 2018-19 and in 14 Districts during 2019-21, as a component of the CIP-APART *Potato Value Chain Program* (CIP, 2022).

In this practice, potato is sown immediately after the *kharif* rice harvest without any further tillage or soil preparation. As a result, there is an efficient use of residual soil moisture, as well as an estimated saving of 10-12 days used otherwise for soil preparation. The zero tillage with paddy straw mulch technique, introduced primarily as a climate-resilient technology, is gaining popularity among potato farmers. It uses paddy straw as a mulching material and ensures water saving (Bhullar et al., 2015; Das et al., 2018).

Recent studies by Mohaniya et al. (2020) at Gwalior, Madhya Pradesh (MP) showed that the highest potato yields and profits were obtained from two rounds of hand weeding at 20 and 40 days after planting (DAP), followed by one hand-weeding at 20 DAP + Straw mulching @ 5 t ha^{-1} at 25 DAP. When labour is scarce, farmers choose the second option or even resort to using only the straw mulching option, applied early at five DAPs (Mohanty et al., 2020).

Studies in Assam have shown that when the potato field is covered with 15-20 cm thick paddy straw, it protects the soil from drying under warm conditions and long days with bright sunlight (**Figures 9-11**). The straw effectively reduces weed emergence, especially broad-leaf weeds, by 90-100%. The straw mulch also reduces the incidences of pests and diseases (99 % reduction in damage by cutworms), and lower post-harvest potato losses and costs of cultivation (CIP, 2022). The general cost of a 15-20 cm thick paddy straw mulch layer in Assam is about INR 6000 ha^{-1}, without the labour costs of mulching it.

Figure 9 Raised bed potato mulching with paddy straw

Figure 10 A typical zero tillage potato with paddy straw mulch field after two months

Mahmood et al., (2002) and Zaman et al. (2009) reported that under paddy straw mulch, potatoes recorded higher yields than other cereal mulches. Paddy straw mulching gave higher yields and net returns and also recorded higher water use efficiencies (WUE) over no mulching (Sadawarti et al., 2013). Mulching increases the system efficiency, cropping intensity and farmer’s profit thus helping in achieving the goal of doubling farmer's income.

In recent studies, Sarangi et al. (2018) reported higher tuber yields of 20.7 tons ha^{-1} under zero tillage with 12 tons ha^{-1} of paddy straw mulching plus foliar sprays of nutrients for potatoes. The Zero tillage method of potato cultivation is particularly suitable for salt-affected coastal regions as well mainly because early harvesting is possible and another short-duration pulse crop, such as green gram can be grown in rotation. The cropping intensity increase can yield profits of up to 300 % (rice-potato-green gram) than with potato cultivation alone (CIP, 2022).

Figure 11 Zero tillage potato produced under mulching with paddy straw at harvest

Conclusions and Future Outlook

At the End of Year of the Potato (2008) review, the FAO's Director General Jacques Diouf said that "*The potato is on the frontline in the fight against world hunger and poverty*" (FAO, 2009). CIP's engagements with the Assamese potato farmers indicate that this statement is valid in Assam too, as most farmers consider potatoes to be a cash crop that can provide quick profits and also alleviate hunger and poverty.

Ahmadu et al. (2021) recently explained that "*peculiar features of potato crop such as its adaptation range coupled with high nutritional value and production ease have aroused the interest of many people to embark on its cultivation*". This interest is present in the whole of North-Eastern India too and has led to steady increases in potato production and consumption. However, in Assam, production constraints, including the management of weeds, pests and pathogens have limited the capacity of the State to produce sufficient quantities of potatoes.

The literature on potato cultivation is expansive already and is increasing as cultivation is popular in many developed and developing countries as it is a short-duration cash crop. Despite potatoes being susceptible to a host of pests and pathogens, and weed infestations, in the last few years, there has been an increase in the production of potatoes and their demand in all of Asia, many parts of Africa, and Latin America. FAO Data (FAOSTAT, 2020) show that production increased from less than 30 million tons a few decades ago to more than 360 million tons in 2020 and 376 million tons in 2021 (**Table 4**).

As the two most populated countries in the world, China and India are the biggest global potato producers. The data show that millions of farmers in the world depend on potatoes for food as well as cash income. FAO (2009) also views potato as a reliable food security crop that can help ease future turmoil in the world's food supply and demand and "*improve resilience, especially among smallholder farmers by providing direct access to nutritious food and, increased household incomes*" (Ahmadu et al., 2021).

