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EDITORIAL

Weeds and Biodiversity: Some Reflections

Nimal R. Chandrasena [1]

[1] Current Address: *Nature Consulting*, 17, Billings Way, Winthrop, WA 6150, Australia

E-mail: **nimal.chandrasena@gmail.com**

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Abstract

With or without humans colonizing species will always be present on earth and continue to play vital roles in stabilizing the earth's ecosystems damaged by the teeming humanity. Therefore, humans need to '*live with weeds*' and utilize their colonizing power for beneficial uses. If people well understand the valuable ecological roles and biodiversity values of colonizing species, it will influence the decision-makers and help them develop better policies towards colonizing taxa.

Agro-ecology helps us to appreciate the critical roles of colonizing taxa in Nature. Concepts such as 'beneficial weeds' and "middle-way path" to weed management allow us to re-think how we may engage in agriculture more sustainably. A change in thinking is required in Weed Science to recognize weeds, not as a production constraint in agriculture and a threat to farming, all the time. As colonizing species, they are significant bioresource assets.

Where the abundance of weeds, at particular times and locations, present problems for other essential and valued human endeavours (such as food production) or natural ecosystems, they need to be appropriately managed. People have done this for millennia. The tools and techniques to do so, to the extent required, are well developed within *Weed Science* – a formidable discipline.

An improved relationship with weeds will develop if they are understood as nothing but colonizing and pioneering taxa, which are adapted to respond to disturbances. Much like humans, they are just opportunistic species. Weeds are no more villainous than humans.

The farmland biodiversity discourses, especially in Europe and the U.K., have awakened research communities to explore a more tolerant attitude towards beneficial weeds. Weedy species contribute pollination benefits for bees and food for other insects. Various fauna use them as food and shelter resources. Colonizing species also play critical roles in mitigating soil erosion, water retention, nutrient cycling and replenishment, improving soil health.

Weedy congeners (relatives) also promote the evolutionary diversification and genes for hybridization with their crop relatives. Such positive contributions offset, at least partially, the losses to biodiversity that people allege weedy species cause. Biodiversity is too important for society to misunderstand it. Biodiversity is critically important for a healthy planet. Human survival on Planet Earth depends on properly interacting with biodiversity. This includes appreciating the crucial roles colonizing species play.

Keywords: Biodiversity, colonizing species, beneficial weeds, middle-way path, weed management

Introduction

With or without humans colonizing species will always be present on earth and continue to play vital roles in stabilizing the earth's ecosystems damaged by the teeming humanity. Therefore, humans need to learn how to '*live with weeds*' and utilize them for societal benefits (Chandrasena, 2019). It will be a bonus if the ideas of utilization influence decision-makers and help them develop better policies towards colonizing taxa.

In precarious times, we have limited options. An improved relationship with weeds could lead to a better world and more efficient management of weed threats. Weed science research and books are replete with examples that show year after year, we fight the same battles with the same 'weedy' foes. As an alternative to an unwinnable conflict, it is worthwhile considering how we may co-exist with colonizing taxa. This requires an appreciation of the beneficial roles weeds play in Nature.

Plants, including the primitive forms of algae, mosses, ferns, are colonizing species, which are fundamental components of the earth's terrestrial and aquatic ecosystems. Evolving through millions of years, they played vital roles as the '*pioneers*' – the first primary producers, capturing the sun's energy and using that energy to fix gaseous CO_2 into sugars. In so doing, they also released oxygen (O_2) into the atmosphere, oxygenating the planet.

Photosynthesis is, therefore, the basis of life on earth, as diverse as it became, over about 3-4 billion years. The importance of ancient colonizing species in oxygenating the planet, including both non-vascular and vascular plants, cannot be overstated. Non-vascular Bryophytes (mosses and liverworts) and vascular plants, including Pteridophytes (ferns and allies), are the oldest colonizers on the earth [1].

Ferns appeared in the fossil record on earth about 360 million years ago (middle Devonian period). But many of the current (extant) families and species did not appear until about 145 million years ago (early Cretaceous period) after flowering plants (Angiosperms) came to dominate many of the earth's environments. The list of exceptionally successful ancient colonizers worldwide is quite impressive. These include peat moss (*Sphagnum* L. spp.), horsetails (*Equisetum* L. spp.), brackens (*Pteridium* Gled. ex Scop. spp.), mosquito ferns (*Azolla* Lam. spp.), salvinia (*Salvinia* Ség. spp.), nardoo (*Marsilea* L. spp.), fishbone fern (*Nephrolepis cordifolia* (L.) C. Presl] and many others.

Imagine the evolutionary adaptations that allowed these plants to exist for so long. They are also not marginal species living a tenuous existence; where they presently occur – they tend to dominate those habitats after establishment. Many are also globally spread, across diverse environments, a testament to their success. They are also hardly in danger of extinction from human-caused disturbances, as far as science can predict.

Science tells us that amphibious plants (liverworts and mosses), ferns and similar colonizers evolved from their ancestors through the Jurassic period (200 to 145 million years ago). They would have coincided roughly with the age of the dinosaurs (65-165 million years ago). Those plants stabilized the pre-historic world.

Early colonizers played significant roles among the first primary producers in those turbulent times when the planet underwent much disturbance. Colonizers were a vital part of the evolution of plant communities, which dominate the earth today.

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To properly appreciate the role of colonizing species in Nature, it is necessary to reflect on the conceptual terms in ecology, such as ecosystems and biodiversity. Ecology evolved as a branch of biology, dealing with the interactions between organisms and their environment. Ancient Greeks - Aristotle (384-322 BC) and Theophrastus ((371-286 BC) referred to *'dwelling places'* and '*distributional areas*' of organisms. Their writings might be considered as where ecological thinking began.

However, modern ecology took shape in the last three centuries with the studies of pioneers, natural historians, and biologists to whom we owe a great deal. Among them, the brightest stars have been Carl Linnaeus (1707-1778), Jean-Baptiste Lamarck (1744-1809), Alexander von Humboldt (1769-1859), Charles Darwin (1809-1882) and Alfred Russel Wallace (1823-1913).

The term 'ecology' (from the German word: *Oekologie*, *Ökologie*) was first coined by the German biologist Ernst Haeckel (1834-1919) in his book *Generelle Morphologie der Organismen* (1866).

A Danish botanist- Eugenius Warming (1841-1924), developed the idea further in 1895 in a thesis on the *Oecology of Plants: An Introduction to Plant Communities*. These early treatises changed the way we conceptualized the natural world, which had long been considered relatively static and unchanging (Willis, 1997). The ecological concepts supported evolutionary thinking. According to Chew (2011), Darwin proposed evolution by natural selection at least 20 years before Haeckel proposed "*Ökologie"*.

Until the latter part of the 19th Century, humans were thought of as the 'supreme being' on the planet. Charles Darwin changed all of this with *The Origin of Species* (1859), highlighting the dynamic, often reciprocal, and complex interactions between organisms. Darwin also emphasized how organisms adapt to the environment for survival, improving on the views of Jean-Baptiste de Lamarck.

Lamarck believed that traits that were acquired during an animal's life would be passed down to the next generation, a view that Darwin disputed by

[1] Vascular plants (Tracheophytes) form a large group of plants (ca. 300,000 known species) that have lignified tissue (the xylem) for conducting water and minerals throughout the plant. They also have specialized non-lignified tissue (the phloem) through which photosynthetic products (food) are distributed. Vascular plants include mosses, ferns, gymnosperms (including cycads and conifers) and angiosperms (flowering plants).

arguing that it is the heritable 'fitness' advantage of an organism that matters for survival [2].

However, modern ecology rose out of the evolutionary debates and emerged as a scientific discipline over a century ago (the Ecological Society of America was founded in 1915) and then evolved rapidly. The well-known ecological term '*ecosystem*' was coined in 1930 by Arthur Roy Clapham (Willis, 1997) when he worked as a demonstrator in Botany at Oxford. It was popularised in 1935 by the British scientist- Arthur Tansley (1935):

> *"…Ecosystems comprise the whole system, including not only the organism-complex but also the whole complex of physical factors forming what we call the environment…".*

Unfortunately, this ecological term is now arbitrarily used by various commentators. The media often describe the benefits of setting up 'start-up' companies as 'ecosystems'. The justification for using the word in this context is that start-up companies have many interacting and complex system components (technologically or otherwise) and a myriad of influential factors. Even Australia's federal parliament is often described as an 'ecosystem'- a misnomer!

In advancing ecology, Eugene Odum (1971), the American ecologist, said an ecosystem is:

> *"…Any unit that includes all of the organisms (i.e. the "community") in a given area, interacting with the physical environment so that a flow of energy leads to clearly defined trophic structure, biotic diversity, and material cycles (i.e. exchange of materials between living and nonliving parts) within the system is an ecosystem…."*

Ecosystems comprise living organisms, interacting plant and animal populations ('biotic' component), and their non-living, physical environment (the 'abiotic' part). The crucial living part comprises 'primary producers', photosynthetic plants that convert atmospheric CO_2 into sugars.

Without plants as primary producers, life will not exist on earth. With an energy-absorbing green pigment (chlorophyll), plants derive energy from the sun's rays to fix CO_2 as sugars. Weedy colonizers, like other green plants, perform this miracle. From the ancient ferns (ca. 145 million years ago), all kinds of colonizing plants achieved this life-sustaining function.

The second principal ecosystem component comprises 'primary consumers' - herbivorous animals, which feed on plants. The third component includes 'secondary consumers' - carnivorous or omnivorous animals, which feed on the primary consumers. Omnivorous humans can be either primary or secondary consumers.

The fourth and equally critical ecosystem components are microbes (mainly bacteria, fungi), macro-invertebrates, and millions of insects who decompose organic matter. Without them, there will be no recycling of dead organic material. All productive living systems will come to a halt if decomposition and recycling stop.

The ecosystem concept was a critical advancement in biological science, as Tansley used the term to replace the 'super-organism' concept. The latter term implied that communities of organisms formed a higher-level, more complex organism, a defunct idea. In the 1970s, the ecosystem idea was used in conjunction with the model of an 'ecological climax'. The 'climax' was proposed as a stable community, in equilibrium with Nature, arising under specific conditions. This idea is also defunct now, replaced by the concept of ecosystems as dynamic entities (Golley, 1993).

We now conceptualize an ecosystem as a dynamic entity, an area, small or large, within which the physical and biological components interact. They are not 'closed' systems; energy, nutrients, and organisms move within and between ecosystems at various spatial and temporal scales. If you looked closely, in any natural ecosystem, you would find colonizing taxa playing important and productive roles within them. They cannot be excluded from any functioning ecosystem.

Ecological research shows that influential environmental factors determine ecosystems' composition of organisms and how they function and live together. Abiotic factors, such as nutrient availability, temperature, sunlight, water level fluctuations, and wind velocity, would be highly influential. Biotic factors, such as grazing intensity, population density, and the presence of natural enemies, would also often be at play in determining the biotic community, which occupies an area.

[2] Lamarck and Darwin agreed that, over time, living animals and plants change (evolve) to become 'progressively' more suited to their environments. However, they disagreed on the specific mechanisms. 'Lamarckism' is the theory of inheritance of acquired characteristics, which get passed on to succeeding generations, whereas 'Darwinism' is based on 'natural selection' and survival of the fittest individuals who perpetuate their genes.

Changes in any of these factors would change the nature of the 'living' ecosystems.

To exemplify, a bushfire in a forest area may completely change the structure of that system, leaving no large live trees standing. Most of the mosses, ferns, herbs, and shrubs that occupied the forest floor could also be gone for a long time. The nutrients in the biomass of trees would be released into the environment. After a lapse of time, recovery will occur through secondary succession.

Before slow-growing native trees establish again, there will be a vegetation mix of under shrubs, typically comprising grasses, herbs, shrubs, and tree seedlings. Colonizing species, tolerating harsh conditions, would thrive on the disturbance and quickly form the supporting vegetation. Typically, colonizers will drive forward the succession in which other slow-growing species may start their new lives.

Weeds and biodiversity

The term biodiversity, abbreviated for biological diversity, was first coined in 1985 by W. G. Rosen to bring political attention to protecting vulnerable species. The event - '*National Forum on Bio-Diversity*', sponsored by the U.S. National Academy of Science (NAS) and the Smithsonian Institute, was held in the U.S. capital, Washington (21-24 Sep 1986) (Franco, 2013) [3].

The term is now used as a rallying call in ecology to convey that Nature is a complex matrix of species interactions between all living forms. However, this idea of a biologically diverse world is not new. More than 2300 years ago, the Greek philosophers understood that the natural world is formed by many life forms interacting with each other (Franco, 2013).

It was the renowned conservationist R. F. Dasmann who first used the term biological diversity- in his 1968 book *A Different Kind of Country*. In the mid-1970s, undergraduate courses emerged in universities, entitled 'plant diversity' and 'animal diversity'. However, it was only in the 1980s that the term 'biodiversity' became common (Franco, 2013).

Thomas Lovejoy, the biologist of *Gaia* fame, used the term biodiversity to warn people of the negative impacts of human actions on the earth's biological systems. The *Gaia* hypothesis posits that the planet is a self-regulating system involving the biosphere, atmosphere, hydrosphere and the pedosphere, tightly coupled as an evolving system. This system seeks a physical and chemical environment optimal for sustaining life. Lovejoy argued that maintaining biological diversity was the most fundamental issue of our time [4].

The modern usage of the term biodiversity encompasses all sorts of physical life forms of living organisms and their genetic diversity. It includes the genes within species, between species, and the ecological complexes they are part of. The definition adopted by the UN *Convention on Biological Diversity* in 1992 reads as follows:

> *"…Biodiversity is the variability among living organisms from all sources including, among other things, terrestrial, marine and other aquatic ecosystems and the ecological complexes of which they are part; this includes diversity within species, between species and of ecosystems…".* CBD (1992)

As Jon Marshall, a British Ecologist, pointed out, the reasons for biodiversity conservation are *moral, aesthetic, social, and economic*. There is now a need to 'look after' and conserve many species whose very existence on the planet is under threat from a range of human activities.

> *"….The reasons for the conservation of biodiversity are moral, aesthetic, social and economic. We steward other organisms for their intrinsic values and because species may benefit humans and have economic value. A culture that encourages respect for wildlife is preferable to one that does not. Biodiversity can easily be lost but is difficult to regain, particularly if species are driven to extinction…".* Marshall (2011)

The most damaging impacts on biodiversity come from the large-scale land clearing and deforestation to grow monocultures of crops and deforestation. The relentless mining for coal,

[3] Matthew Chew (2015) explained that Rosen is supposed to have quipped that he invented the term by taking '*the logical out of biological'* transforming an object of scientific inquiry into an object that could be used for advocacy. The quote appears in David Takacs - *The Idea of Biodiversity: Philosophies of Paradise* (Baltimore: Johns Hopkins University Press, 1996; p. 37). Takacs interpreted this comment as 'ironic', but that should not be taken to suggest it was flippant or untrue.

[4] Lovelock's *Gaia* theory proposes that living organisms interact with their inorganic surroundings on earth to form a synergistic, self-regulating system that maintains the conditions for life on the planet. Lovelock was a chemist. He formulated the idea with one of his colleagues- Lynn Margulis, a microbiologist. *Gaia* was the primordial goddess who personified the earth in Greek mythology (**https://en.wikipedia.org/wiki/Gaia_hypothesis**).

minerals, oil, gas, and mega-scale infrastructure projects, such as oil and gas pipelines, damage landscapes on a scale hitherto unknown on earth.

It is no wonder that species extinction rates are rising worldwide, in all landmasses - islands and continents, and oceans and rivers. Nearly all species on the planet appear vulnerable to the harmful footprint of the human species.

The moral imperatives for biodiversity conservation include respecting all organisms solely for their intrinsic biological values and presence on the earth. Large-scale land clearing, land reclamation and drainage of wetlands for uses, such as agriculture, mining, and urbanization, are the primary causes of terrestrial biodiversity losses in most countries. Australia, unfortunately, is a prime example. Removal of giant trees, along with understorey shrubs, heath, and grasslands, has been unstoppable in Australia, causing habitat losses for native plants and wildlife.

Changed fire regimes, salination resulting from altered hydrology and dams across rivers have caused significant changes in biodiversity. Added to the list must be the changes in plant species composition, which result from deforestation and over-grazing and trampling by large herds of introduced livestock (cattle and sheep), farmed over vast territories (Preece and van Ooosterzee, 2017).

We must add other human influences, such as contaminating waterways with industrial chemicals, fertilizers, and pesticides. Nutrient enrichment (eutrophication) causes large-scale changes in the biotic components of aquatic habitats, including the dominance of cyanobacteria.

Many cations, anions, metals, metalloids and synthetic organic molecules are now at previously unknown levels. They diminish the ability of ecosystems to sustain the full range of species. In such situations, colonizing aquatic taxa would be the best organisms with the adaptive capacity to tolerate those chemical stresses in waterways.

Globally, the current rates of biodiversity losses are the highest for at least 60 million years. Estimates of global losses of species can be as high as 25% for the next 30 years. We all know that biodiversity can be easily lost but difficult to regain.

The track record of successive Australian governments in taking action to protect the continent's iconic species and vegetation cover is abysmal. Mis-information and half-truths dominate. Australian scientists have recently lamented the current Australian Government's tendency to suppress information on the environment and biodiversity (Driscoll et al., 2020).