In Assam, as in many other developing countries, the food security challenge is to produce much and waste fewer potatoes through better pre- and post-harvest management. Pre-harvest and post-harvest management in potatoes, including the management of weeds, pests and diseases; as well as storage, processing and value chain efficiency, are much larger problems than in grain cereals and other vegetable foods. Research in Assam and other States of India and elsewhere have clearly shown that the main causes of potato losses are poor crop and harvest management, infested tubers by pests and diseases, a high percentage of small tubers and weather conditions: frost and heavy rains etc.

The increasing awareness about the nutritional, agronomic, and cash-creating advantages potato provides is likely to further increase its status as a global crop, particularly in developing subtropical and tropical countries. The development and adaptation of integrated pest management will be crucial for sustainable and more resilient and profitable potato production in all potato-growing regions worldwide.

In Assam and other States of India, the selection of varieties for rapid emergence and early canopy development in future potato breeding line evaluations is highly recommended. These useful competitive traits could be incorporated by potato breeders into new cultivars while maintaining desirable end-use characteristics. Emphasis should also be given to using biological approaches in weeds and pest management. This will reduce the dependence on insecticides as well as reduce the risk that insect populations develop resistance against insecticides.

The CIP experiences in Assam agree with the observations of Colquhoun et al. (2009) that potato cultivar selection in the near term will most likely continue to be determined based on end-user and consumer-desired quality characteristics and not competitive ability. However, cultivar selection is critically important for practically implementing IWM and reducing the overall reliance on herbicides.

The CPRI (2021) Annual Report provides details of the potato germplasm being conserved, genetic manipulations, breeding and development of disease-resistant and competitive cultivars, as well as those that can utilize nutrients more effectively. The development of hardier varieties without yield penalties is of considerable significance for future potato production in India and elsewhere.

Despite the success of chemicals, well documented in the global literature (Bellinder et al., 2000; Baranowska et al., 2016; Gugała et al., 2018; Barbaś and Sawicka, 2020), the cost of herbicides is a significant barrier to weed management in potato, especially in new cultivation areas. This means that research on inter-row, band applications and the integration of sulfonyl ureas and other soil-applied herbicides with cultural practices is a high priority to improve Assam's potato production.

The benefits of manipulating available mulches for controlling weeds and crop rotations, particularly with pulses and cereal crops, are well recognized in Assam. Nevertheless, the adoption of well-proven practices is severely constrained in Assam by the local socio-economic factors affecting the growers.

Table 4 Some Potato Production Statistics – Top Ten Countries (Source: FAO, 2020)

Country	2020 Metric Tons	2020 Hectares	Country	2021Metric Tons
1. China	78,183,874	4,218,188	1. China	94,362,175
2. India	51,300,000	2,158,000	2. India	54,230,000
3. Ukraine	20,837,990	1,325,200	3. Ukraine	21,356,320
4. Russian Federation	19,607,361	1,178,098	4. USA	18,582,370
5. USA	18,789,970	369,930	5. Russian Federation	18,295,535
6. Germany	11,715,100	273,500	6. Germany	11,312,100
7. Bangladesh	9,606,000	461,351	7. Bangladesh	9,887,242
8. France	8,691,900	214,500	8. France	8,987,220
9. Poland	7,848,600	225,740	9. Poland	7,081,460
10. Netherlands	7,020,060	164,500	10. Egypt	6,902,816
World Total	**359,000,000**	16,500,000	World Total	**376,000,000 (4.9%⇧)**

* FAO Data from 140 potato producing countries (**http://www.fao.org/faostat/en/#data)**.(2) Latest Global Potato Data: (**https://www.potatonewstoday.com/2023/01/21/global-potato-statistics-latest-fao-data-published/**)

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PERSPECTIVE

Prospects for Applied Weed Research – a Perspective

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Editor's Note:
This perspective from Stephen Moss is re-published for the benefit of weed scientists in the Asian-Pacific region. Originally, the Author posted his perspectives on the *European Weed Research Society* (EWRS) Website on 6th April, 2023 (see: **https://www.ewrs.org/en/info/Blog//109**). Although written primarily from a western European agronomic perspective, the ideas about applied weed research activities that Stephen Moss presents are scientifically sound, and, more importantly, practically relevant to all weed scientists globally.

Introduction

As I will soon retire from active research, after over 50 years, I thought a list of applied topics requiring more research might have merit. I am certainly not suggesting that all of these are original, novel or have never been studied previously. But, in my opinion, there is scope for undertaking more research that is both good scientifically and, more importantly, has real practical application.

If I have one criticism of current weed research it is that too much emphasis is placed on knowledge acquisition rather than its practical application. And surely, weed research is an applied discipline?

In the UK, there has been a catastrophic decline in the number of research centres conducting applied, independent, agricultural research during the last 40 years. These are documented in an article in the *UK Crop Production Magazine* (CPM) to celebrate my 'golden' research anniversary [1]

State funding tends to be focussed on basic studies, and research centres are increasingly dependent on commercial organisations for funding more applied projects. So, what is the difference between 'basic' and 'applied' research? Put simply, 'basic research' can be considered an 'end in itself' and judged purely on its scientific merit ('high impact' research papers). In contrast, 'applied research' can be considered 'a means to an end' and is better judged by its impact in the 'real' agricultural world. Ideally, a continuum would exist right across the research spectrum but, in the UK, funding tends to be polarised at one end or the other, with the 'valley of death' of translational research in between. My greatest achievement is surviving in the 'valley of death' for over 50 years.

The topics I wish to highlight below are presented with a limited amount of explanation. They are predominantly from a UK and a grass-weed perspective but have wider relevance too. Topics are listed under four broad categories: Weed Biology; Herbicides; Weed Evolution; Student-type projects.

[1] See pages 8–12 in the October 2022 issue: **https://www.cpm-magazine.co.uk/back-issues/crop-production-october-2022/**).

Stephen Moss's presentation is also available for viewing on U-Tube (**https://www.youtube.com/watch?v=gDmpdhLs8As**).

Weed Biology

**Topics currently being studied in a Syngenta-funded PhD at NIAB/University of Lincoln.*

1. Reducing weed seed return. Harvest Weed Seed Control (HWSC) is receiving a great deal of attention, but other aspects are important too.

a. In-crop patch spraying with glyphosate is widespread but what are the practicalities and benefits of spraying the same patches for several years? Factors to consider include spraying strategies, environmental benefits, impact on resistance and cost savings.

Drones could be used to detect and spray small weed patches annually. How much do the benefits vary with weed species?

b. Hand roguing (hand-pulling) – effectiveness and feasibility with different species. What is realistic?

c.* Grass-weed head 'surfing' - cutting weed heads just above crop pre-harvest. Factors to consider: crop/weed height differential; timing and benefit of multiple cuts; effect on seed viability and dormancy; regrowth; crop yield response.

Do crop growth regulators or drilling date affect the crop/weed height differential and can this be used to improve control?

d. 'Hoovering' up recently shed weed seeds from the soil surface immediately behind the combine header before straw is deposited on top (ideally combined with HWSC for seed destruction).

2. Post-harvest stubble management to maximise weed seed loss. Research has shown that incorporating freshly shed seeds of most weed species into the soil helps preserve them, whereas leaving them on the soil surface encourages loss. Despite this, many UK farmers cultivate straight after harvest to incorporate straw residues and encourage germination of crop volunteers.

a.* Is delaying cultivations by several weeks prior to sowing spring crops a realistic option, what delay is acceptable and are there soil/environmental benefits? How do cover crops affect this?

b.* Can we better quantify any benefits, and how they are influenced by the numerous variables which include: weed species, the relative number of freshly shed vs older seeds in the seedbank, duration of delay, type and amount of crop residues, type of cultivation, the weather, seed dormancy, and sowing date? This requires investigation in real field conditions, at multiple-sites, over multiple-years, to reach robust, practical conclusions.

3. Maximizing the value of grass leys/non-crop cover crop breaks/fallowing within arable rotations. Any 'break' in an arable cropping sequence has the potential to totally prevent any grass-weed seed return. This should result in a substantial reduction in the weed seedbank of annual grass-weeds, such as slender foxtail (*Alopecurus myosuroides*) and ryegrass (*Lolium* spp.), which typically have annual seedbank declines of about 70%. But lack of cultivation means that seed decline is likely to be less than under annual tillage regimes.

a. There is a lack of information on the best policy to adopt at the end of a non-crop 'break': is it 'maximum' cultivation (to encourage germination of residual seeds) or 'minimum' cultivation (to leave buried residual seeds undisturbed)?

b. In theory, maximum cultivation during conditions favourable for weed seed germination, followed by a stale seedbed lasting several weeks and glyphosate spray prior to sowing the next crop should be the best approach to exhaust the weed seedbank.

Practical evidence to support this is needed and also to determine what delay to sowing the next crop is desirable (weeks or months?) to maximise the benefit. Failing to adopt the best approach could potentially undermine the benefit achieved over several years.

4. Increasing crop competition to increase weed suppression in the field. Hardly a novel concept but are glasshouse/CE weed/crop competition studies ever relevant to field situations? A pertinent question. Certainly, there is scope for more applied, field-based studies. For example:

a. The principle that some varieties of a wide range of different arable crops are more competitive against weeds than others has been demonstrated numerous times. Applying this in practice has been less successful, partly because the commercial life-span of any individual variety tends to be short.