Suppressing expert knowledge can hide environmentally harmful practices and policies from public scrutiny. Driscoll et al. (2020) found Government (34%) and industry (30%) respondents reported higher rates of undue interference by employers than did university respondents (5%). Internal communications (29%) and media (28%) were curtailed most, followed by journal articles (11%) and presentations (12%).

When university and industry researchers avoid public commentary, it is mainly due to fear of media misrepresentation. At the same time, government employees were often constrained by senior management and workplace policy. One-third of respondents reported personal suffering related to suppression, including job losses and deteriorating mental health.

Substantial reforms are needed, including codes of practice, and governance of environmental assessments and research, so that scientific advice can be reported openly, on time, and free from interference (Driscoll et al., 2020). Scientists in all fields of study and government officials in many developing countries suffer in silence due to gag orders from governments.

The world now recognizes that human activities have placed many iconic species in a precarious state (Ripple et al., 2016). Taking action to safeguard them and their habitat has been at the forefront of conservation science since the 1980s. As Ehrlich (1988) pointed out, despite the increased efforts, the threat of species extinctions persists:

> *"…The primary cause of the decay of organic diversity is not direct human exploitation or malevolence but habitat destruction that inevitably results from the expansion of human populations. Many of the less cuddly, less spectacular organisms that humans are wiping out are more important to the future than most of the publicized endangered species…".*

> *"…People need plants and insects more than they need leopards and whales (which is not to denigrate values of the latter). Other organisms have provided humanity with the very basis of civilization in the form of crops, domestic animals, industrial products, and many important medicines. Nonetheless, the most important anthropocentric reason for preserving diversity is the role that microorganisms, plants, and animals play…".*

Preserving biodiversity should protect *all* organisms, not just large and small animals and plants (Ehrlich, 1988). Ecological science has proven how vital microorganisms (fungi, bacteria), small insects, worms, snails are for biological transformations. Preserving this biodiversity and soil health is part of conservation farming, organic agriculture and regenerative agriculture.

How much insects, pollinators, and birds depend on weeds has been studied by ecologists for decades. More than 60 years ago, John Harper (1958) used common ragwort (*Senecio jacobaea* L.) to explain how herbicide-based control of ragwort '*might affect all the organisms in the food chain*'.

In the last two decades, in the UK. and Western European countries, interest in weeds as vital components of biodiversity has been awakened. Ornithologists established that in most British farms, both weeds and farmland birds have declined (Siriwardena et al., 1998).

Losses accelerated towards the end of the 20th Century with intensive agriculture. The ornithologists called the current decline in farmland birds the *Second Silent Spring* (Krebs et al., 1999). Farmland birds and various invertebrates also decreased.

The main factors were monoculture farming, the introduction of new crops, changes in irrigation patterns and the sowing season and declines in the weed-rich winter crop stubbles on farmlands. Changes in cultural practices, such as the increased use of fertilizers, herbicides, and insecticides, were also responsible for declining many seed-eating farmland birds (Robinson and Sutherland, 2002).

In the UK, farmers are now encouraged to retain some crop residues (about 10%) and weed-rich stubbles as a resource for the higher trophic groups. The government-sponsored schemes promote farming to strike a balance between adequate weed control and biodiversity requirements so that the populations of farmland birds and pollinator bees may recover. The schemes do not downplay the importance of other good crop management practices, including preventing the build-up of soil seed banks of difficult weeds in farmlands (Marshall, 1988; 2002; Vickery et al., 2002).

The challenges in the new approach are related to managing some of y long-lived perennial species while sustaining beneficial, annual species at economically acceptable levels within a diverse farming landscape. Grass-killing herbicides are essential tools in meeting such challenges while leaving unharmed most broadleaf species.

As primary producers in any ecosystem, different plant parts provide a range of resources for animals. Leaves and stems may be browsed by insects; pollen and nectar are resources for pollinators. Stem, tree hollows, and barks provide shelter and organic matter as food and shelter for myriad organisms.

Plants are also vitally important as reproductive sites and for refuge. Pants offer environmental heterogeneity in space and time. These are exploited by macro-invertebrate animals and microorganisms.

Colonizing taxa may play some, or, perhaps, all of these roles. Some colonizers may even be 'keystone species', playing vital roles at specific locations. Keystone species maintain the local biodiversity of an ecosystem, influencing the abundance and types of other species in a given habitat, filling ecological niches that no other species can. Without them, an entire ecosystem could radically change. However, a keystone species in one environment may not be the same in another (Hillocks, 1998; Jordan and Vatovec, 2004).

Beneficial weeds

The term 'beneficial weeds' is not a misnomer. In the still-evolving discourse on biodiversity values of colonizing taxa, weeds are seen not as an insignificant part of the biological diversity of farming landscapes but as critical components. From a narrow frame of mind, retaining pioneering plants (commonly referred to as 'weeds' with the meaning they are 'undesirable') in and around farmlands to support biodiversity may seem unacceptable.

Doubters may even suggest that it would lead to the long-term build-up of problem weeds. However, decades of weed research show that human-disturbed agricultural environments are not 'weed-free' and should not be. If one or more pioneer species becomes a specific problem, we have various cultural practices well developed within integrated weed management (IWM) to manage them. One only has to look at organic agriculture to see how this is done.

Reconciling biodiversity and crop production will be necessary for sustainable farming. It must include ways to manage low populations of 'beneficial' weed species with little or no threat to crops. These species may only engage in low-level competition but have enormous potential value as a resource for higher trophic consumer groups, including humans.

The concept of beneficial weeds need not be limited to agriculture. It should apply to all colonizing taxa that provide ecosystem services and societal benefits outside agriculture.

In the UK, Marshall and co-workers identified a range of tolerable arable weeds with three primary attributes: (1) the number of insect species associated with them; (2) the number of and the importance of weed seeds in the diet of farmland birds; and (3) a competitive ability index. Their evaluation resulted in species, such as annual meadowgrass (*Poa annua* L.) and prostrate knotweed (*Polygonum aviculare* L.), as being more important for biodiversity in arable systems compared with species like blackgrass (*Alopecurus myosuroide*s Huds.) and speedwell (*Veronica persica* Poir) (Marshall, 1988; 2003).

Storkey's trait-based analysis added to this research theme, identifying beneficial weeds in British cropping fields. He focused on species, which were similar in the balance between their competitive ability and biodiversity value. This study identified two beneficial groups of weeds that could be managed to reconcile biodiversity and crop production (Storkey, 2006; Storkey and Westbury, 2007).

The first group included spring-germinating species- fathen (*Chenopodium album* L.), smartweed (*Persicaria maculosa* Gray) and prostrate knotweed. The second group of autumn-germinating species had both fathen and smartweed, and others- groundsel (*Senecio vulgaris* L.), meadowgrass and chickweed [*Stellaria media* (L.) Vill.]. Species in the latter group grow luxuriantly but well below the crop canopy, maturing early, avoiding crop competition late in the season. As a result, they utilized, in part, resources that the crop was unable to capture for its growth (Storkey, 2006; Storkey and Westbury, 2007).

The premise is that the total productivity of the system will be increased without potential waste, as the colonizing plants will decompose to return those resources. These plants may also conserve soil quality, prevent nutrient losses, increase the organic matter content and promote microbial transformations. Those with deeper roots relative to the co-occurring crops may also transfer nutrients from deeper soil layers, which are not captured by shallow-rooted crops.

Storkey's view (2015) is that a certain amount of non-competitive plant biomass can and should remain in cropping fields with hardly any crop yield losses. These would be "good weeds", referring to weed species combining a relatively low competitive ability with high importance for invertebrates and birds. In his view, beneficial weeds present a possible 'win-win' situation in farming, and some 'guilds' of weeds should be retained for biodiversity benefits.

It has been difficult for agriculturists in our region to promote research on the manifold benefits of biodiversity management in productive landscapes. This is primarily due to the market-based production models that require profits at any cost and lack of funding for ecological research into colonizing species and government interest. This area of opportunity, therefore, remains under-studied in many parts of the world, including the whole of the Asian-Pacific region and Australia.

In contrast, since around 2000, there has been a region-wide re-awakening in Western Europe to reconcile biodiversity with agriculture. The damage done by the overuse of pesticides used in agriculture has been the primary driver for requiring continent-wide changes. Concepts, such as 'land-sparing', 'wildlife-friendly farming', or 'farm-scaping', are a part of this new discourse (Phalan, 2018). Other countries and regions should begin complementary work.

Agriculture yields or biodiversity conservation? This dilemma often comes up when talking about food security and sustainability. Increasing farm yields to feed a growing population seems an objective at odds with conservation that aims to defend animal and plant biodiversity against the dangers of intensive farming.

Against this background, debates on how best to use the land and the need to feed the world have polarized in two different ways to manage the land: land sharing and land sparing. Both approaches accept the desirability of feeding the world's growing population. But the means of achieving the outcome differ. Both aim to simultaneously maintain the variety of species (biodiversity) and farming productivity.

Based on agro-ecology principles, the push from conservation biologists has been to recognize the value of 'land sparing' (high-yielding agriculture on a small land footprint) and 'land-sharing' (low-yielding, wildlife-friendly agriculture on a more extensive land footprint), both of which are expected to promote better outcomes for landscape-scale local, regional and global biodiversity (Phalan, 2018; Grass et al., 2019). Questions remain, though, whether such agriculture could meet the growing food demands of the ever-increasing human population.

The conservation-oriented, 'back-to-ecology basics' approaches aim to foster sustainable agriculture, compared with large-scale monocultures. Recent research proves the productivity benefits (higher crop yields) from farming lands, interspersed and surrounded by conserved vegetation remnants, woodland lots, and forests within the broader agricultural landscapes (Sousaa et al.,2019).

Within this framework, weed research must become more ecologically based, applied across agricultural and non-agricultural landscapes, instead of being just limited to 'paddock-based' simplistic, herbicide-based solutions to specific weeds or assemblages of weeds.

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Most weed research in the Asian-Pacific region and elsewhere is focused, with justification, on optimizing weed control in agriculture. But discussions on colonizing plants affecting agriculture must step out of agricultural landscapes into the broader catchments and environments disturbed by humans and other animals without abandoning the desirable goal of feeding all. In terms of their genetic makeup and botanical-ecological attributes, there is not much difference between weeds of agriculture (agrestals) and those that dominate waste places disturbed habitats (ruderals)

In the Asian-Pacific region, there is a heightened awareness of the need to manage weeds by integrating non-chemical methods, mainly because herbicides are too expensive for small-scale farmers. Holistic farmland biodiversity is not a significant concern for most struggling small-holder farmers. The lack of farmland biodiversity and ecological research in the Asian-Pacific region reflects this.

Admittedly, incorporating beneficial weeds into production systems as bio-resources is challenging. Collaborative research across countries and institutions would help, but it is not common. It seems that weed researchers are uneasy about writing proposals to study ecological values and roles of weeds partly for fear of rejection.

Another reason might be that the ecological language is still evolving and unfamiliar to most scientists, especially grant proposal evaluators. When a sub-theme, such as 'beneficial weeds', is still relatively new within weed science, it is challenging to draft compelling research proposals that have sufficient justification. Such work may also be seen as a significant, unacceptable diversion from what weed researchers are supposed to be doing (R. Zimdahl, *pers. comm*., Dec 2021).

Once convinced, perhaps, public support for potential societal benefits from colonizing taxa may drive the issue forward. Presently, it is quite a challenge for farmers in developed countries to concede that weeds have biodiversity values.

Selecting some beneficial weed species that farmers could tolerate in their fields to provide an ecological balance is a new idea among weed scientists. Ideas about beneficial weeds have been limited to those mainly used as medicines or eaten.

In many countries in the Asian-Pacific region, beneficial weedy species are usually fossicked from areas where people live. They are common in rural areas, in habitats associated with farmers' fields. Besides medicinal and edible species, future weed research should focus on other species that may provide ecosystem services: organic matter, soil health improvement, nutrient cycling and pollination.

Recognition of the beneficial effects of weeds, and therefore, tolerating them, is not new to traditional farming, including *'slash and burn'* agriculture and others like mixed-cropping. Ancient forms of agriculture are still practised widely by rural people across the globe. In '*slash and burn'* (called '*chena cultivation*' in Sri Lanka, or '*jhum cultivation'* in India), the vegetation of a relatively small area is cut down and burned to clear the land for cultivation.

In this farming, when cropping for a few years makes the plot 'less fertile', the farmer moves to a new area and does the same again. The used plot, helped by the fast-growing colonizing taxa, including the omnipresent grasses, recovers its vegetation and soil fertility over time. The critical factor is indeed – *time*. The longer the time left for recovery and replenishment, the better.

In 20-year *jhum* cycles, colonizing taxa act as the primary nutrient sinks, rapidly building biomass, taking up nutrients from deeper soil layers, and preventing losses in the disturbed plots. Subsequently, as this biomass decomposes, the stored nutrients return to the soil, conserving up to 20% of soil resources (Swamy and Ramakrishna, 1988; Ramakrishna, 1992).

From an ecological viewpoint, shifting cultivation is secondary plant succession. For those who practice this form of agriculture, saving energy is important. They consider weeds a Nature's blessing - an indicator of soil fertility, an invaluable resource and, occasionally, a minor nuisance (Paull, 2009; 2015). In this farming, the well established colonizing taxa are cut down, burnt, allowed to decompose, and recycled as sources of mineral nutrition for soil or used as fodder for animals. Shifting cultivation is still prevalent in many parts of rural South Asia, South-East Asia, Africa, and Central America.

One way to expand production and increase the returns is by intensifying farming in the existing croplands. 'Multiple cropping' is the growing of two or more crops within the same space. It can take the form of 'double-cropping' - a second crop planted immediately after harvesting the first crop (Borchers et al., 2014; Waha et al., 2020).

'Relay cropping' is another form where a second crop starts amid the first crop before its harvest. 'Mixed cropping' involves sowing several crops on the same plot. The 'mixture' would have various types of beans, tuber crops, grains and millets, harvestable at different times.

In the Asian-Pacific region, South and Central America and Africa, multiple cropping practices evolved out of agro-forestry, a land-use management system in which trees or shrubs are grown around or among crops or pastureland. In this farming practice, the aim is to optimize the resources available for plant growth, both vertically (access to sunlight with plants of different stature, grown in the mix) and horizontally (access to varying depths of soil resources with shallow- or deep-rooted plants).

Often, this type of agro-forestry farming and related alley- or avenue-cropping also draw on resources and ecosystem services provided by pollinators and other animals in undisturbed remnant vegetation nearby. These forms of poly-cultures are characterized by minimum tillage. They also rely heavily on large biomass-producing, fast-growing colonizing shrubs and trees, green leaf manure, mulching and shade for weed control. These multiple cropping practices hardly use herbicides to control weeds, in contrast with monocultures.

Ecological principles underpin multiple-cropping, agro-forestry and similar cropping practices. They combine species combinations that can both share and exploit available resources. For instance, many legume species will fix atmospheric N and enrich the soil, making this critical nutrient available to other species. Tuber crops and others with rhizomes and deep root growth will loosen compacted soil. The mixtures of plant species also leave behind nutritious residues that encourage different kinds of microflora, which degrade organic matter and promote other biological transformations in soil.

In established, traditional forms of agriculture, not all weeds can ever be fully controlled, nor do they have to be. Subsistence farmers do not clear large areas of vegetation for farming. They have a 'relaxed' attitude to weeds and never spend much energy on weed control. In many developing countries, women and children are the ones who often do 'weeding'. They can ill afford to spend energy on weeds.

Of the few well-studied cases, corn farmers in the lowland tropics of Tabasco, Mexico, leave some areas unweeded in their farms. The basis of this 'relaxed' weeding is a classification of non-crop plants according to their positive effects on soil. These include their benign effects on crops, soil tilth, and harbouring of beneficial insects. Accordingly, the Mexican farmers recognized 21 plants as 'bad weeds' (*mal monte*) and 20 as 'good weeds' (*buen monte*). This recognition allowed and tolerated moderate populations of the more desirable weeds that can serve as food, medicines, ceremonial materials, teas, soil improvers, etc., alongside crops while removing the more harmful species (Altieri, 1999).

The relevance of Agro-ecology approaches

In 1988, Altieri, along with Matt Liebman, laid out the conceptual framework for what we may call ecological weed management (Altieri and Leibman, 1988). Their book - *Weed Management in Agro-ecosystems: Ecological Approaches* - was a beacon of light within *Weed Science*, which was already crowded with books, dominated by content devoted to herbicide-led weed control.

The ecological weed research remained somewhat at the margins of the mainline herbicide-dominated *Weed Science* discourses for a while. But they are now at the centre of most discussions on current weed issues, including how to manage herbicide-resistant weeds, safeguard pollinators, reduce pollution due to herbicides and preserve biodiversity and multiple species interactions within ecosystems. Agro-ecology opened the door for weed scientists to think beyond herbicides and holistically approach weed management.

The new generation of weed researchers must start with agro-ecology. A key message in the landmark Altieri and Leibman (1988) book was for scientists to consider ways beneficial influences of weeds could be integrated into farming while controlling the problematic ones to the extent required, based on an ecological understanding.

Many of the chapters in the book showed how weeds could be better managed by integrated methods, with less reliance on herbicides.

The book promoted weed management to be approached as a form of plant population management. And to do this well, one must understand the biology and life cycle strategies of individual species, multiple interactions between species and the whole ecology of the system (Radosevich et al., 1997; Leibman et al., 2001).

In agro-ecology, the basic principle is to reduce intensive monoculture farming, which simplifies the agro-ecosystems and surrounding environments and encourage self-sustaining systems. Its ecological basis is the premise that complex interactions among organisms (i.e., biodiversity) regulate the sustainable and effective functioning of any ecosystem. In promoting these principles, Altieri's call (1999) that eliminating 'all weeds from the farm ecosystem is a bad idea' has reverberated through *Weed Science*.

The critical idea of agro-ecology is to go beyond alternative farming practices to develop agro-ecosystems with minimal dependence on high agrochemical and energy inputs. It consists of applying ecological science to the study, design and management of sustainable agro-ecosystems. In practice, it seeks to diversify farming systems to promote beneficial biological interactions and synergies among the agro-ecosystem components. These may allow for the regeneration of soil fertility, maintain productivity and crop protection.

Such principles of agro-ecology encompass (a) recycling of nutrients and energy on the farm, reducing external inputs; (b) enhancing soil organic matter and biological activity; (c) diversifying plant species and genetic resources in agro-ecosystems; and (d) integrating crops and livestock and optimizing interactions and productivity of the total farming system, rather than the yields of individual species.

Based on decades of research, Altieri (1999) opposed 100% 'weed-free' farming, practised in herbicide-based, monoculture agriculture. His view, backed by field research, is that such practices often destroy habitat for natural enemies of insect pests. In the end, 'weed-free' farming increases the costs for pest and disease control.

> *"…Sustainability and resilience are achieved by enhancing the complexity of farming systems via polycultures, rotations, agro-forestry, use of native seeds and local breeds of livestock, encouraging natural enemies of pests, using composts and green manure to enhance soil organic matter, thus improving soil biological activity and water retention capacity...".* Altieri (1999)

That plants play multiple and complex roles in ecosystems, influencing each other is undoubted. Functioning ecosystems do not care whether a species is native or exotic. Plants, including pioneer species, produce food for all primary and secondary consumers. It is those complex interactions between plants, animals and soil microbes that anchor essential ecosystem services that matter. Such interactions anchor nutrient recycling processes in soil and the breakdown of organic matter, mainly by microorganisms. Plants also regulate the microclimate of the agro-ecosystems. Their interactions suppress pest and pathogenic organisms and detoxify even pollutants in soil.

Weeds feature heavily in the agro-ecology discourses, as part of the sustainable food production systems, promoted as suitable for most developing countries to adopt. As another example, Altieri recorded how much the Tarahumara Indians of the Mexican Sierras depend on a range of edible weeds. Their food included amaranths (*Amaranthus* L. spp.), fathen (*Chenopodium* L. spp.), and several brassicaceous species (*Brassica* L. spp.), from April through July, before the maturing of traditional crops (maize, beans, cucurbits, and chillies). Bravely, Altieri stretched the argument further to say that: '*complete stamping out all weeds from arable fields could contribute to malnutrition in some societies*' (Altieri, 199; Altieri and Toledo, 2011. Maybe, he is right, at least in some situations.

For tribal communities, edible weeds are insurance against crop failure. Almost any weed serves as food for grazing animals when fodder is in short supply. Based on research, Altieri (1999) showed how *P'urhepecha Indians* in Mexico continually gather weeds for food, fodder, firewood, and other uses. Using weeds as bio-resources stem from long-standing cultural traditions of agriculture in those communities (Altieri and Toledo, 2011). Such practices are prevalent in Africa, South America, South Asia, and South-East Asia, too.

It is common knowledge that farmers from any country have a great deal of respect for weeds. Generally, all farmers know that weeds contribute organic matter, and their abundance improves the soil of arable lands. Some farmers also understand that the variety of plants on the surface is causally related to the diversity of microflora and earthworms in the ground and thriving weed communities contribute significantly to this diversity. Farmers also know that removing leguminous, nitrogen-fixing, fast-growing high biomass species (e.g., *Albizia* Duazz. spp., *Gliricidia* Kunth spp.) will reduce soil nitrogen.

Most traditional farmers understand the importance of a healthy groundcover of living plants for conserving soil moisture. They are also aware that any groundcover - weeds or not, would reduce soil erosion. Many farmers are also aware of the beneficial role of weeds in supporting butterflies, spiders, bees, dragonflies, ladybugs, and other insects and birdlife. Most farmers appreciate that animals sharing rural landscapes also need food and habitat to live. The idea of 'co-existence' with those inhabitants sharing some resources is not new in farming communities.

Farming in developing countries is essentially a subsistence economy, not monetarily profitable. But those who engage in farming are not inferior in knowledge. They carry a vital understanding of crops and the ability to produce food upon which our survival depends. These farmers, poor they may be, know how to mitigate weeds, pests, and diseases through crop rotation. They also know the importance of soil quality in producing healthy crops.

Separation of crops 'in time' and 'in space' are ancient practices. Growing crop mixtures of different life forms in the same patch of land ('inter-cropping') separate the crops physically in 'space'. Diversifying the resources available for different crop species leads to the suppression of weeds while supporting crops. In comparison to monoculture cropping, crop rotations and inter-cropping are vital strategies for concurrently managing soil fertility, reducing pests and diseases (by attracting natural predators of pests, and breaking disease and pest cycles).

The beneficial effects of crop rotations depend on the selection of crops. For example, a rotation of a legume crop, row-crop, tuber crop or cereal crop may sequentially offer the following benefits: (a) nitrogen fixation, thereby improving soil fertility; (b) breaking-up of soil, stimulating weed germination; (c) weed suppression due to smothering, and (d) addition of organic matter to the soil.

One may add to this list weed suppression achieved by high planting densities or depth of seeding and other cultural practices. Mixed cropping and different crops rotated in a system would promote weeds to germinate at various times but with fewer individuals per species. In contrast, continuous monocultures often lead to the development of locally-adapted, populations of weed, which can compete severely with the crop, as well as similarly adapted populations of pathogens and pests. Monoculture farming, of the industrial scale it is practised, is highly profitable. Still, it comes with a considerable cost to the environment, natural ecosystems and biodiversity.

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Diversity in organisms is one of the keys to rejuvenating the soil and farming landscapes. In many situations, to increase biodiversity within sustainable ecosystems, one may have to introduce species with specific characteristics that can perform essential functions. Such services include providing pollinators with nectar, insects and farmland birds with food, shelter, and other resources. Additionally, functionally diverse farmland vegetation should consist of various life-forms – trees with deep and spreading roots, shrubs, forbs, runners and woody or soft perennials. This is because different plant habits influence the soil differently.

Retaining soil from being eroded, either by wind or water; recycling both water and nutrients are other additional benefits fast-growing colonizing species bring to functioning ecosystems. Also, species with fast growth and large biomasses can recycle while adding degradable leaf litter and other organic matter to the soil (Altieri and Leibman, 1988; Altieri, 1999).

Moreover, in riverine ecosystems and floodplains, especially those associated with agricultural landscapes with irrigation canals, colonizing taxa play critical protective roles. They stabilize river and stream banks, prevent soil erosion and allow other slow-growing species the time required for establishment. It is in their nature to play an ecological guardianship and protector role. They do this simply by life cycle strategies, viz., how their populations occupy habitats, establish, grow, spread and thrive.

The lessons from agro-ecology are that where there is inadequate biological diversity in farming ecosystems, they may fail in the long run. In designing sustainable agro-ecosystems, it is vital to consider local factors. These include variations in climate, geography, soil types and their nutrient status, suitable crops, the existing local vegetation, including annual and perennial colonizers, pest complexes, etc. The interplay of such factors influences the development of beneficial organisms. A challenge is to select appropriate levels of inputs (i.e., fertilizers, pesticides, herbicides, and water regimes), which are influential factors.

In Table 1, I have summarized some of the most significant agro-ecological benefits of colonizing taxa. The specific benefits they provide depend on the botanical attributes of the species in question, such as how fast they grow, the total amounts of biomass produced, the extent of horizontal spread or vertical depths to which their root systems can reach, and the like. Apart from the species I have selectively given, there are many similar genera in different bio-geographical regions and continents, playing similar functional roles in different polycultures.

Monoculture cropping simplifies the farming environment. It 'homogenizes' landscapes and vegetation over vast areas and contributes to biodiversity losses. Agro-ecology has helped agriculturists in industrialized countries to realize the folly of this approach. Enormous profits derived from monoculture crops, such as wheat (*Triticum aestivum* L.), corn (*Zea mays* L.), cotton (*Gossypium hirsutum* L.), soybean [*Glycine max* (L.) Merr.], and sugar cane (*Saccharum officinarum* L.) ensure that they will not be discontinued anytime soon.

However, it is heartening that the mega-scale Western economies are now making significant efforts to regain and re-install biodiversity over large landscapes (Phalan et al., 2011). In the USA, many farmers and scientists are also exploring strategies to increase the vegetative cover in annual cash-crop fields. These include planting annual cover crops in a relay with cash crops, inter-seeding cover crops with cash crops, and developing perennial groundcover crops (PGCs) as an emerging technology to sustainably intensify agriculture (Schlautman et al., 2021).

Table 1 Agro-biological benefits from colonizing taxa in polycultures *

Categories	Observations
All colonizing taxa, including agricultural (agrestal) or ruderal weeds (in disturbed and unused or waste places)	• Weeds can reduce soil erosion, recycle nutrients from deeper soil layers, increase organic matter, improve nitrogen levels and conserve soil moisture.
Perennial Grasses – e.g., cogongrass (*Imperata cylindrica*), torpedograss (*Panicum repens*), Bermudagrass (*Cynodon dactylon*); elephant grass (*Pennisetum purpureum*); Guineagrass (*Megathyrsus maximus*)	• Colonizing grasses with rhizomes can penetrate soils deeply. They recycle nutrients and retain moisture. Their biomass accumulation prevents nutrient losses. • Perennial grasses improve soil through structural effects and chemical changes through exudates. Some exudates nurture soil microbes.
Cover-crops – e,g., kudzu (*Pueraria phaseoloides*), 'stylo' (*Stylosanthes gracilis*), 'calapo' (*Calapogonium mucunoides*), 'hyacinth bean' (*Dolichos lablab*), Singapore daisy (*Sphagneticola triloba*);	• Many cover crops are fast-growing colonizers. Some are widely used in plantation agriculture (tea, rubber, coconut) and horticultural crops (orchards and vineyards) as permanent 'living mulches'. • They provide ecological diversity and stability, habitat for beneficial insects, activate soil biology, organic matter and modify the microclimate. • Legumes fix nitrogen. Many species are prolific seed producers. However, their extensive growth is vegetative.
Wind-breaks, hedgerows, shelter-belts, living fences and shade-trees – e.g., willows (*Salix* spp.), boxthorn (*Lycium ferrocissimum*), briar rose (*Rosa rubiginosa*), gliricidia (*Gliricidia maculata*), prickly acacia (*Acacia nilotica*)	• Colonizing taxa, used in agricultural landscapes as windbreaks, shelter-belts, shade trees and living fences, improve the local climate and provide habitat for wildlife and beneficial insects. • The species grow fast, providing food sources, organic matter and resources for pollinating animals. • They also prevent soil erosion by wind and water. • They modify wind speeds and microclimates around cropped fields. They allow organisms to circulate across large agricultural landscapes. Willows protect river banks and floodplains from erosion.

* Sources: Karlan and Rice, 2015; NAS, 2017; Miner et al., 2020; Schlautman et al., 2021

It is important is to note the vital elements of colonizing taxa in these roles. Once established, colonizers spread, extending and increasing regional biodiversity. Managing biodiversity for ecological benefits ('farm-scaping') can easily be implemented at the 'on-farm' scale. Wind-breaks, living fences, hedgerows and undisturbed vegetated strips can serve as habitat refuges or *'biological corridors'* or *'ecological compensation areas'* around farmlands and associated landscapes.

Colonizing species are nearly always robust, sturdy, and fast-growers. When sheltered until established, their populations will increase, allowing beneficial organisms to disperse, circulating biodiversity across vast landscapes (Jordan and Vatovec, 2004). However, they need to be managed within cropping systems to derive benefits (NAS, 2017; Schlautman et al., 2021).

If assembled correctly in time and space, colonizing taxa, and their robust stands, would provide food, shelter, and nesting sites for diverse fauna and organic matter for detrivorous fauna and microbes. Their flowers will be resources for pollinating bees and other nectivorous insects. While improving habitat for wildlife, they will also promote interactions between a diversity of beneficial insects and soil microflora. Their roots will also hold soil in place, preventing erosion.

Cover crops are almost universally strongly colonizing fast-growing species. Their roles are well recognized in the healthy soil discourses because of multi-faceted ecological benefits. Strongly-colonizing over crops could be seen by some farmers as a bother that can harm marketable crop yields.

The growth of cover crops and subsequent incorporation of their biomass usually improve the health of the soil. The soil incorporation involves mechanical methods, which disturb the soil. As a result, crop yield outcomes of soil health practices with cover crops show considerable variations across different countries (NAS, 2017). The positive effects depend on how well these are incorporated into the cropping systems (Schlautman et al., 2021).

The use of various legume and non-legume cover crops in plantation crops (i.e., tea, rubber, coconut and citrus fruits) is well established in the Asian-Pacific region. Increased crop yields depend on how well the growers manage the annual and perennial cover crops and deal with robust species.

Crop rotation, climate, growing season length, tillage, soil type, the species, the timing and method of termination, and how long a cover crop is grown are all critical factors (Miner et al., 2020). The general know-how to manage these factors in good farming is well established. However, practical applications will depend on the specific cropping system.

Thankfully, regenerating soil health in agricultural landscapes is being discussed once again in responding to the current crises concerning food shortages. Regenerative agriculture is based on healthy soils, the foundation of thriving ecosystems and societies (Karlan and Rice, 2015). They are directly tied to food and nutritional security, water quality, human health, climate change mitigation and adaptation, and biodiversity.

Organic farming and permaculture

Agro-ecology principles are embedded in the organic farming and permaculture approaches, two counter-culture movements of the 20th Century. These 'eco-friendly' farming practices emphasize maintaining soil health, reducing erosion, conserving water, biodiversity, landscape and ecological functionality. They are designed to make agriculture sustainable. Both recognize the critical ecological roles of the annual and perennial colonizer.

Organic agriculture refers explicitly to a farming system that enhances soil fertility through the efficient use of local resources (recycling of organic matter) while foregoing pesticides, herbicides and mineral fertilizers. The organic farming movement first appeared in Europe in the 1920s and in the USA in the 1940s, representing farmers and citizens refusing agrochemicals and willing to persevere with traditional practices (Kuepper, 2010).

Crop residue management, animal wastes and 'green' manure, tillage for weed control and soil incorporation of organic matter are vital components. The organic farming movement is now quite strong with international representatives, although it is globally, still small [5].

Permaculture originated from the *Landcare* movements in the 1970s, which advocated '*working with rather than against Nature*' [6]. Permaculture emphasizes management designs that integrate the elements in a landscape and consider the landscape's evolution. In this approach, there is a significant role for trees, perennial plants and fast-growing species to stabilize degraded, human-modified lands (Mollison and Holmgren,1978).

In a sense, permaculture is a large-scale revegetation strategy. Its ultimate aim is to aid self-reliance through productive and sustainable gardens and farms, including producing food locally with minimal outside inputs, creating healthy ecosystems, building soil, constructing housing based on local, renewable resources, ending pollution, erosion and degradation of landscapes. Permaculturists view every plant as useful. Colonizing species are no exception. An often-used slogan in the movement is '*one person's weed is another's medicine or building material*' (Mollison and Holmgren, 1978).

Although the number of people committed to the austere lifestyle promoted by the permaculture movement is still minuscule, its attitudes, favouring sustainable land-use thinking, resonate with the view that plant resources should not be devalued.

Organic farming and permaculture's noble goals are improved sustainable systems, which operate 'in tune' with the local biodiversity. To be more broadly accepted and adopted, these approaches need to meet landholders' and farmers' aspirations. They also must meet the broader environmental, socio-economic and political agendas of governments.

What is important is that these movements appreciate the value of weeds in their landscapes much more clearly than conventional agriculture. They acknowledge that weeds <u>*do*</u> cost in terms of labour (time and energy) to manage them. Still, they equally appreciate weeds as a vital part of nature.

Permaculturists recognize that weeds begin the succession process in vacant areas, playing essential roles. The weed cover reduces erosion, absorbs, conserves and drives nutrient recycling while providing edible food, medicinal herbs and valuable habitat for beneficial animals.

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Given the multiple interactions between weeds, other pests or diseases, and ecosystem service providers, it is clear that weed control studies cannot occur in isolation from various aspects of biodiversity. Weeds need to be considered along with other biological components of any ecosystem – man-

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[5] The *International Federation of Organic Agriculture Movements* (IFOAM) is based in Bonn, Germany (**http://www.ifoam.org/**).

[6] Permaculture founders - Bill Mollison and David Holmgren, in their 1978 book *Permaculture One: A Perennial Agriculture for Human Settlements,* coined the term 'permaculture' a contraction of "permanent agriculture" (Mollison and Holmgren,1978).

modified and perpetually disturbed, agricultural ecosystems or otherwise, and the broader catchment areas in which human population pressure disrupts ecological systems (Franco, 2013).

The focus of future agro-ecological research should be to prove the beneficial roles of colonizing taxa and their interactions with other biotic components of the agricultural system. The latter include pollinators, insect pests, and plant pathogens associated with crops. One only needs to observe varied insects visiting the small but pretty flowers of different weeds to realize their importance.