What is required is the development of a simple, field-based, protocols that can be used routinely to assess the competitive ability of new varieties, ideally before release. One approach might be to use a split plot design with, for each variety, crop only (e.g. wheat) compared with crop + model sown weed (e.g. wheat plus rye-grass).

The number of rye-grass heads would be a direct measure of variety competitiveness and relative crop yield would be a good metric of direct relevance to farmers. Crop traits, which confer competitiveness advantages, could be investigated in the field.

Even if unsuccessful, such research would not detract from the more practically useful information that can be obtained.

b. In the UK, oilseed rape crops direct drilled into cereal stubble will usually receive some fertilizer at sowing. If this is applied to the soil surface, weeds such as *Alopecurus myosuroides* benefit as much as the crop, but if this is placed below the crop seed, the emerging oilseed rape plants may gain a competitive advantage over the weeds due to greater access to nutrients. Additional benefits may be that the less vigorous weeds are more easily controlled with post-emergence herbicides (e.g. propyzamide) and the crop more able to withstand pest attack (e.g. cabbage stem flea beetle).

More broadly, this topic seeks to answer the question: can the relative competitive ability of crops and weeds be assessed under contrasting agronomic situations and the practical benefits quantified in a practically useful way?

Herbicides

1. Pre-emergence herbicides issues. With *Alopecurus myosuroides* and *Lolium* spp., ever-increasing resistance to post-emergence herbicide has resulted in ever-increasing reliance on pre-emergence herbicides. Three related issues deserve field investigations:

a. The negative impact of increasing soil organic matter on the efficacy of pre-emergence herbicides. Reduced tillage, or the addition of organic manures, can result in rapid increases in surface organic matter. Although this situation is beneficial from a soil health perspective, one downside is the likely reductions in efficacy of residual herbicides due to adsorption. Any reductions in efficacy are likely to be gradual and vary with individual herbicides.

b. Resistance. Despite resistance to the pre-emergence herbicides used for grass-weed control in the UK being widespread, resistance tends to be partial and increase slowly. Hence, pre-emergence herbicides have had greater longevity than many post-emergence herbicides.

c. Enhanced microbial degradation in soil. Previous research has demonstrated enhanced degradation of many of the pre-emergence herbicides currently used in Europe (e.g. pendimethalin, prosulfocarb, tri-allate). However, the impact of this on efficacy in the field has rarely been characterised.

Each of these three factors is likely to reduce the efficacy of pre-emergence herbicides in a slow, progressive manner – changes that are likely to be undetectable in the field in the short-term. However, the combined impact could be at least additive, especially if future regulatory restrictions require rates of use to be reduced.

With increased reliance on pre-emergence herbicides in cereals, the impact and interaction of the above three factors on long-term herbicide efficacy deserves attention. Do different active ingredients respond to each of the three factors differently?

Almost certainly, the answer is yes, but I am not aware of any independent research done on this in a systematic way. Modelling the effects of the three factors alone, and combined, might help in predicting long-term impacts. This would make a great Ph.D. project for a future student.

2. Why does the efficacy of pre-emergence herbicides vary between farms? In the UK, flufenacet + pendimethalin and flufenacet + diflufenican have been widely used for pre-emergence control of grass-weeds for over 20 years.

On average, both give the same control of *A. myosuroides* (mean 71% across 375 field trials, Hull *et al,* 2014). But on individual fields, one mixture can be consistently superior to the other. Why? We don't know - and there is anecdotal evidence that the efficacy of other herbicides (e.g. prosulfocarb) also varies consistently between fields.

a. At least 12 factors influence the efficacy of pre-emergence herbicides: soil moisture; rainfall intensity; seedbed quality; soil organic matter; surface crop residues; weed seed distribution in soil; weed germination pattern; application technique; temperature; enhanced microbial degradation, cultivations and resistance. Determining the relative influence of each of these individually, and combined, is a considerable challenge. However, investigating their relative impact on individual herbicides - and how they might be modified – would be useful. Surely, it is farmer's long-term interests to know what herbicides work best – and the underlying reasons for this – on their own individual farm?

3. Benefit of adjuvants, water conditioners, new nozzles and other herbicide 'performance enhancers'. These all have valid uses but most claims in the UK farming press for the benefits of specific products are not supported by any truly independent evaluation.

Farmers and agronomists would benefit greatly from simple multi-site and multi-year trials conducted fully independently. Studies at half the recommended herbicide rates might more readily demonstrate their potential benefits, even if overall control was inadequate. This experimental approach should be used more widely.

4. Herbicide Resistance. There is an ongoing need to detect and investigate new types of resistance, especially those conferring partial resistance where interpretation can be problematic.

Resistance may evolve faster under the reduced tillage systems which are now being actively promoted. Diagnostic assays that are readily accessible to farmers and agronomists are needed, as is availability of well characterised reference populations. Detection and interpretation of resistance should not be left solely to the agrochemical industry.

Weed Evolution

These topics are more ‘academic’, but also have some practical relevance. Weeds are often under intense selection pressure and many species can evolve rapidly with time. Herbicide resistance, now prevalent in many species, is a good example. Relevant studies include:

1. Have individual weed species become genetically more competitive over time? If herbicides can select for more resistant individuals, would one not expect intense competition from crops also to select for genetically more competitive individuals? Changes in agronomy (e.g. sowing date) may affect crop/weed competitive balance too, which would affect phenotypic expression of competitiveness, so this is a challenging academic study.

Are ‘superweeds’ evolving? (Since drafting this section, I was pleased to note the publication of the first study providing direct evidence of evolution of competitive ability in a plant species (*Setaria faberi*); Ethridge *et al.*, 2023, Weed Science 71: 59-68.)

2. Have weed germination and emergence patterns changed? Claims about changing patterns of grass-weed emergence are not well supported by good independent data. The influence of changing cropping and cultivation practices (and possible indirect effects of resistance) on emergence patterns of *Alopecurus myosuroides*, *Lolium* spp. and *Bromus* spp. would be a useful study and relevant to IWM. Quantifying and explaining inter-population variation would be very useful too.

3. Do resistant weed seeds survive longer in the soil than susceptible ones? If so, then this is likely to be weed species and resistance mechanism specific.

If proven, it would indicate (for the first time?) selection pressure for herbicide resistance operating in the absence of herbicides - the proportion (but not number) of resistant individuals increasing with time.

4. Do resistant weed seeds have greater dormancy than susceptible ones? If so, then this is likely to be weed species and resistance mechanism specific. In UK, the *Alopecurus myosuroides* population with the greatest ability to metabolise herbicides (Peldon population) has shown the highest degree of innate dormancy in each of the past 20 years, based on annual seed collections totalling over 700 populations. This seems an unlikely coincidence.

However, the fields at Peldon have, for over 50 years, been in continuous winter wheat which has always been sown relatively late in autumn. Selection for high innate dormancy could be a consequence of late sowing, or pleiotropically linked to enhanced metabolic resistance, or both factors, or neither. A degree of enhanced metabolic resistance occurs in most *A. myosuroides* populations in the UK, so it is possible (but unlikely) that changes in emergence patterns are directly linked with resistance. Determining the factor(s) responsible would be relevant to IWM and resistance management.

5. How important is ‘pre-selection’ for resistance to herbicides? It has been hard to explain the speed – often less than 10 generations – at which weeds evolve resistance to a level which impacts on control in the field. One factor that has often been overlooked is the low level of selection (= ‘pre-selection’) conferred by herbicides that make no claims for control of a specific weed.

For example, in the UK, metsulfuron has been widely used for broad-leaved weed control for over 35 years. While there are no label claims for control of grass-weeds, it does have activity on weeds, such as *Alopecurus myosuroides* and *Lolium* spp. The relatively low level of selection conferred in such situations might well be important in relation to the speed of subsequent selection conferred by herbicides with greater grass-weed activity (e.g. mesosulfuron). Studies on such ‘low level pre-selection’ might help explain the dynamics of resistance evolution and help quantify longer-term resistance risks.

6. How quickly can ‘weediness’ traits evolve? At least some ‘weedy’ traits (e.g. extended germination patterns, longer seed persistence, greater competitiveness and resistance) have evolved in the cultivated grass species *Lolium multiflorum* in the UK.

This was introduced into the UK in 1831 for grazing and hay making and plant breeding has subsequently produced a wide range of cultivars with different characteristics. It is now found increasingly as a weed of arable crops and resistance is widespread. This makes it an ideal candidate for a UK study on how a 'crop' becomes a 'weed' – especially as other weedy *Lolium* species (e.g. *Lolium rigidum*) are rare. (*Lolium perenne* is very common but rarely occurs as a major arable weed in the UK).

Important questions include: how much do weediness traits vary between field populations; how might these traits evolve further in future; are resistant populations in the UK derived from identifiable cultivars? has resistance evolved independently in specific cultivars or has it been introduced via pollen from existing resistant populations?

Are some cultivars more resistance-prone than others and, if so, why? Do modern breeding techniques make 'weediness' more, or less, likely to evolve? There may be other, more appropriate candidate species, in other countries. Characterising the dynamics, mechanisms and implications of how such a crop evolves into a weed would make a great academic study.