In this regard, ecological systems design is somewhat more advanced away from agriculture. In many modern 'eco-friendly' urban living systems designs, many colourful colonizing taxa are incorporated well by landscape architects. Many cities now boast such urban designs with various types of perennial grasses, sedges and fast-growing broadleaf species. Once established, they all play critical ecologically stabilizing roles in newly-created urban settings. They also look after themselves as stress-tolerant and hardy plants.

With the increasing recognition of biodiversity values of weeds in farming, semi-rural and urban landscapes (Davis et al., 2012), relevant questions are: *Which weeds to control? And which ones to live with?* They can only be answered by directing more weed research towards ecological questions. This requires emerging from our silos.

The most critical ones are entomology (studies of insects and other arthropods - such as spiders, earthworms, and snails), plant pathology (study of plant diseases caused by fungi, bacteria, viruses, protozoa, nematodes, and parasitic plants) and ecological restoration of land and water resources.

Such a multi-disciplinary approach to weed research was what the discipline's founders wanted more than 70 years ago. They expected that entomologists would find and manipulate insects for biological weed control. Similarly, plant pathologists were encouraged to look for pathogens that could be developed to suppress weeds (Harper, 1960).

Indeed, successful biological control of specific weeds has been a significant contribution of *Weed Science* to agriculture. There are direct spin-offs of this science and technologies to managing other crop pests (Norris and Kogan, 2000; Capinera, 2005; Wisler and Norris, 2005).

Weed diversity and a 'Middle-Way' Path to manage weeds

In a recent paper, Storkey and Neve (2018) asked: *what good is weed diversity*? They asserted that regardless of how weeds are perceived, ecological principles should underpin the approaches to managing weeds. This argument is not new; it has been made for several decades but with little impact.

In agricultural landscapes, Storkey and Neve (2018) suggest that farmers tolerate and retain a more diverse weed community, which will be less competitive and less prone to be dominated by the evolving, herbicide-resistant species. More research will be needed to prove this and develop ways to put this theory into practice.

When the discourses are hijacked by the proponents of herbicide-tolerant crops and those who sell robotics and drones for herbicide spraying, even in developing countries, it is difficult to bring about such changes towards ecological weed research.

Ecology has shown us that large-scale monoculture-cropping, practised in many countries, homogenize agricultural landscapes. The result has been to reduce diversity and the resilience of cropping systems, allowing the build-up of highly adapted, herbicide-resistant weeds. Suggesting weed diversity could be essential in making future agriculture more sustainable, Storkey and Neve (2018) optimistically wrote:

> *"…As weed biologists…whose research focuses on environmental and production endpoints respectively, we are convinced that the loss of weed diversity and the escalation of resistance to herbicides are mediated by an identical underlying cause: the simplification of agro-ecosystems and their associated weed management strategies...".*
>
> *"…Given this, we propose that the goals of designing weed management systems that maximize production and maintain ecosystem functioning are entirely compatible and mutually reinforcing. We would, therefore, echo the call made by Fernandez-Quintanilla et al. (2008) and Jordan and Davis (2015) for weed scientists to integrate their work within the transdisciplinary framework required to meet the challenge of sustainable intensification and the transformation of cropping systems…."*

"…In so doing, we would move weed science from being a parochial discipline towards an integral part of a broader research effort focused on transforming the current, flawed paradigm of modern intensive agriculture...".

These efforts to re-align the discipline towards recognizing the beneficial roles of colonizing taxa in the agro-ecosystems are commendable. However, against those profits of the industrialized, intensive, monoculture agriculture, it is challenging to revert to less-intensive farming practices. Creating biologically diverse landscapes and tolerating some colonizing species for biodiversity values is even more challenging. Farmers are notoriously resistant to change and want quick profits.

The ecological knowledge we have is that within biologically diverse systems, weed management would be *less challenging*. There will also be increased pest regulation through natural control of plant pests and reduced incidences of plant diseases. Diversified farming also achieves optimal nutrient recycling through diverse soil biota. The design of sustainable farming systems that would satisfy everyone, not just humans, but also other stakeholders – plants and animals and Mother Earth remains the central challenge.

In agriculture, a return to diversified farming, including organic farming, should lead to healthier crops, sustainable yields, energy conservation, and less dependence on external inputs (such as herbicides, other pesticides, and synthetic fertilizers). However, the wide-scale adoption of such approaches will depend on weed scientists and ecologists collaborating with others to demonstrate the synergies of biodiversity conservation and the economic profitability of farming.

It must be emphasized that managing weeds with sustainable approaches is only one part of the solution. A starting assumption should be that weeds have beneficial biodiversity values worthy of preserving. European researchers are moving fast in this direction, changing how farming is done in the 21st Century. Much is anticipated from research over the next decade on cultural practices that can control damaging levels of weed infestations while maintaining cohorts of beneficial weed species. Herbicides are not entirely excluded in these approaches as they are vital management tools.

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In promoting a '*middle-way*' approach to managing agricultural weeds, in 2015, Nicholas Jordan and Adam Davis promoted a new conceptual framework, which they termed '*net agro-ecosystem aggradation*'. They wrote as follows:

"…Sustainable intensification is a widely shared idealistic vision for agriculture, in which production and other ecosystem services jointly increase to meet the future needs of humanity and the biosphere. Realizing this vision will require an outcome-driven approach that draws on all available practices and technologies to design agro-ecosystems that negotiate the difficult trade-offs associated with reconciling sustainability with production, economic, and environmental performance dimensions...".

"…To create "middle-way" strategies for sustainable intensification, we call for strongly trans-disciplinary research that coordinates integrative research among major streams of agriculture via ethical and philosophical orientation provided by purposive disciplines, such as applied ethics. Middle-way research partnerships can be strengthened by linking outcomes to mutually agreeable goals, such as net agro-ecosystem aggradation…". Jordan and Davis (2015)

The "*middle way*" is a Buddhist and Aristotelian notion of living and doing things in 'moderation' without going into the two extremes [7].

Jordan and Davis explained that a *middle way* philosophy would allow researchers to explore 'inclusive pathways' toward sustainable intensification of farming, considering many factors, including weeds, as well as herbicides (to a much lesser extent) that polarize people's opinions. It is easy to agree with their viewpoint. But *how can this approach be used in managing weeds?*

The term Jordan and Davis (2015) favoured- "*Agro-ecosystem aggradation*" – refers to the accumulation of "resource stocks" or "capital" over some time. It includes the sum total of biophysical, human, and social resources needed to provide ecosystem services identified as 'valuable' by stakeholders in any agro-ecosystem.

[7] Gautama Buddha (563-480 BC) preached 'the middle path' as the pathway to a peaceful way of life, balancing the extremes of religious asceticism, worldly self-indulgence and pleasure seeking. It was the pathway to sublime bliss – "Nirvana" - the end of suffering. Aristotle (384-322 BC) said that "virtue" is achieved by maintaining the 'golden mean', the balance between the two excesses. "Courage", for example, is a mean regarding the feeling of fear, between the deficiency of rashness (too little fear) and the excess of cowardice (too much fear). (**https://en.wikipedia.org/wiki/Golden_mean_(philosophy)**).

These "resource stocks" include the soil, water, local climate, biodiversity, beneficial microorganisms, insects and other fauna. The "capital" also includes preserving valuable ecosystem properties, such as soil regenerative capacity, efficient nutrient cycling, regulation of pest organisms, resilience to variable and extreme weather and various disturbances [8].

The '*middle way*' weed management systems, therefore, should aim to avoid going to any either extreme (i.e. conventional herbicide- and pesticide-based farming; or organic farming that relies heavily on soil disturbances, mechanical weed control and crop plant nutrients to be supplied from decomposing plant or animal manures).

Integrating methods from conventional, organic, and diversified production systems can achieve adequate yields and profits, produce other highly valued ecosystem services at sufficient levels, and drive 'net aggradation' of natural and human capital (Jordan and Davis, 2015). The authors suggested three design principles:

- Diversifying crops with contrasting phenology (life-cycle related), physiology, and management requirements, which would minimize selection pressure on weed communities resisting control in any given crop.
- Identifying management interventions based on 'in-field' knowledge of the weed community, gathered by field-based scouting, rather than on prophylactic treatments and cultural practices (i.e. clean-seeds, etc.).
- Implementing weed management techniques to manage the long-term population dynamics of specific species, or species assemblages, in the agro-ecosystem. The objective should be to reduce weed seed bank densities over time and not just the in-season weed biomass.

These design principles are in line with the basic IWM principles. Applied consistently, they can reduce the herbicide inputs significantly. A positive outcome would be reducing resistance development in weeds and pollution that the chemicals may cause.

The broader aim in weed management should be to achieve the task with fewer herbicides and lesser volumes. This can be achieved simply by better-targeted applications. Herbicides could 'tune' rather than drive any weed management system (Davis et al., 2012).

Identifying targets in space and time allows herbicide applications to supplement insufficient control of weeds by non-herbicidal methods. Judicious herbicide use can support other weed control tactics, such as biocontrol, competitive crops, cover crops, crop rotation, etc., usually applied under the banner of IWM.

Conservation agriculture is increasingly practised in the Asian-Pacific region. It is indeed a '*middle-way*' strategy. These combine cover crops, minimum tillage, crop residue management and crop rotations with reduced agrochemical inputs. The reduction of herbicide inputs is a crucial component. Such approaches seek complementarity among conventional, organic, and diversified farming systems.

The '*middle-way*' approach must be developed region-specific, field-specific and case-by-case. The focus in agro-ecosystem management should be on *all* components and not just on weeds. If the abundance of a specific colonizer is problematic in any system, the management strategy should implement integrated control methods.

These should not be harmful to other ecosystem components. Adaptive management is a crucial element. Economic sustainability, along with protection of the socio-cultural milieu and the health of ecosystems (soil, water, flora and fauna), must be essential considerations. Herbicides are not excluded in the '*middle-way*'. Still, they can be a valuable tool for managing specific problems in agro-ecosystems or others.

Ecologically friendly, agricultural diversification, managing soil, biodiversity and weeds, without compromising yields is not wishful thinking. This was proven in a recent study by Tamburini (Swedish University of Agricultural Sciences) and a team (Tamburini et al., 2020). The group conducted an international study comparing 42,000 examples of diversified and simplified agricultural practices.

Diversification practices included multiple crops in rotation. They also include planting flower strips, reducing tillage, cover crops and incorporating residues into the soil and establishing species-rich habitats in the landscape surrounding cropping fields. Crop yields were even increased under diversified practices. Enhanced biodiversity benefited pollination and pest regulation by natural predation. It also improved water regulation and preserved soil fertility.

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[8] 'Aggradation' is a term borrowed from geology and soil science. In Geology, it describes the increase in land elevation, typically, in a river system, due to the incremental deposition of sediments. Aggradation occurs in areas where sediment supply is greater than the material that the system can transport. See: **https://en.wikipedia.org/wiki/Aggradation**.

The evidence is compelling that instead of monocultures, diversification can reverse the negative impacts of simplified forms of cropping on the environment. However, there is no 'one-size-fits-all' (Tamburini et al., 2020).

Perhaps that critical message from agro-ecology, initially championed by Miguel Altieri and Matt Leibman (Altiery and Leibman, 1988; Altieri, 1999) and carried forward collectively by others (Altieri and Toledo, 2011; Davis et al., 2012) is finally heard. If correctly assembled in time and space, and it is a big *if* - biological diversity, of which weeds are a part, can make agro-ecosystems more sustainable.

Such systems can also be more productive. As agro-ecology has shown for at least three decades, these techniques must be locally fine-tuned to specific crops and regions. The target should maximize the ecological benefits from multiple species interactions, reducing inputs.

Much more investment is needed to support the adoption of diversified farming practices through research, incentives and extension programmes. A paradigm shift to a '*middle-way*' recognizes that weeds need not be considered a production constraint in agriculture and a threat to farming all the time. Sufficient knowledge is now available to design specific production systems using practices that support biodiversity.

The interplay between diverse organisms will repair agricultural landscapes in both structure and function. Such interactions between organisms will improve soil fertility, increase crop protection by regulating pests and pathogens. Along with the increased productivity, practices that support natural processes will diversify soil organisms, a seldom recognized crucial component.

In all of the above and protecting biodiversity, colonizing species have a role to play. Weedy species will contribute pollination benefits for bees and food for other insects (Altieri et al., 2015). Various fauna will use them as food and shelter resources. More importantly, weedy congeners (relatives) will promote the evolutionary diversification and genes for hybridization with their crop relatives. They will also be critically important for water retention and nutrient cycling, and replenishment. Such positive contributions indeed must offset, at least partially, the losses to biodiversity that people allege weedy species cause.

Biodiversity is too important to be ignored, misrepresented or misunderstood. Biodiversity is critically important for a healthy planet. Human survival on Planet Earth depends on properly interacting with biodiversity. This includes appreciating the crucial roles colonizing species play.

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PERSPECTIVE

ETHICS IN AGRICULTURE: WHERE ARE WE AND WHERE SHOULD WE BE GOING?

Robert L. Zimdahl and Thomas Holtzer[1]

[1] Professors Emeriti, Department of Agricultural Biology, Colorado State University, Fort Collins, CO 80523, USA

E-mail: **r.zimdahl@colostate.edu**

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Abstract

Agriculture's dominant focus is feeding the human population. From an ethical perspective, this is clearly very positive. Still, it does not absolve agriculture from critical and ethical examination of the totality of agriculture's effects. To earn the public's ongoing support, agriculture must be*gin regularly* examine its full range of effects and be sure they align with the highest ethical values. Agriculture's *productive* record is enviable in the science and technology associated with its primary ethical concern, but we need to do more to address the broader ethical issues that are the public's increasing concern. The entire agricultural community needs to become engaged in the discussion.

The classroom offers an effective starting place*, but* curricular offerings (focusing on ethical principles, agricultural applications, and expectations of agricultural professionals) are rarely available at public universities. *E*thics study should become a key component of agricultural education.

Keywords: Agriculture, classes, ethics, food system, survey, values

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Introduction

Agriculture, the essential human activity, is the most widespread human interaction with the environment and is central to human health and well being. We now live in a post-industrial information age. But no one will ever live in a post-agricultural world. Therefore, agriculture's sustainability and productive capability must be assured. Appropriately, the dominant focus of those involved in agriculture is how to achieve the moral obligation and challenge of feeding the human population, *projected to grow* to 10-12 billion by 2100.

However, many people throughout the world, in developed and developing countries, *are* concern*ed* about agriculture and our food system that have ethical dimensions beyond the central need to feed humanity.

Some of the most important concerns are:

- availability and use of surface and ground water,
- soil erosion,
- water pollution from excess fertilizer,
- loss of small farms and rural communities,
- pesticides in soil and food,
- the rise of corporate farming,
- the power and lack of transparency of agri-businesses and corporate food processors,
- nutritional value of foods provided to consumers by the food system,
- emission of greenhouse gases,
- cruelty to animals,
- known and unknown effects of biotechnology/GMOs,
- loss of crop genetic diversity,
- pollution from confined animal feeding operations, and
- exploitation and inhumane treatment of farm labour.

Figure 1 An image of vast scale monoculture farming reliant on herbicides and pesticides (Photo Credit: UCL, London, U.K.)[1]

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

From an ethical perspective, feeding the growing world population is clearly a very good thing. Still, it does not absolve the agricultural community from critical, ethical examination of the totality of agriculture's effects. We are obligated to consider broad ethical concerns and to examine the ethical values that guide us.

Largely because agriculture has succeeded in providing abundant food, the agricultural enterprise is generally viewed positively by the public. Ongoing public support is critical for the future.

To earn it, the public must trust the agricultural community to vigilantly examine the full range of the human and environmental effects mentioned above and to be taking actions assuring they align with the highest ethical values.

The future demands a new vision that supplies the energy and intellectual effort to create agricultural and ecological sustainability and moral certainty.

Scientific and technological *achievements* have been and will continue to be necessary to increase food production. But they are not sufficient to address the public's concerns.

Healthcare provides an instructive example. The healthcare system employs scientific understanding and advanced technology to improve human health and cure disease. Yet, the public expects healthcare professionals to embrace ethical standards that go far beyond the science and technology of their central moral focus. Our view is that healthcare professionals are acutely aware of these expectations and their obligation to meet them.

The agricultural community has an enviable record in science and technology associated with producing food. However, *more must be done* to address the broader ethical issues of concern to the public. What can our land grant and other public universities do within our missions of education, research, and outreach?

We in agriculture are not the only segments of land grant universities that face the need to address broader ethical issues – particularly as the public becomes more attentive to the ethical standards and behaviour of many once-trusted institutions and organizations. Our colleagues in business, engineering, and human and veterinary medicine also are affected by this reality. They have responded by integrating ethical considerations into their disciplines. Agriculture lags behind, and change is necessary across all aspects of our mission.

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[1] Image from UCL Nature & Conservation Society, London, U.K. (https://studentsunionucl.org/).

We cannot simply say: we are feeding the world, and that is enough. There is much to be done, and progress is not likely to be easy or rapid. But we need not be overwhelmed. Our research (Zimdahl, 2000, Zimdahl and Holtzer, 2016) suggests a place where we can make progress – the classroom.

Figure 2 The Agriculture Classroom is critical to discussing ethical issues in Agriculture (Image Credit: Colorado State University [2]

While curricula in business, engineering, and veterinary medicine (for example) typically include course work in professional and discipline-related ethics, our research on the prevalence of courses in agricultural ethics shows that similar course work (focusing on general ethical principles, applications of these principles to agricultural issues, and ethical expectations of agricultural professionals) is available at only a small minority of land grant and other public universities with agricultural offerings.

Our findings indicate that for the 73 institutions studied, such course offerings declined from 15 to 10 from 1999 to 2013. Since our 2016 publication, the Colorado State university course is no longer taught - thus, the total is now nine.

While we did not collect demographic information on students in these courses, we suspect from our own experience that the courses attract students widely from across their universities, but relatively few agriculture undergraduates participate.

We suggest this is because the College of Agriculture faculty who determine curricula and advise undergraduates do not regard studying ethics, and the ethical values demonstrated in agriculture as essential preparation for agricultural professionals.

Teaching a successful course in agricultural ethics requires commitments of faculty time and other resources. Unfortunately, there are few faculty members with both broad expertise in agricultural issues and in ethical theory.

In our experience, a good solution is a team approach with one or more participants from philosophy and agriculture who have some background in the complementary area. Critically important for the team is respect for the validity of the other members' perspectives and enthusiasm for learning about them.

One way for agriculturalists to gain knowledge about applied ethics is to participate in short courses. If workshops and short courses specifically targeting ethics applied to agriculture are not available, more broadly focused bioethics programs may be useful.

An essential ingredient for developing a successful agricultural ethics course is leadership at the faculty and administrative level.

Offering more courses in agricultural ethics and encouraging students to enrol will not alone quickly increase the overall emphasis on ethical considerations within the agricultural community. But that step will be an essential recognition of the need for agriculture to address its ethical dimensions and for the entire agricultural community to engage in the discussion. We urge taking that step.

Acknowledgements

We thank Dr. Nimal Chandrasena, the Editor-in-Chief of *WEEDS,* for pointing that our views may not have been much publicized in the Asian-Pacific Region and, therefore, deserves to be re-published. We concur and hope that our ideas would open up stimulating discussions in the Asian-Pacific Region and elsewhere.

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[2] Image from Colorado State University (**https:// economics.colostate.edu/wp-content/uploads/ sites/7/2021/02/05032_00087.jpg**).

OPINION

Climate Change: Confronting Invasive Species - Where to from here?

Florentine Singarayer [1,*] Talia Humphries[1], Amali Welgama[1], Jason Roberts[1]

[1]School of Science, Psychology and Sports, Federation University, Mt Helen Campus,

[*]E-mail: s.florentine@federation.edu.au

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Abstract

For the last two decades or so, concerned workers have been investigating the effects of climate change on invasive species and related agronomic issues. As researchers working in this space, we emphasize the importance for current research findings to be translated into practical, real-world management strategies that can be actioned by the end-users. This opinion article is offered as a contribution to this area. It attempts to illustrate the general direction and intensity that research work has taken concerning climate change and its relationship to the problem of invasive species. In addition, we discuss the likely nature of future research in this field. To provide a balanced overview of this activity, we consulted six key scientific Journals, which have consistently offered core articles related to this question. Although we recognized that a considerable amount of laboratory work and field-based research is taking place across the globe on climate change and invasive species, we have settled on 113 articles, which are directly relevant to this discussion.

We note that North American researchers have published most papers in this space since 1979. Several studies have indicated that under anticipated climate change conditions, many invasive species are more likely to grow faster and more extensive than agriculturally important crops, and their reproductive outputs may also significantly increase. If this finding reflects the general case for agronomic weeds of particular concern, then it is clear that extra caution will need to be taken with management strategies. Developmental work and an increased range of stakeholders will be required to reduce the burgeoning impacts of these species on economic, agricultural production. We encourage researchers to communicate more widely on the outcomes of their work and promote more collegiate engagement with the researchers in other parts of the world to share their knowledge and insights into efficient and effective management approaches.

Keywords: climate change; weed science; weeds; invasive species; crops; weed management

Introduction

The United Nations predicts the global human population is expected to reach between 8 and 10 billion by 2050 (Leridon, 2020). This will significantly increase the demand for food. It is anticipated that by 2050 we will need to at least double the current production output.

Consequently, our existing food production systems will come under extreme strain. Exacerbating the food supply problem, agricultural practices, in general, are already increasingly open to a series of concurrent and interacting disturbances. Issues such as deteriorating soil quality, the rising intensity of insect attacks and aggressive weed invasion, together with more frequent and severe flood and drought events, have already raised significant concerns for this essential industry.

Furthermore, in the last decade or so, sharp increases in atmospheric CO_2 levels, which have occasioned associated climate change conditions, have added additional pressure on crop productivity, increasing the vulnerability of farmers, food production systems and food suppliers.

It is essential that to alleviate the effects of the above pressures on the agricultural community, researchers need to provide some consolidated answers to problems facing crop production and management. In this brief Opinion article, we have initially examined research articles published in six key Agricultural Journals, which have addressed invasive pest and weed studies and agricultural issues related to climate change effects.

Whilst we do not intend this opinion piece to be an exhaustive literature review of the above issues, our objectives are: (i) to illustrate the general direction and intensity that research work has recently taken regarding climate change and its relationship to the problem of invasive species, and (ii) to subsequently highlight the nature of future required research.

In addition, we examined the relative publication rates from countries where the research has been conducted, to see if there is a particular focus on this issue.

Invasive species and climate change publications

Publication statistics

To provide a quantitative measure of the current work in this area, we searched six well-established and relevant English language scientific Journals for articles specifically addressing the effects of climate change on invasive plant species. The Journals were: *Weed Science*, *Weed Research, Biological Invasions, Journal of Ecology, Functional Ecology,* and *Oecologia*. The criteria used to determine the suitability of an article for entry into the listing were the paper specifically addressed the effects of climate change parameters on one or more invasive species. We only considered plant species and vegetation communities.

In the research articles examined, we included laboratory and field studies, reviews, computer modelling, or a combination of these investigations. We found a total of 113 relevant articles published in the six journals selected since 1979, with the majority (27) of the articles published in *Functional Ecology* (Figure 1).

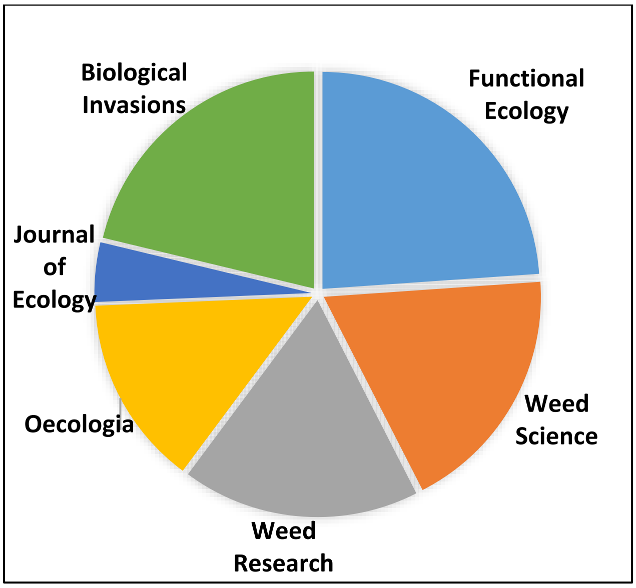

Figure 1. The proportion of articles published in selected journals that address the effect of climate change on invasive plants

Only *Weed Science* and *Oecologia* had published papers addressing this topic before 2000 (Figure 2). However, it is of interest that both *Weed Science* and *Oecologia* have significantly reduced the number of papers regarding the impact of climate change on invasive plants since the 1990s and 2000s. Indeed, *Oecologia* did not publish one relevant article between 2000 and 2009. *Weed Science* has evidenced a notable decline in publications related to climate change effects since 2010 (Figure 2).

We comment that, although global change ecology is listed as one of *Oecologia's* core focus areas, it appears that invasive species' research is not within their primary scope, and this could justify the reduced number of publications in this field.

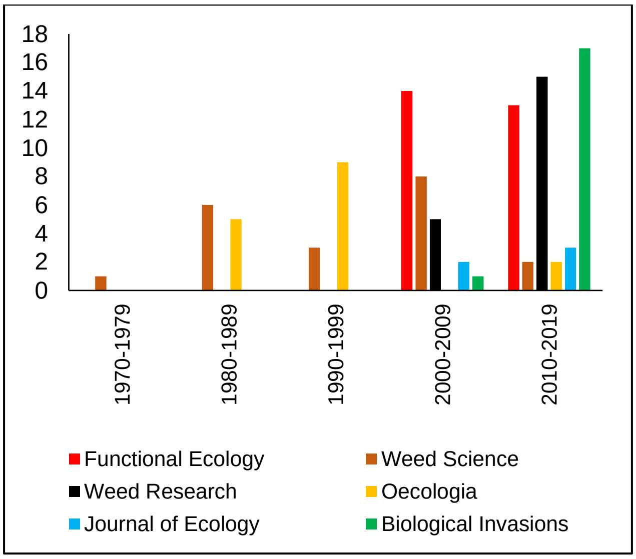

Figure 2. The total number of articles investigating the impacts of climate change on invasive species across each decade since 1971

In contrast, the other four journals have seen a significant increase in publications relevant to the effect of climate change on invasive plant species, particularly since 2000 (Figure 2).

In the last decade, *Biological Invasions* published 17 relevant papers, mainly modelling and simulation-based, addressing potential climate change effects. It is possible that other journals, such as *Weed Science,* are being selective in accepting articles, which may be argued as falling just beyond or outside their specific mandates.

Publication generators

Authors from North America contributed the most significant proportion of literature (59 articles), with the United States providing 56 (Figure 3). Almost all the articles pre-2000 were from North American authors. These studies appeared to have been published at a relatively consistent rate (Figure 4). We have deliberately excluded conference papers and book chapters from this analysis to focus on peer-reviewed material

Overall, approximately three-quarters of the research was conducted in either North America or Europe during the review period, suggesting that research outcomes and findings will be skewed towards invasive plants of the Northern Hemisphere. The most frequently observed studies conducted were those under controlled laboratory conditions (44 articles); however, studies that observed the effects of climate change *in situ* were also prominent (34 articles) (Figure 4).

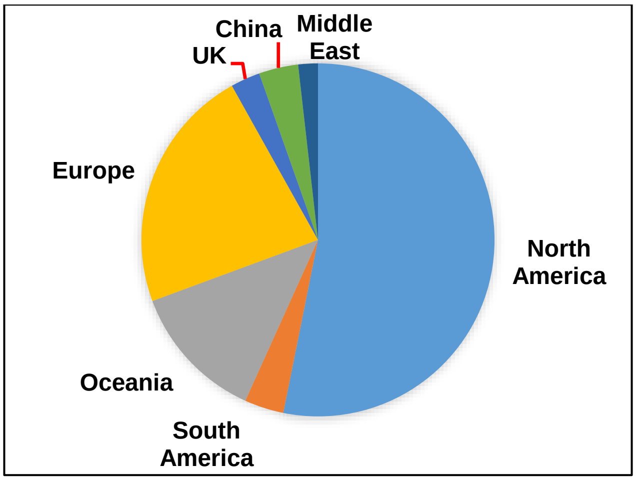

Figure 3. Published articles on Climate Change and invasive species in the six journals shown as a proportion of the originating region. The USA contributed the highest proportion of the research (56 articles)

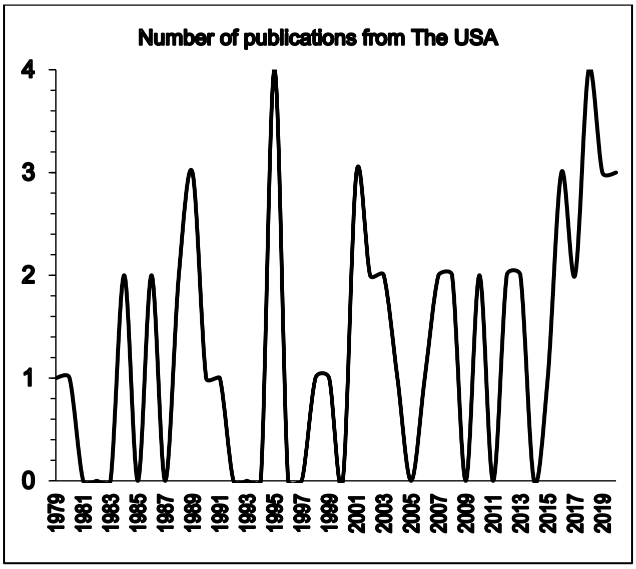

Figure 4. The number of publications produced in the USA was consistent from 1979 to 2020, with an average of 1.3 articles published per year.

Publication foci

Issues dominating these publications suggest that climate change will exacerbate the stresses on agriculture due to increased drought (Chirino et al., 2017). There will be a significant contribution to management difficulties reducing the efficacy of many herbicides when applied to control invasive plants (Waryszak et al., 2018).

It has been established that in many cases, under climate change conditions, exotic species are likely to grow faster and more extensive than crops (Valerio et al., 2013). Their reproductive outputs have also been observed to significantly increase (Bajwa et al., 2019). These changes are the basis of the anticipated increased future threat to agriculture and food security posed by invasive plant species under climate change scenarios. These transformations are also generally threatening ecosystems worldwide (Ziska et al., 2012).

However, given this context, it is surprising that only a relatively small number of studies, published in these leading Journals since the 1970s, specifically explore the effect of climate change on invasive plants.

If the bioclimatic envelopes are known for a target species, with the available preliminary biological research, computer modelling can predict potential changes in spread under different climate change scenarios such as warmer temperatures, drought, or high rainfall. All bioclimatic modelling research appears to have been conducted in Australia and New Zealand. While this method can predict changes in distribution as a response to selected environmental parameters, it does not consider all climatic variables and their interactions as effectively as laboratory or field-based experiments (Heikkinen et al., 2006).

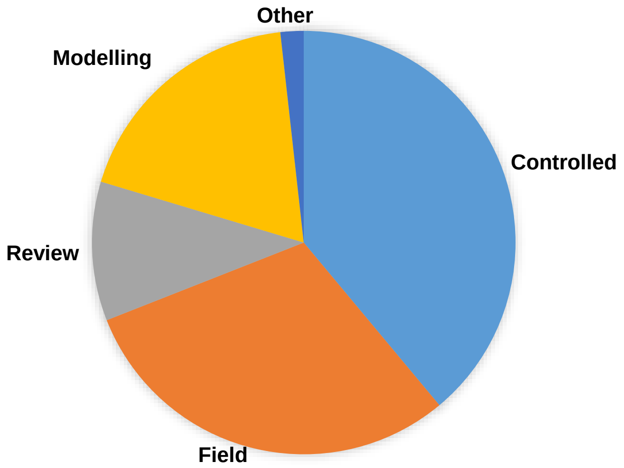

Figure 5. The proportion of the types of research articles published in the journals. The highest number of studies (44 papers) were conducted under controlled laboratory conditions

A reflection on research findings and management implications

Research findings to date suggest that the relationship between climate change effects and invasive plant species' consequences on crop outputs is a complex issue, primarily because of the varying responses of C_3 and C_4 plants to increased CO_2 levels. Publications suggest that under predicted elevated CO_2 levels, C_3 crops, such as soybean (Glycine max L.), rice (*Oryza sativa* L.) and wheat (*Triticum aestivum* L.), will be favoured with higher photosynthetic rates compared to C_4 weeds (e.g., waterhemp (*Amaranthus rudis* L.), Palmer amaranth (*A. palmeri* S. wats.) and kochia (*Kochia scoparia* L.) (Elmore and Paul, 1983).

However, C_3 weeds (lambsquarters (*Chenopodium album* L.), velvetleaf (*Abutilon theophrasti* Medik.), common ragweed (*Ambrosia artemisiifolia* L.) and giant ragweed (*Ambrosia trifda* L.) will also be favoured under elevated CO_2 levels, thus imposing severe competition on C_4 crops, such as corn (*Zea mays* L.), sorghum [*Glycine max* (L.) Merr.] and sugarcane (*Saccharum officinarum* L.) (Varanasi et al., 2016).

As a corollary of these reactions, any expected positive impacts of future climate changes on many C_3 crops are likely to be nullified by increased invasive species competition (Varanasi et al., 2016). In addition to this growth rate factor, weeds are expected to demonstrate improved survival mechanisms under predicted future climatic changes due to their high intraspecific genetic variation and physiological plasticity.

At the same time, the efficacy of commonly used herbicides is being significantly influenced by the predicted climate changes, since environmental factors such as temperature, soil moisture, and precipitation play a significant role in all phases of herbicide activity (Kudsk and Kristensen, 1992; Varanasi et al., 2016; Ziska, 2016). In light of these changes, the current consensus is that weed management strategies for all major crops, as well as general weed management, will have to be significantly altered in the future.

Increasing atmospheric CO_2 levels can either favour the crops or weeds in the same cropping area, depending on whether they are C_3 or C_4 species (Ziska et al., 1999).

In addition, under expected, more frequent and severe drought, deep-rooted (perennial) plants are predicted to be favoured (Storrie and Cook, 2007; Stratonovitch et al., 2012). This suggests that under these climate change parameters, perennial weeds could become a more significant management challenge in annual cropping systems (Rodenburg et al., 2011). Rodenburg et al. (2011) identified at least 26 invasive perennial species that will become a more significant threat to rice fields under projected climate change parameters.

To address the potential adverse effects of climate change on crops in the future, based on research to date, we suggest the implementation of a dual adaptive approach. The selection of crop cultivars with superior survival attributes is one such approach, where drought tolerance, heat-stress tolerance, weed-suppressing ability and allelopathy are key attributes (Varanasi et al., 2016).