7. Why don't *A. myosuroides* and *Lolium multiflorum* co-exist as weeds of arable crops? These are both major weeds of UK arable crops and, while mixed populations do occur, one species usually dominates. Infestations comprising similar densities of the two species are rare — although they may occur in different patches within the same field. Why?

The obvious reasons, such as cropping and herbicide history, soil type and drainage do not appear to offer a full explanation. *Lolium multiflorum* is twice as competitive as *A. myosuroides* on an individual plant basis and this may be a contributing factor. Is the reason these two species 'do not like each other' some allelopathic effect? Could it be linked to subtle differences in resistance to herbicides, which is common in both species in the UK? Research on this topic would be relevant to a better understanding of the dynamics of patches of such weeds.

Student-type projects

The following are smaller scale student-type projects , which can be on specific issues.

1. Is fresh, or dry foliage weight a better metric for determining herbicidal effects on plants in glasshouse pot tests? Foliage weights are often used to quantify the degree of herbicidal activity on weeds, as a representation of 'aliveness' and 'deadness'.

Recording dry weights, after the removal of the major constituent of living plant material, namely water, seems illogical. Despite this, reviewers of papers submitted to journals often favour use of dry weights. But foliage fresh weights, recorded immediately after cutting, may not only be a better metric scientifically, but also save time, energy and money. A critical study on this would be useful. (Of course, dry weights are a better metric in many other scenarios, especially where plants wilt before weighing).

2. Why does % emergence of cereals (and other crops?) tend to decline with increasing seed rate? In the UK, higher cereal seed rates are one of the most widely used ways of increasing crop competitiveness against grass-weeds.

It has been noted in field trials that % establishment decreases with increasing seed rate, although the reasons for this are rarely explained. Clearly, this effect will result in diminishing marginal benefits as seed rate increases, so investigating this could be useful in avoiding wasting crop seeds as a consequence of increasing seed rate excessively.

3. Can the assessment of herbicide resistance in Petri-dish assays be speeded up? Petri-dish seedling growth assays for determining herbicide resistance often require a time-consuming assessment of shoot length for each germinated seed [2]. Visual assessments of % reduction in seedling growth, relative to no-herbicide controls, are quicker, but are subjective and accuracy is also dependent on the experience of the assessor.

An alternative, but more objective assessment, could involve recording the amount of 'greenness' per dish using a green canopy cover mobile phone app, such as Canopeo (**https://canopeoapp.com/**). Ideally a comparison of different assessment methods could be done, including time taken.

4. Do resistant arable grass-weeds in predominantly livestock farming areas, occur as a consequence of seed movement in contaminated straw or equipment? Resistant weeds such as *Alopecurus myosuroides*, *Lolium multiflorum* and *Avena* spp. are considered a minor issue in areas where livestock farming and grassland predominate (e.g. Wales). However, resistant weed seeds may be introduced into fields in contaminated straw (used for bedding or feed), in equipment (e.g. balers and combines) or in crop and grass seed.

Resistance tests on weed seeds collected from arable fields in such areas, especially if never treated with grass-weed herbicides, would be informative.

[2] A detailed protocol for '*The Rothamsted Rapid Resistance Test*' is available at: **https://ahdb.org.uk/knowledge-library/the-weed-resistance-action-group-wrag**.

The findings might encourage timely prevention and management strategies, such as hand roguing.

5. Do ALS-resistant seeds of *Papaver rhoeas* have less innate dormancy than susceptible seeds? ALS-resistant *P. rhoeas* occurs in 10 European countries, where it is one of the most commonly encountered resistant broad-leaved weeds.

The seeds of this species are very persistent in soils so the 'buffering' effect of older, less selected seeds, might have been expected to greatly moderate the rate of evolution of resistance.

But, if resistant seeds have less innate dormancy, this might explain why resistance has been recorded so widely. A study on the seed dormancy of a range of European populations, susceptible and resistant, could clarify this issue.

6. Do pre-emergence herbicides 'sensitise' weeds to post-emergence applications? It has often been claimed that weeds surviving pre-emergence herbicides are more easily killed by subsequent post-emergence applications.

The pre-emergence herbicides are considered to be 'sensitising' the survivors. This could occur if, for example, surviving plants are damaged and are therefore, more easily killed by a subsequent application. However, there is very little independent evidence to validate this claim, or to show how best to utilise it in practice. Questions to answer include: is this herbicide-specific? Can the effect be quantified; Is it a consistent trait?

7. Is a cost/benefit analysis of non-chemical weed control compared with herbicides useful? Integrated Weed Management (IWM) is promoted as a means of reducing reliance on herbicides and involves using a range of non-chemical alternatives. Individually, these alternatives may be less effective than herbicides despite costing more. However, there may well be additional benefits apart from weed control (e.g. crop rotations may have pest control and yield benefits).