For example, in a recent study, a competitive wheat genotype has shown that weed abundance and the amounts of herbicides applied can be reduced up to 50% by improved above-ground weed suppression (Travlos, 2012). Recent research has also focused on stimulating competitive and advanced allelopathy potential in crop weed suppression (Bertholdsson et al., 2012; Worthington and Reberg-Horton, 2013). The introduction of such advanced breeding programs to develop and release improved cultivars to overcome the future effects of climatic changes and weed competition is thus critical.

Again exemplifying the complex nature of this issue, our reading suggests that according to the meta-analysis conducted by Liu et al. (2017), native plant species will not respond in similar ways to climate changes as compared to invasive species.

The broad discrepancies in data indicate that while some may benefit by expanding their ranges, invasive plant species can also be helped or discouraged under global environmental changes. However, within the general ecological context, invasive plant species may benefit more from elevated temperature and atmospheric CO_2 levels compared to native plant species regardless of their carbon fixation pathway (Liu et al., 2017).

Authors have evaluated 74 and 117 invasive alien and native plants species, respectively, in the attempt to understand if alien plants benefit more from the global environmental change than native species. Liu et al. (2017) reported that elevated temperature and CO_2 enrichment enhanced the growth of invasive alien plants more than native species.

Our reading has indicated that despite the substantial number of research investigations conducted in the review period comparing native and invasive species' responses to a single climate effect, studies evaluating their responses to multiple co-occurring climate effects are scarce (Liu et al., 2017). Therefore, it is clear that future research must focus more on the basic biological studies evaluating the interactive effects of predicted climate changes of invasive species' responses.

Where to from here?

It is commonly agreed that climate change will significantly influence flora dynamics and interactions in both agricultural and native landscapes. It is expected that many invasive weeds, such as *Datura stramonium* L. (Ramesh et al., 2017) and *Cirsium arvense* L. (Ziska et al., 2011) are likely to undergo a more extensive range expansion in comparison to many agricultural weeds or native species (Chauhan et al., 2014). This is most likely because 'weedy' species have high genetic variability, an intensely competitive nature, and physiological plasticity (Wainwright and Cleland 2013).

Despite the current bioclimatic modelling providing helpful information on predicted species distribution, future research and modelling should consider how localized land use will change in response to climate change (Ramesh et al., 2017).

Such information will be critical for the future planning of agricultural and native landscapes. It will assist land managers in adapting and utilizing the most suitable species or cultivars for a given region. Selecting suitable crop species that will withstand or benefit from the driving pressures of climate change will reduce agricultural losses resulting from competing weeds (Bloomfield et al., 2006). To achieve this, however, future research should investigate further how several climate change scenarios, such as drought, elevated atmospheric CO_2 levels, floods and increased temperature, can influence land use and species interactions.

It is generally agreed that invasive plant species management is required to maximize global crop production. Whilst several studies have suggested that herbicide applications are the most common treatments to control invasive weeds around the world (Gianessi, 2013; McErlich and Boydston, 2014), problems are developing with this approach.

Evolution of herbicide resistance in weeds leading to significant economic losses to the sustainability of agriculture. This has now become a significant problem associated with the continuous use of herbicides (Mwendwa et al., 2020; Heap, 2021). Although there are clearly many positives in using herbicides, an increasing number of opinions hold that future research and management should carefully consider the impacts that climate change may have on the efficiency of chemical control.

In this respect, recent research suggests that certain herbicides may become less effective over time due to changing climatic conditions such as elevated atmospheric CO_2 levels, highly variable rainfall and increased temperature (Chauhan et al., 2014; Ziska and McConnell, 2016; Ziska, 2016).

In many cases, this increased tolerance can be attributed to improved metabolic efficiency, allowing the plant to rapidly translocate herbicide away from the treated leaf (Matzarif et al., 2019; Refatti et al., 2019). This increased tolerance has been repeatedly observed in glyphosate, one of the world's most commercially important herbicides, in species such as couch grass [*Elymus repens* (L.) Gould] (Ziska and Teasdale, 2000), barnyard grass [*Echinochloa colona* (L.) Link] (Mollaee et al., 2020) and Canadian fleabane [*Conyza canadensis* (L.) Cronquist] (Matzarif et al., 2019).

Indeed, such changes may result in specific 'modes of action' becoming less effective over time and result in a more substantial number of herbicide-resistant weeds (Loladze, 2014). This strongly suggests that future research should investigate and evaluate how herbicide applications may be altered under predicted climatic scenarios. We also recommend that future research be developed to examine a range of integrated management treatments (such as biological control, fire management and mechanical control) to help reduce the long-term economic and environmental impact of invasive weeds under predicted climatic scenarios (Bhat and Jan, 2010; Ramesh et al*.,* 2017).

As explored in this article, our view is climate change will exacerbate the stresses on agricultural and native species, thus favouring the domination of invading weeds. This situation clearly increases the pressure on land managers and researchers to develop new and improved approaches to combat what is likely the most challenging environmental topic of our generation. It is surprising that since 1979 only 113 relevant articles have been published in six key international Journals, most conducted in the Northern Hemisphere.

Further, it is also expected that several current management treatments, such as herbicide application, may become less effective over time due to plant mutations and adaptions to changing climatic conditions. In this respect, future research should investigate how changing climatic conditions influence land use and how this change may impact the interaction between agricultural, native and invasive species. This will help formulate a greater understanding of species interactions in response to future climate change and help to develop and maintain long-term sustainable land systems.

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PERSPECTIVE

Direct-Seeded Rice (DSR) in India: New opportunities for Rice Production and Weed management in post-COVID-19 pandemic period

N. T. Yaduraju[1], A. N. Rao [2], M. S. Bhullar[3], J. S. Gill[4] and R. K. Malik[5]

[1] Director (Retired), ICAR-Directorate of Weed Research (DWR), Mysore-570020, India

[2] Consultant Scientist (Weed Science), Hyderabad - 500033, India

[3, 4] Department of Agronomy, Punjab Agricultural University, Ludhiana, Punjab, India.

[5] International Maize & Wheat Improvement Centre (CIMMYT), NASC Complex, New Delhi 110012, India

Corresponding Author E-mail: **nyaduraju@gmail.com**

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Abstract

In India, rice is predominantly grown as puddled transplanted rice (PTR) under irrigated or assured rainfall conditions. The share of groundwater in net irrigated area, as compared to the area under surface irrigation, is more than 60% at present. The over-exploitation of groundwater through the explosion of tube wells has raised sustainability issues. India's Central Groundwater Board has warned of critically low groundwater availability by 2025.

Rice cultivation under PTR is labour and energy-intensive. The rising costs of labour and energy in India is making PTR less profitable. PTR is also not very environment-friendly due to its relatively higher methane emissions. Due to the above concerns, the shift of rice cultivation to direct-seeding (DSR) has been well researched and developed in India. The technology has also been actively promoted and disseminated for farmers to adopt across many Indian states.

The advantages of the DSR system can be obtained only by alleviating the significant constraints, including weed problems and issues related to crop nutrition. The research carried out at different agro-ecological conditions in India has amply proved that the adoption of improved DSR technologies results in several advantages over PTR. The benefits include savings in labour (40–45%), water (30–40%), fuel/energy (60–70%), and reductions in greenhouse gas emissions. In this paper, we briefly discuss the historical aspects of DSR in India, the advantages of DSR, the reasons for inadequate adoption of DSR during the pre-pandemic period, the farmers' adoption of DSR during the pandemic making the crisis an opportunity. We also discuss the potential and research/extension needs for further upscaling DSR in India during the post-pandemic period.

Keywords: Rice, Direct-seeded rice, Labor migration, COVID-19, Weed management

Introduction

Indian agriculture has made substantial progress in food grain production, increasing from 55 Mt in 1950-1951 to a new record of 308.65 Mt during 2020-2021. The robustness and resilience of Indian agriculture were amply reflected during the COVID-19 pandemic, with a positive growth of 3.4% in 2020-21, when growth in all the other sectors declined. The share of agriculture in the country's GDP, which showed a decreasing trend until 2019-20, increased from 17.8% in 2019-20 to 19.9% during 2020-21 (Government of India, 2021). This is a record in attainment in the past 17 years by agriculture within India's GDP.

. While India and the world were combating COVID-19, the Indian rice farmers in the north-west region saw an economic and resource use efficient opportunity during the crisis. They increased the area under direct-seeding of rice (DSR) as an appropriate rice establishment method. As the most popular staple food, rice provides food security to the majority of the Indian population.

India has the largest area under rice cultivation, 44.4 Mha, with a record production of 122 Mt during 2020-2021 (USDA, 2021). In India, rice is commonly grown by transplanting rice seedlings into the puddled soil (wet tillage) in lowlands (PTR).

Alternately, direct-seeding of rice (DSR) is done by (i) dry-seeding (dry-DSR), (ii) wet-seeding (wet-DSR), and (iii) water-seeding (water-DSR) (Rao et al., 2007; Kumar and Ladha 2011; Rao et al., 2017a). As the rice seeds are sown directly, the dry-, wet- and water-DSR methods are often collectively referred to as DSR. At present, 23% of the rice area is direct-seeded globally (Rao et al., 2007; 2017c).

Of these rice establishment methods, recently in several Asian countries, including India, dry-seeding (dry-DSR) has gained importance. The primary reasons are - it requires less irrigated water than other direct-seeding methods, and freshwater resources worldwide are declining year after year.

Dry-DSR (referred to in this paper as DSR from hereon) consists of sowing dry seeds on dry (unsaturated) soils. Seeds can be broadcasted, drilled, or dibbled. DSR production is practised traditionally in most Asian countries in rainfed upland ecosystems. In India, the upland rice is grown in 23 states, covering about 13% of the country's total rice area but contributing only 4% to the rice production (Singh et al., 2011).

Dry-DSR is also grown in irrigated areas with precise water control as aerobic rice. In certain states of India, farmers cultivate dry-DSR with the onset of monsoon and convert it to irrigated lowland rice after releasing the assured canal water in the system (Rao et al., 2015).

India's water resources

India has 18% of the world population, with only 4% of the world's freshwater. A whopping 80% is used in agriculture. India receives an average of 4,000 billion cubic meters of precipitation every year (Dhawan, 2017). Only 48% is used, and the rest flows into the oceans. Irrigation is the major contributor to increased food production in India, with more than 30% of global irrigated land (FAO, 2013).

The area under irrigation in India increased from 18.8% to 60.4% from 1951 to 2016 (Jain et al., 2019). The net irrigated area from different sources (canals, tanks, wells, and tube-wells and others) was around 68.38 Mha in 2015 (MOSPI, 2018). There has been a significant shift in the sources of irrigation (Jain et al., 2019). In 1950-51, the canal irrigated area was 8.3 Mha, and as of 2014-15, it stood at 16.18 Mha. The relative importance of canals has come down from 40% in 1951 to 24% in 2014-15.

On the other hand, the well and tube well accounted for 29% total irrigated area in 1950-51, and now they share 63% of the total irrigated area (Jain et al., 2019). This expansion reflects the reliability and higher irrigation efficiency of 70–80% in groundwater irrigation compared with 25–45% in canal irrigation. While proving to be a valuable source of irrigation expansion, injudicious utilization of groundwater through the explosion of tube wells has raised several sustainability issues.

The aquifers rapidly depleted across much of India because of high extraction rates. It is predicted to have critically low groundwater availability by 2025 (Central Groundwater Board, 2021; Rodell et al., 2009; Shah, 2009). India's total annual replenishable groundwater resource and net annual groundwater availability (AGWA) are around 433 billion m^3 and 398 billion m^3, respectively. Of the available groundwater, 230 billion m^3 is withdrawn annually (Dhawan, 2017).

A survey by the Central Groundwater Board (2021) indicated that around 39% of the wells show a decline in the groundwater level. Out of 6,607 assessment units in the country, in 15 States and two Union Territories,1,071 units have been categorized as "over-exploited" based on withdrawals and the long-term decline in the groundwater level. Aquifers in poor, densely populated regions, such as north-west India, are under maximum stress [1]

Rice, a low-water-use cereal, is the primary irrigated crop in India. The total area under irrigated rice in India is about 22 Mha, accounting for about 49.5% of the total area under rice crop in the country (RKMP.DRR, 2013). Thus, developing agronomic practices to reduce water use in rice is considered essential to minimize groundwater depletion in India.

In irrigated areas of India, rice is commonly established by transplanting seedlings in puddled soil. The method is resource-intensive (water, labour and energy), proving to be less economical as the needed resources become increasingly scarce and costly. In addition, the puddling and transplanting method of raising the rice crop deteriorates the physical properties of the soil. It adversely affects the establishment and performance of succeeding upland crops. More significant emission of greenhouse gasses (GHG) in PTR is another concern, considering its impact on climate change.

The years of research has shown that it is possible to get rice yields under DSR similar to PTR. The farmers in India have been exhorted for years to shift from puddled transplanting to dry-DSR in irrigated rice ecosystems because of the advantages mentioned above (Rao et al., 2015). However, despite efforts by various agencies, the shift has not happened at the desired pace.

This paper aims to discuss the historical aspects of DSR in India, the advantage of DSR, the reasons for lesser adoption of DSR during the pre-pandemic period, the farmers' adoption of DSR during the pandemic, which made the crisis an opportunity, and potential and research/extension needs for upscaling DSR in India during post-pandemic period.

Historical aspects of DSR in India

Dry direct-seeding is probably the oldest method of rice establishment. During the initial periods of rice domestication, rice was known to be dry sown as a mixed crop with other dryland crops under the shifting cultivation system, as per the historical accounts (Grigg, 1974). DSR continued to be the primary method of rice stand establishment for about six decades. It was replaced with PTR during the 1970s in most parts of the world (Pandey and Velasco, 2005).

With the expansion of area under irrigation, primarily through the construction of dams across rivers, farmers' first choice across the country has been to shift to PTR, as it offered higher productivity and profitability. DSR was practised during the early 1950s when rainfall was more uniform across crop seasons in the *Krishna* delta. However, this method lost its popularity due to new canal systems, which provided an assured water supply (Palanisami et al., 2014). With the abundant labour, water and land, farmers shifted to PTR under irrigated ecosystems.

The rapid shift to PTR was mainly due to the problem of weeds and the non-availability of cost-effective herbicides for controlling them in DSR. The introduction of high yielding, dwarf rice cultivars, tailored to respond to external inputs, also favoured the cultivation of PTR (Pandey and Velasco, 2005). However, in the 21st Century, the rapid decline in water resources and the scarcity of labour coupled with a sharp increase in wages are forcing farmers to shift towards DSR (Mortimer et al., 2005).

Employment data generated from National Sample Survey Office (NSSO) shows that the percentage of people employed in agriculture has been consistently declining in India, from around 60% in 1999-00 to 49% in 2011-12 (FICCI, 2015) and 41.49% in 2018-19 (data.worldbank.org). Between 2004-05 and 2011-12, there has been a net reduction of 30.57 million labour from the agricultural sector. This highlights the net migration of labourers from agriculture to other sectors.

DSR offers advantages, such as labour saving, faster and easier seeding, lower water requirements, greater drought tolerance, higher or similar yields, lower costs of production and increased profits. DSR also provides energy-saving opportunities and better soil physical conditions for the next crop (Balasubramanian and Hill, 2002), lower GHG emissions and resilience to climatic variations (Ladha et al., 2016; Chakraborty et al., 2017).

Flooded rice culture with puddling and transplanting is considered one of the significant sources of methane (CH_4) emissions. It accounts for 10-20% (50-100 Tg/year) of global annual methane (CH_4) emissions (Reiner and Aulakh, 2000). Methane emissions from the Indian rice fields were estimated

[1] NASA GRACE Satellite data; **http://www.jpl.nasa.gov/news/news.php?feature=4626**)

to be 3.6 ± 1.4 Tgy^{-1} (Ramachandra et al., 2015). Joshi et al. (2013) reported a 30-58% reduction in CH_4 emissions under DSR compared to PTR.

These advantages notwithstanding, several production constraints are encountered in DSR in which heavy weed infestation is the major one (Rao and Nagamani, 2007; Rao et al., 2007; Rao and Ladha, 2011; Shekhawat et al., 2020).

Development of weed management technologies for DSR in India

The success of DSR lies in the effective management of weeds. DSR crop is exposed to a more diverse and competitive weed flora than PTR. It is reported that 136 weed species belonging to 82 genera are associated with DSR in India (Rao and Nagamani, 2007). Further, both the crop and the weeds emerge together. It is often difficult to differentiate between rice plants and the grass weeds (like *Echinochloa* spp.) in the initial stages (Rao, 2021). During the earlier years of DSR adoption in Punjab, typical rice weeds, such as

Echinochloa crus-galli (L.) Beauv, *E. colona* (L.) Link, *Cyperus iria* L., and *C. difformis* L., dominated the weed flora. But after more than two years of continuous adoption, Bhullar et al. (2018) recorded a shift towards aerobic grasses, such as *Dactyloctenium aegyptium* (L.) Willd., *Leptochloa chinensis* (L.) Nees and the perennial sedge *Cyperus rotundus* L.

In DSR, the competition by weeds for growth factors is very intense. Failure to control weeds in time results in low rice yields and may even lead to total crop failure (Rao et al., 2007). The extent of weed competition depends on the type of weed species, density, and cultural practices farmers follow. The critical weed-free period in DSR ranges from 11.8 to 83.2 days after sowing, which is longer than PTR (Singh et al., 2014); higher weed pressure increases the duration of the critical period.

Timely weed control is therefore crucial in improving the productivity of DSR. Both indirect (preventative) and direct techniques are employed for managing the weeds. Some of the indirect methods include tillage (Singh et al., 2015), cultivars (Mahajan et al., 2014), manipulating the seeding rate (Mahajan et al., 2010; Ramesh et al., 2017) and nutrient management (Hemalatha et al., 2020).

Other indirect methods include intercropping (Singh et al., 2007; Joshi et al., 2019), brown manuring (Singh et al., 2007), cover cropping (Singh et al., 2015), mulching (Yadav et al., 2018), live mulches (Singh and Kumar, 2020), weed control through solarisation (Khan et al., 2003), manipulating water regimes (Singh and Tewari, 2005) and establishing conservation agriculture cropping systems (Baghel et al., 2020).

The direct weed control techniques in DSR include manual and mechanical methods and herbicide use (Rao and Nagamani, 2007; Rao et al., 2014a; Rao and Chauhan, 2015; Chandra et al., 2020). However, it is widely acknowledged that in DSR, no single approach will address weed problems satisfactorily. An integrated approach involving two or more methods, preferably with an understanding of the biology and ecology of weeds, is likely to provide effective and sustainable solutions to weed problems (Singh, 2005; Rao and Nagamani, 2010; Rao et al., 2017a, c; Chandra et al., 2020).

Manual weeding is the predominant method of weed control practised by the majority of the farmers in India. In the case of rice, over 20% of the total labour requirement is required for weeding operations (FICCI, 2015). It involves hard labour and is gender-biased as weeding is mainly carried out by women. The efficiency of the work is often lowered by hot and humid weather during the rainy season. Multiple studies have shown that herbicides are an effective way to reduce the dependency on labour.

Herbicides are cost-effective in DSR and often increase crop yields. Hand weeding is about 4-5 times more expensive than herbicides, especially as labour is scarce and costly (Rao et al., 2007; Rao and Nagamani, 2007; Rao and Chauhan, 2015).

As DSR fields are characterized by floristically diverse weed communities (Rao et al., 2007), a single herbicide fails to provide effective and season-long weed control of all weeds (Khaliq and Matloob, 2011). The integration of pre-and post-emergence herbicide application decreased rice yield loss by 23-27% compared with pre-emergence herbicide only (Bhullar et al., 2016).

Singh et al. (2015) reported a 14-27% lower rice yield with pendimethalin followed by bispyribac-sodium than the weed-free check. They attributed this loss to the biomass build-up by weeds that escaped the herbicides. Sequential applications of pendimethalin and bispyribac-sodium effectively controlled *Echinochloa* sp. and *Digitaria sanguinalis*

(L.) Scop. while poorly managing *Eragrostis* sp. and *L. chinensis* (Brar and Bhullar, 2012).

Azimsulfuron and ethoxysulfuron controlled a wide range of broad-leaved weeds and sedges (Walia et al., 2008). Tank-mixture application of fenoxaprop-ethyl and ethoxysulfuron enhanced the efficacy of fenoxaprop-ethyl against *L. chinensis* and *Digitaria ciliaris* (Retz.) Koeler. In addition, Chauhan and Abugho (2012) reported that tank mixing of cyhalofop-butyl - with penoxsulam enhanced cyhalofop-butyl's efficacy against *L. chinensis*.

Tank mixing of fenoxaprop-ethyl with ethoxysulfuron improved the control of *E. crus-galli* and *E. colona* by 43-69%. Mixing it with azimsulfuron was antagonistic and reduced the control of *L. chinensis* by 86%. Tank mixing fenoxaprop-ethyl with bispyribac-sodium was also antagonistic. The mixture performed poorly against the grasses *D. aegyptium*, *Acrachne racemosa* (B. Heyne ex Roem. & Schult.) Ohwi and *L. chinensis,* compared to fenoxaprop-ethyl alone (Bhullar et al., 2016).

New herbicide molecules, such as florpyrauxifen-benzyl + cyhalofop-butyl at 25 + 125 g/ha (Mounisha and Menon, 2020; Wright et al., 2021), performed well in controlling the diverse weed flora in DSR. No antagonism was observed when florpyrauxifen-benzyl was tank-mixed with systemic herbicides like 2,4-D, bispyribac-sodium, cyhalofop-butyl, fenoxaprop-ethyl, halosulfuron, imazethapyr, penoxsulam, quinclorac, and triclopyr (Miller and Norsworthy, 2018). The herbicides used in DSR in India are summarised in Table 1.

The delay in weed emergence relative to the crop should be a fundamental principle in weed management strategies (Chauhan and Johnson, 2010). This may be achieved by management practices, such as herbicide application or mechanical cultivation that kill a cohort of weeds or reduce their growth. When the germination of *Echinochloa* spp. was delayed relative to that of rice, weed survival and rice yield losses were significantly decreased (Gibson et al., 2002).

Stale seedbed preparation is yet another effective way to control weeds in DSR. A light pre-sowing irrigation encourages weed seed germination. Such weeds are controlled either with shallow cultivation or application of a non-selective herbicide. The combination of stale seedbed with tillage, pendimethalin and bispyribac-sodium provided the highest DSR grain yield (7.3 t/ha) (Singh et al., 2018). The stale seedbed decreased the viable seed bank of *E. colona* and *D. aegyptium* by 25-30%. Singh et al. (2015) suggested that conservation practices, such as zero tillage and cover cropping, alongside herbicides, could form an essential component of integrated weed management in DSR.

An innovative approach popularly referred to as "Brown Manuring" could be used for weed management in DSR (Singh et al., 2007). Here, the rice and the popular green manuring crop *Sesbania* are planted together. The crop is sprayed with 2,4-D at 0.5 kg/ha to kill *Sesbania* 25-30 days after sowing. *Sesbania* acts like a live surface mulch conserving soil moisture and suppressing weeds.

On decomposition, following control with 2,4-D treatments, it supplements the crop with 10-15 kg N/ha. In areas where soil crusting is a problem, the germinating *Sesbania* helps in breaking the crust and facilitates the emergence of rice seedlings. Bhullar et al. (2020; 2021) provide details of different integrated weed management practices for the effective management of weeds in DSR.

Weed management with herbicide-tolerant crop technology

Weedy rice (*Oryza sativa* f. *spontanea*), also referred to as red rice and wild rice, is widespread in many rice-growing regions and countries, including India (Rao et al., 2007; Roma-Burgos et al., 2021). Weedy rice is reported to cause huge rice yield losses. It is challenging to control weedy rice due to its morphological similarities with the rice crop and similar plant growth requirements.

Several research reports suggest shifting from PTR to DSR would accentuate the weedy rice problem. This would be a considerable challenge as herbicides recommended for DSR do not control weedy rice. The GM technology employed globally in other crops to impart herbicide resistance traits has not been adopted in rice. However, using the non-GM approach, herbicide-tolerant rice varieties have been developed and cultivated commercially in many countries (Avila et al., 2021).

Referred to as Clearfield ™ rice, the technology uses herbicides to control weeds, including weedy rice. However, the technology used alone for long periods has led to herbicide-resistant weedy rice populations due to the gene flow effects.

In India, too, three herbicide-tolerant rice varieties, developed through the non-GM approach, have been released recently (Pandey, 2021). With these new varieties, farmers could use imidazoline herbicides (such as imazethapyr) to control weeds, including weedy rice. It is a new paradigm worth exploring with strict stewardship guidelines adoption.

Table 1 Herbicides used for managing weeds in dry direct-seeded rice in India (Rao et al., 2017c)

Herbicide(s)*	Dose (g/ha)	Time of application (DAS) *	Weeds controlled	
			Good control	**Control not satisfactory**
Azimsulfuron	17.5-35	15-20	Annual and perennial sedges, including *Cyperus rotundus* L. Some grasses, broad-leaved weeds are also controlled.	*Echinochloa* spp.
Bispyribac-sodium	25	15-25	*Echinochloa* spp. (Other grasses, broad-leaved weeds and annual sedges are also controlled).	*Dactyloctenium aegyptium, Eleusine indica, Leptochloa chinensis, Eragrostis* spp.
Carfentrazone	20	15-20	Broad-leaved weeds.	Grasses not controlled.
Cyhalofop-butyl	120	15-20	Annual grassy weeds.	Broad-leaved weeds and sedges not controlled.
Ethoxysulfuron	18	15-20	Broad-leaved weeds and annual sedges.	Grasses uncontrolled. Perennial sedges, such as *C. rotundus*, are poorly controlled.
2,4-D ethyl ester	500	15-25	Broad-leaved weeds and annual sedges.	Grasses are not well controlled
Fenoxaprop-ethyl	60	25	Annual grassy weeds.	Broad-leaved weeds and sedges not controlled. (Toxicity to rice if applied before 25 DAS)
Fenoxaprop-ethyl + safener	60-90	15-20	Annual grasses.	Broad-leaved weeds and sedges not controlled
Oxadiargyl	90	1-3 (adequate moisture essential)	Grasses, broad-leaved weeds and annual sedges.	-
Pendimethalin	1000	1-3	Most grasses, some broad-leaved weeds and annual sedges	-
Penoxsulam	22.5	15-25	Grass, broad-leaved weeds and annual sedges.	*L. chinensis, D. aegyptium, E. indica, Eragrostis* spp. are poorly controlled.
Triclopyr	500	15-20	Broad-leaved weeds.	Grasses not controlled.
Bispyribac-sodium + Azimsulfuron	25+17.5	15-25	Grass, broad-leaved weeds and sedges, including *C. rotundus.*	Grasses other than *Echinochloa* spp.
Chlorimuron + metsulfuron-methyl	4	15-25	Broad-leaved weeds and annual sedges.	Grasses not controlled.
Bispyribac-sodium + Pyrazosulfuron	25+25	15-20	Grasses, broad-leaved weeds and sedges, including *C. rotundus.*	Grasses other than *Echinochloa* spp.
Fenoxaprop-ethyl + Ethoxysulfuron	56+18	15-25	All major grasses, including *L. chinensis* and *D. aegyptium*. Broad-leaved weeds and sedges.	-

* Days after seeding

The advantage of DSR to farmers - resource use and economics

DSR is proved to have several advantages over PTR. DSR saves labour (40–45%), water (30–40%), fuel/energy (60–70%), and reduce greenhouse gas emissions (Kumar and Ladha, 2011; Ladha et al., 2016; Ali et al., 2018). In a farmer's field, a survey in Punjab found that DSR resulted in savings of 14 person-days/ha and 18 to 20% irrigation water compared to PTR (Bhullar et al., 2018).

The labour required in DSR was about one-third of the transplanted rice (Ho and Romli, 2002). Balasubramanian and Hill (2000) reported that DSR had higher resilience to water deficiencies and more profits in assured irrigation areas. DSR saved irrigation water by 11-18% (Tabbal et al. 2002) and reduced the labour required by 11-66% compared to PTR, depending upon location, season and type of DSR (Kumar et al., 2009; Rashid et al., 2009).

Easy planting, improved soil health, reduced methane emission and often higher net returns in assured irrigation areas were some of the other benefits of DSR (Kumar and Ladha, 2011; De, 1986; Pathak et al., 2009). In addition, rice matures 7-10 days earlier under DSR than PTR, allowing timely sowing and higher yields of succeeding wheat (Giri, 1998; Singh et al., 2006).

This has been found to compensate for any minor yield penalty in rice yield occasionally observed in direct seeding. With production costs being low (44-48%), the DSR is found to give significantly higher net returns (23%) compared to PTR. The benefit-cost ratio was substantially higher (69%) in DSR (Soriano et al., 2018). Higher yields and other advantages of DSR have been reviewed in detail by Rao et al. (2007), Kumar and Ladha (2011), Pathak et al. (2011) and Ladha et al. (2016).

Adoption of DSR in India: the potential

Rice in India is mainly grown by hand-transplanting rice seedlings in puddled (wet cultivation) fields. The transplanting method of rice establishment has been in practice for many years as farm labour was abundantly available with reasonable wages. Opening up the economy, increased urbanization and intensification of agriculture and allied activities have resulted in labour shortage with higher wages.

Simultaneously, the rural wages have been growing by 17% on average since 2006-07, outstripping the urban wages. There has been an increase in wages by 26-30% between 2015-16 and 2019-20 (Government of India, 2021). Further, many government schemes intending to improve the income and livelihood of under-privileged populations also added to the labour scarcity in the country. The shortage of labour and increasing wages have impacted agriculture adversely, particularly the PTR, which is more labour-intensive.

The increased cost of cultivation and over-exploitation of groundwater associated with PTR have influenced the scientific community to focus on developing rice production systems that are sustainable and efficient in utilizing resources with enhanced farmers profitability.

DSR adoption in Punjab

The agriculture in Punjab is heavily dependent on migrant labour. A large labour force coming from relatively economically poorer areas of Bihar and eastern Uttar Pradesh participate in agricultural operations, such as transplanting, seeding and harvesting of rice and wheat, the major crops in the State. However, following the implementation of the Mahatma Gandhi National Rural Employment Guarantee Scheme (MGNREGS) by the Indian government in 2005, the inflow of labour has decreased with a concomitant increase in wages (Deininger et al., 2016).

The cost of manual transplanting increased from INR 1500 in 2005 to more than INR 5000/ha in 2012 (Gill et al., 2013). DSR was introduced in Punjab in 2009-2010 as an alternative to PTR to save labour, water and energy. Labour scarcity, higher costs and declining groundwater table have forced farmers in Punjab to look for alternative methods of rice establishment (Bhullar et al., 2018).

In 2009, a few farmers in Punjab started experimenting with DSR on a small scale. The adoption was then rapid, and by 2014, the DSR area grew to 115,000 ha (Anonymous, 2014). The declining groundwater levels forced the state government to encourage DSR by extending subsidies to farmers to purchase seed drills, which played an essential role in adopting DSR on large acreages. The improvements in rice seeding machinery, high-yielding varieties, improved technologies, including weed management, and the enhancement of farmers' skills through training programs accelerated the adoption of DSR in Punjab (Singh et al., 2016; Bhullar et al., 2018).

To begin with, the DSR had a 2-5% yield penalty compared to PTR. However, the yield loss was compensated for by the higher productivity of the following wheat crop that could be planted 10-15 days earlier than PTR. The total net returns from the DSR-wheat system, therefore, exceeded the PTR-wheat system by INR 5050 to 8100/ha (Bhullar et al., 2018).

Adoption of DSR in other regions

The increased labour costs and reduced water availability made the farmers in the other States also adopt DSR. In 2012, the drought-hit *Krishna* River Basin of Andhra Pradesh saw a massive increase in the area under DSR from 200 ha to 35,000 ha (Palanisami et al., 2014). In Raichur district, Karnataka (Rao et al., 2015) and Krishna (Rao et al., 2008) and Guntur (Reddy et al., 2019) districts of Andhra Pradesh, the late release of water in irrigation canals, due to erratic rainfall, encouraged farmers to adopt DSR by sowing rice seed directly with the onset of monsoon and convert it as irrigated rice crop after the release of the canal irrigation.

The dry-seeded sowing practice in Raichur District of Karnataka state was estimated to be about 13,000 ha (Gumma et al., 2015). DSR is a common practice among farmers in West Singhbhum and Saraikela -Kharsawan Districts of Jharkhand due to the uncertainty of monsoons, water shortages and labour scarcity (Barla et al., 2021). In Jharkhand, Odisha, Chattisgarh and Madhya Pradesh, about 8% of farmers practice DSR (Malhotra, 2021).

Hindrances for the adoption of DSR

The adoption of DSR in India has been inconsistent. This is due to below-par performances of rice cultivars that were usually meant for puddle transplanted conditions. Other influential factors include poor weed control undertaken during the initial crop growth period, higher spikelet sterility in specific environments, crop lodging, iron chlorosis in some areas, nematode infestation during the initial dry period, and lesser awareness on improved DSR production technology (Bhullar and Gill, 2019; 2020).

Other significant hindrances to the adoption of DSR have been the non-availability or non-accessibility of suitable machinery for seeding rice, lack of effective herbicides and applying the technology under non-optimum conditions. DSR performs better in medium to heavy textured soils. However, in some parts of India, enthusiastic farmers raised DSR in light-textured soils (Bhullar and Gill, 2019; 2020).

Between 2010 and 2015, the area under DSR in Punjab increased continuously from a few hundred ha to 150,000 ha. However, the DSR area decreased sharply to less than 10,000 ha in 2016. The key issues identified for the decline in the DSR were - over-enthusiasm of some farmers who took up DSR in light-textured soils, the problem of weeds and the non-availability of rice varieties suited for DSR conditions.

The Punjab Agricultural University (PAU) re-visited and further refined DSR technology and, in association with the State Department of Agriculture, drew up a strategy for broader adoption of DSR, which included identifying and mapping of areas suitable for DSR, preparation of soil maps, consultation among all stakeholders and recommendation of new herbicides for the control of a broader spectrum of weeds.

Other actions included the design and development of appropriate machinery capable of sowing and applying herbicides simultaneously, introduction of short duration varieties (*Pusa Basmati 1509* and *PR 126*) and rescheduling nitrogen fertilization to match the crop's needs more effectively. With these interventions, the DSR area in the State increased again to 23,300 ha in 2019.