There may be scope for additional studies on this topic comparing short-term (single year) and long-term (five years +) rotational benefits. The environmental and greenhouse gas impacts of non-chemical weed control, relative to herbicides, also deserve more scrutiny. This study could be useful in determining the most cost-effective and environmentally-favourable approaches and may encourage farmers to adopt the most appropriate IWM strategies on their own farms.

Final Thoughts

In relation to applied disciplines, like weed research, I fully support the view that:, *Knowledge without potential application is wasted.* The decline in funding for independent applied research in the UK is unlikely to be reversed. This situation also applies in some other countries too. Consequently, limited resources need to targeted on those projects which:

1. Require truly independent research, which companies either won't undertake, or are unlikely to do in an objective manner.

2. Produce durable information, of relevance in the long-term.

3. Give priority to delivering robust, practical outputs rather than mere 'academic' studies.

4. May require multi-year and multi-site studies to convincingly answer simple questions.

5. Are not: (1) reinventing the wheel; (2) ignoring previous relevant research; (3) simply using impressive new techniques for their own sake but delivering nothing 'new'.

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Editor's Note: About the Author

Stephen Moss has spent over 45 years in weed research, largely on grass-weeds and especially black-grass (*Alopecurus myosuroides*). Starting in 1975, following his B.Sc. in Agriculture at Wye College in 1972, he worked at the Weed Research Organization (WRO) at Oxford, then at Long Ashton Research Station, where he gained his Ph.D. and, from 1990, at Rothamsted Research.

He has published numerous research papers, book chapters and technical reports, and contributed to a large number of articles in the popular farming press. He has given numerous talks to farmers, consultants and agrochemical company staff. Stephen was the Secretary of the UK Weed Resistance Action Group and a UK representative on the European Herbicide Resistance Working Group. He now runs a private consultancy, Stephen Moss Consulting.

Book Review

"The Virtuous Weed"

'*Weedy by Name Only, Not Weedy by Nature*'

Nimal R. Chandrasena

Vivid Publishing, Freemantle, Western Australia

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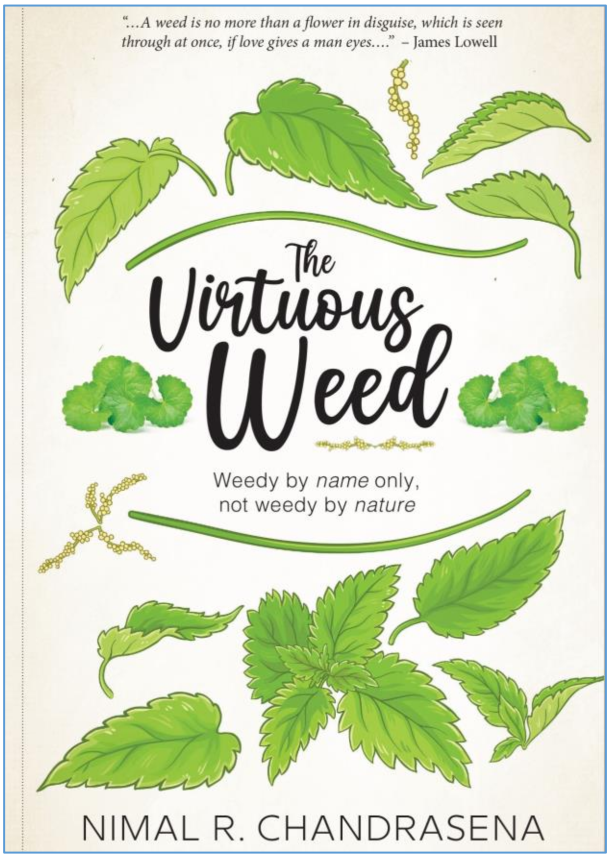

This book urges the reader to critically reconsider the definition of what makes a plant species a 'weed'. It provides an argument for us to cease shunning such plants, and instead admire them for their colonizing potential as pioneering species. As discussed, knowing why a particular weedy species does so well in certain environments provide clues for their management. After several centuries of European colonial expansion, weeds of one type or another have found their way into every corner of the world.

The history of weeds, as outlined in this volume, is essentially a record of the expansion of agriculture, which began independently in several parts of the world about 12,000 years or so ago. The full title of the book can be read as a warning that many species, including native Australian plants, are potentially weeds if placed in a favourable environment.

The author, Nimal R. Chandrasena, has spent his working life investigating all aspects of the numerous plant species that the world has come to classify as weeds. This high level of expertise means that he is imminently qualified to write this definitive book on weeds. The book is skilfully written in an accessible style and yet is well-referenced for scholars who need to drill much more deeply into the published materials from which the book is drawn. The provision of numerous tables helps to summarise the data.

The most commonly used plant names appear in the text, but the inclusion of their scientific name in brackets helps to clarify the species. The use of endnotes enables the readers to proceed unencumbered by numerous references that would otherwise be placed within the main narrative.

The readership of *The Virtuous Weed* is chiefly comprised of academic botanists, ecologists, environmentalists and university biology students. In addition, landowners, environmental groups and local councils, who manage weeds on their assets and properties may also find this book of great interest. The strengths of the work include its insightful investigation of what makes a weed, the rich description of the 'war' raged on weeds, and its demonstrations of how weeds could end up being very useful to humanity – if only we stop 'waging a war' or ignoring them.

At the centre of the definition of a weed are perceptions concerning whether or not the presence of the species concerned is a potential problem. Of course, as Chandrasena demonstrates, being seen as a 'nuisance plant' is dependent upon such things as whether the observer is a farmer, conservationist or an urban dweller.

His insights and data demonstrate that a sense of aesthetics and the cultural background of people are also factors in determining whether a particular plant is a weed or perhaps, something more special that should be cherished, albeit still under some form of control, where necessary.

While many exotic species have become established in new areas, usually in partnership with the expansion of agriculture, only some species pose a sufficient enough threat that requires some form of management. Chief among the perceived threats of weeds is the negative impact on the natural environment, with traits such as being poisonous to wildlife and stock, having the ability to cause more severe bushfires or change the water table, and possible displacement of more desirable species.

Chandrasena has shown that not all weeds are introduced plants, with some indigenous species of herbs, that appear suddenly during certain seasons, also being seen as weeds. For instance, a plant that is frequently recorded by ethnobotanists working in Western and Central Australia is a 'native' but 'weedy-looking' annual daisy [Asteraceae] called the 'toothed ragweed' [*Pterocaulon serrulatum* (Montrouz.) Guillaumin]. It grows thickly after a bushfire, along with other weedy species, in creeks and along roadsides (Latz, 1995).[i]

While some observers would see this plant as weedy and a nuisance when having to pass through it, others actually find this strongly-scented species very useful. Chandrasena draws attention to the Australian Aboriginal use of the toothed ragweed, stating that the '*Aromatic leaves are used to treat colds; inhaled by chewing or crushed to make a decoction*'.[ii] The plant is known by several Aboriginal names, and was used for treating people with very bad influenza, or with 'flu-like symptoms. The leaves are ground up and mixed with animal fat to make an ointment. This ointment is rubbed into the chest and the back of the sufferer, and into any aching joints.

As a practising ethnobotanist, on field trips, I have often encountered exotic plant species growing alongside indigenous plants in nature reserves. Initially, when commencing my study of traditional Australian Aboriginal plant uses in the 1980s, I tried to ignore such exotic weedy species that appeared to be threatening the coexistence of the native plants and animals, since they were not part of the landscape just before European settlement.

To my surprise, I soon found that Aboriginal people had come to use many of them. For instance, Aboriginal people based in temperate parts of Australia considered *thalgi*, which is the common sow thistle (*Sonchus oleraceus* L.), to be an important food and medicine.[iii]

The fact that sowthistle, a weedy colonizer, had come from Europe and Western Asia in the early days of British colonization was of little or no significance to my Aboriginal instructors. This same species is of significant interest to Chandrasena, and in *The Virtuous Weed* he provides the nutritional values of the sow thistle and records that in addition to its Aboriginal use in Australia, the '*Tender parts are used as a potherb from ancient time in Europe; cooked into curries in Java'*.[iv] As an edible green, the author highly recommends the growing of sow thistles, as well as the related prickly sow thistle (*Sonchus asper*), in community gardens.

Nimal Chandrasena remarks that: '*Colonizing species will always be the ultimate survivors in the conflict with man. Rather than zero tolerance towards weeds, it seems reasonable to propose 'ecological management' of problematic populations, with an eye on their potential benefits, on a 'case-by-case' basis* '[v]. This work is a valuable contribution to the history of the interactions between plants and people and should be of interest to weed scientists, ecologists and others who are interested in weedy species..

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[i] *Atlas of Living* Australia (**https://bie.ala.org.au/species/https://id.biodiversity.org.au/node/apni/2898547**).

[ii] Chandrasena (2023, p.155).

[iii] Clarke (1986, 2013, 2015).

[iv] Chandrasena (2023, p.183).

[v] Chandrasena (2023, pp.371-372).