Adopting DSR during the pandemic: making the crisis an opportunity

The world witnessed the outbreak of the COVID-19 pandemic during the early part of 2020. The lockdown imposed by the government to minimize the spread of the virus affected the movement of people and impacted the economy significantly. The uncertainty of the situation led to what is referred to as 'Reverse migration' with millions of labours working in both urban and rural areas heading back to their homes.

The north-western part of India represents Punjab, Haryana and parts of Rajasthan and western Uttar Pradesh, where rice farming is dependent on migrant labour from Eastern Uttar Pradesh and Bihar were particularly adversely affected. The extraordinary situation forced rice farmers in this part of the country to opt for alternatives to the manual transplanting method of rice establishment that requires a minimum of 15 to 20 labour for one-hectare transplanting. Meanwhile, the labour shortage led to a sharp hike in wages, too, thus making PTR cost-prohibitive.

The SAUs in the region and the concerned state Departments of Agriculture seized the opportunity and pursued farmers to adopt DSR technology. DSR enabled rice planting at the cost of INR 12,000 to 15,000 per hectare using a hired seeding machine capable of covering 10-15 ha/day. The Punjab Government incentivized the DSR adoption and sanctioned 4,000 seeding machines in the 2020 season on a subsidized (40-50%) basis (The Hindu, 2020).

The availability of farm machinery, such as the *Lucky Seed Drill*, developed by Panjab Agricultural University (PAU), which does sowing and herbicide application, simultaneously encouraged farmers to try out the DSR technology (Singh et al., 2020). Based on five years of research and validation at the farmers' field, a novel DSR technique coined as '*Tar-wattar* DSR' was developed and recommended in April 2020 (Gill and Bhullar, 2020).

The new DSR technique involved agronomic, genetic and mechanical interventions. In this technique, pre-sowing irrigation is applied on a laser levelled field and seedbeds are prepared under *Tar-wattar* conditions (sufficiently high but workable soil moisture) by shallow cultivations and two to three plankings in the evening hours and sowing of imbibed and treated seed immediately with the *'Lucky Seed Drill'*. (Figure 1).

The significant departure from earlier practice is the delay in the first post-sowing irrigation, which is applied 21 days after sowing (Figure 2). The delayed post-sowing irrigation offers: (i) higher saving in irrigation water (15-20%), (ii) lesser weed problems, and iii) reduced incidence of nutrient deficiency, especially iron.

In 2021, the "*Lucky Seed Drill"* was fitted with a press wheel attachment that helped: (i) preventing crust formation that is encountered in case of rain after sowing, (ii) enhancing herbicide efficacy, and iii) conserving soil moisture for a more extended period (Gill and Bhullar, 2021).

Figure 1. *Lucky seed drill* machine seeding the rice seeds and spraying pre-emergence herbicides in one pass. The optimum depth of seeding and uniform herbicide application is critical for establishing DSR with adequate control of the first flush of weeds

Figure 2: The initial growth of DSR. The first irrigation to the crop is delayed to discourage weed growth and to encourage better root growth of rice seedlings

The '*Tar-wattar'* DSR technology was widely adopted in Punjab, and the area under DSR went up to 540,000 ha in 2020. and was taken up on a large scale. In the neighbouring State of Haryana also, the DSR area increased from 10,000 ha in 2019 to 25,000 ha in 2020, with many farmers adopting PAU's '*Tar-wattar'* DSR technology. Highly successful growth and establishment of the DSR crops are shown in Figures 3-5.

Figure 3. Excellent establishment of direct-seeded rice crop which was not flooded but irrigated based on crop requirement

Figure 4. Luxurious growth of direct-seeded rice in a farmers field in Punjab, India

Figure 5. The interactions amongst the farmers and scientists from the Punjab Agricultural University, Ludhiana, in a DSR farmer's field in Punjab, India

Although the primary reason for the sharp increase was labour shortages during the pandemic, the efforts of the scientists of the SAUs and the push given by the State Governments also played a significant role. DSR technology has been undergoing refinement for over five years, with a substantial number of innovative farmers adopting the technology.

This readiness has helped change the mindset of farmers who were aware of the merits of the technology but were initially cautious about adopting it. The increase in DSR area to 600,000 ha in 2021 in Punjab, despite an improvement in the labour supply, indicates farmers' confidence in the new DSR technology.

The area under DSR in Punjab is close to 20% of the total rice area. Dubbed as a 'silent revolution', this is reported to have resulted in savings of around INR 6.0 billion in monetary terms besides 30 % savings in groundwater and associated pumping costs (Singh et al., 2021).

DSR: the way forward

Considering the many positives of the DSR technology and its success in Punjab and Haryana, it is pertinent to explore possibilities of extending the acreage under DSR across the country. With this objective in view, a National Seminar on Promotion of DSR was organized by the ICAR-Agricultural Technology Application Research Institute (ATARI), Ludhiana, on 12-13 June 2021.

The event, attended by stakeholders including scientists from ICAR, SAUs, IRRI, CIMMYT, senior administrators and policymakers and farmers, took stock of the developments following the COVID-19 pandemic and discussed the DSR technology and the possibilities of its wider adoption (Singh et al. (2021a). The significant observations made at the seminar are summarised below:

- Academia should take the lead in sensitizing the various state Departments of Agriculture and policymakers on the merits of the technology.
- The most significant benefits, such as resource-use efficiency, farmers' profitability, climate resilience, lower groundwater use and lower GHG emissions, need special mention.
- DSR may not suit all ecologies. The first step would be to map areas suitable for DSR.

- Crop breeding programs may be intensified to identify and develop varieties suitable for DSR. Key attributes include early vigour, a more robust root system and greater competitiveness with weeds in the early stages of crop growth.
- The accessibility of machinery (laser leveller, machinery for seeding and spraying of herbicides) be ensured, particularly to small and medium-sized landholders, through custom hiring centres.
- Perennial weeds - purple nutsedge (*Cyperus rotundus* L.), Bermuda grass [*Cynodon dactylon* (L.) Pers.] and weedy rice - are likely to increase with continuous cultivation of DSR.
- Stale seedbed, brown manuring and other cultural practices are integrated with herbicide use for sustainable weed management.
- Scouting for herbicide-resistant weeds is to be given priority.
- The inclusion of summer moong in rice-wheat or green manuring of *Crotolaria juncea* L. are to be explored for reducing nematode infestation.
- The use of microbial inoculants for seed treatment should be explored for better nutrient cycling and reducing the losses of nitrogen.
- As farmers' "fear of failure" is one of the critical reasons for the slow or non-adoption of DSR, serious efforts are required in educating and training them.
- Labelling of the DSR produce for its low carbon footprints may be explored to boost exports.

Opportunities for upscaling DSR

Climate change is expected to increase the variability of monsoon rainfall and the risks of early or late-season drought. The DSR system increases the capacity of poor farmers to cope with climate-induced change by offering a choice of rice establishment methods and by reducing the amount of water required for crop establishment and subsequent crop growth.

The DSR technology received an uplift due to the COVID pandemic. The DSR area in Punjab increased from 235,000 in 2019 to 600,000 in 2021. The Punjab State government and the PAU have promoted DSR and kept the momentum from 2019 to 2021. The neighbouring Haryana State, too, is conscious of the problems associated with PTR and has been striving hard to promote DSR technology.

The *Tar-wattar* technology received wide publicity in local print and social media during the last two years. The PAU, partnering with other stakeholders, organized several activities, including field visits for farmers.

The National Seminar on the promotion of DSR organized in June 2021 (referred to above) attracted over 2000 participants. It successfully sensitized all the stakeholders related to the DSR technology. The scientists from other regions are expected to try out the technology in their areas in the coming years. The adoption, therefore, is expected to have a cascading effect.

In the meantime, the Prime Minister of India has released two rice varieties resistant to herbicides developed by the IARI, New Delhi, in June 2021 (Pandey, 2021). Developed through mutagenesis, these varieties (*Pusa Basmati 1979* and *Pusa Basmati 1985*) are tolerant to imidazolinone herbicides. This breakthrough research will help farmers control weedy rice- one of the most problematic weeds in DSR in many parts of the country. Punjab and Haryana states cultivate *Basmati* rice, mostly grown for export.

The new HT *basmati* rice varieties are expected to find rapid adoption. However, a similar technology (Clearfield Rice ™) has led to the rapid evolution of herbicide-resistant populations of weedy rice due to gene flow from HT rice in Malaysia in Asia and the USA. For the long-term sustainability of herbicide-tolerant technology, it is therefore essential to develop and follow a strong stewardship program to avoid/delay resistance development in weeds against HT-rice herbicides.

The ecology and production practices in eastern IGP (EIGP) - east Uttar Pradesh, Bihar and Odisha, are different. The constraints and potential of DSR adoption EIGP have been eloquently discussed by Singh et al. (2020). The crop is predominantly raised as PTR with supplemental irrigations during the initial periods of crop growth. If crop establishment is delayed, farmers face the problem of yield loss due to lateness. This will lead to delayed planting of the following wheat crop (with lower yield) and lower total system productivity.

Due to late rains, farmers had to make additional expenses on pumping water from borewells. Poor crop growth allows more weeds to increase and add to the extra weed management costs. Thus, a shift to DSR from PTR would address the direct and indirect problems related to water shortages during the initial 2-3 weeks of the crop's growth. The stale seedbed preparation with pre-sowing irrigation is followed by shallow tillage before seeding rice. Referred to as soil-mulch DSR (Dhillon et al., 2021; www.csisa.org), this simple technique has multiple benefits such as limiting evaporation losses, thereby reducing early irrigation requirement, better weed control, lower cost of cultivation and more profits.

This is almost similar to *Tar Wattar* DSR practised in Punjab. Based on the large scale farmers participatory evaluation trials in Bihar and Eastern Uttar Pradesh (N= >600), it has been reported that soil mulch DSR gave yield similar to PTR but higher than conventional DSR with sowing in dry soil followed by irrigation (**www.csisa.org**).

The DSR technology benefits from intensifying the rice-fallow cropping system (RFCS) in regions like Odisha. The early establishment through DSR facilitates the timely establishment of a succeeding wheat crop, leading to higher system productivity and profitability (**www.csisa.org**). In Odisha, dry-DSR performed better than the existing practice of *beushening* (Panneerselvam et al., 2020).

They found that the costs on establishment were USD 49 and 58 and on weed control USD 184 and 67 for the *beushening* method and DSR, respectively. That would need rebalancing the time of crop establishment and then fitting the whole system of evolution of new varieties.

At the cropping system level, DSR not only addresses the primary drivers of the rural change, such as rising scarcity of labour and water, the rising cost of cultivation and declining farmer's income, but also bring opportunity for early rice establishment.

We also believe that the dry DSR has vast potential in canal irrigated systems in peninsular India. The potential has already been captured in Raichur district of Karnataka State (in the tail-end area of *Upper Krishna* and *Tungabhadra Project* command area), where due to the canal water reaching the fields late, the farmers sow dry direct-seeded rice and later convert it as irrigated rice on the release of canal water (Rao et al., 2015).

The DSR is now spreading to Sindhanur, Gangavati areas (Gumma et al., 2015) and is becoming a widespread rice cultivation practice in Karnataka (Gurupadappa et al.,2018). Working in that area, one of us (A. N. Rao) found the farmers very enthusiastic and have successfully perfected the DSR technology, including laser levelling of the fields, dry sowing and applying herbicides using machinery and equipment much similar to the practices followed by the Punjab farmers.

International organizations, such as IRRI and CIMMYT, are also running pilots in collaboration with SAUs, State Departments of Agriculture and civil society organizations to popularise DSR technology in many parts of India. In Karnataka, they introduced the farmers to modern machinery and provided the required technical know-how. Due to their combined efforts, the area under DSR has gradually increased over the years. Presently, DSR is practised over 40,000 ha. Similar adoption is underway in the neighbouring Telangana State also.

Dry-DSR is also popular during the *Kharif* season in Nalgonda (*Nagarjuna Sagar* project area) and the Krishna and Guntur districts of Andhra Pradesh. In the State of Tamil Nādu also, a vast potential exists for farmers to adopt the DSR method under canal irrigated areas. With the initiatives such as the one made in Karnataka, it is possible to untap the technology's substantial potential to improve the farmers' profits and the environment. Agriculture in India is a State subject.

Each State could proactively explore possibilities for greater adoption of DSR. The SAUs have a pivotal role to play in testing and re-visiting the technology and fine-tuning it to suit the local conditions and scaling up the technology in collaboration with State Departments of Agriculture and other stakeholders.

The cost of establishment, irrigation and weed management in DSR compared to PTR cultivation (as an example in Punjab) is given in Table 2. Overall, there are 45-48% savings with DSR cultivation compared to PTR, with the highest contribution coming from crop establishment (65-68%), followed by irrigation (52-53%).

The weed management cost in DSR, however, is 20-38% higher than in PTR. Considering other expenses on crop production being the same in both methods of crop establishment, a farmer can expect a total saving, ranging from INR 9114 to 10192 per hectare, by adopting DSR cultivation.

Assuming a saving of INR 10,000/ha, each million ha DSR adoption would result in an economic benefit in the range of INR 10.0 billion (=USD 133 million). This, benefit is besides the significant reduction in groundwater use and GHG emission of GHGs that DSR brings about. We believe that a substantial acreage of PTR in India could be brought under DSR, with such positive social, economic and environmental effects.

Table 2 The relative investment for crop establishment, irrigation and weed management in the cultivation of DSR and PTR (per ha)

	DSR		PTR		
		Cost (INR)		Cost (INR)	Saving with DSR (%)
1. Crop establishment					
a. Tractor time (hr.)	2.0-2.5	1040-1300	2.5-4.0	1300-2080	20 to 38
b. Diesel (litres)	12.5-15.0	1050-1250	25 -30	2075-2500	49 to 50
c. labour (man-days)	2.5-5.0	1125-2250	15-20	6750-9000	75 to 83
2. Irrigations (No.)	12-16	2496-3328	25-30	5200-6240	52 to 53
3. Weed management		2500-4000		2000-2500	-20 to -38
4. Total		8211-12128		17325-22320	45 to 48

Details: Labour wages - INR 450/man-day, INR 208/ha for one irrigation, Diesel- INR 83.3/l.

Conclusions

It has been demonstrated quite emphatically that DSR has the potential to provide similar levels of productivity and greater economic returns to farmers as compared to conventional PTR. The adoption of DSR reduces the unsustainable exploitation of groundwater and minimizes GHG emissions, thereby positively assisting the environment. The Punjab and Haryana States of India used the opportunity of labour shortage following the COVID-19 pandemic in popularising DSR technology successfully.

All-out efforts should be made to reach out to more areas of the IGP and other DSR suitable areas in India. The success stories should be communicated widely with the emphasis on minimizing the cost of production to increase farmers' profits. The senior administrators and the policymakers in other parts of India need to be sensitized to promote the DSR technology.

The SAUs will have to proactively work towards fine-tuning the technology to suit the local conditions and forge a partnership with all stakeholders for its upscaling in their respective areas.

The accessibility of machinery should be ensured, particularly to small and medium farm holders through custom hiring centres. The right kind of policy support and incentives are critical in the faster upscaling of DSR in India.

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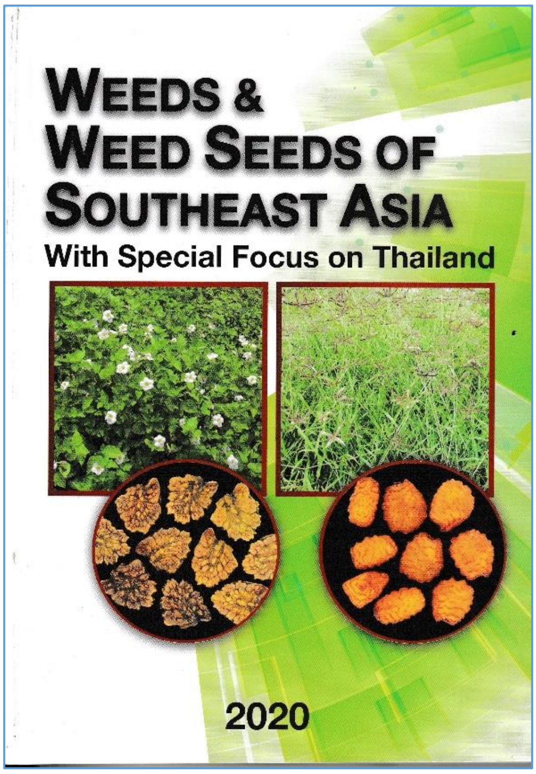
Common and chemical names of herbicides used in this paper:

Common name	Chemical name
azimsulfuron	N-[[(4,6-dimethoxy-2-pyrimidinyl) amino] carbonyl]-1-methyl-4-(2-methyl-2H-tetrazol-5-yl) -1H-pyrazole -5-sulfonamide
bispyribac-sodium	2,6-bis[(4,6-dimethoxy-2-pyrimidinyl) oxy] benzoic acid
chlorimuron	2-[[[[(4-chloro-6-methoxy-2-pyrimidinyl) amino] carbonyl] amino] sulfonyl] benzoic acid
cyhalofop-butyl	(R)-2-[4-(4-cyano-2-fluorophenoxy) phenoxy] propanoic acid
ethoxysulfuron	2-ethoxyphenyl [[(4,6-dimethoxy-2-pyrimidinyl) amino] carbonyl] sulfamate
fenoxaprop-ethyl	(6)-2-[4-[(6-chloro-2-benzoxazolyl) oxy] phenoxy] propanoic acid
florpyrauxifen	4-amino-3-chloro-6-(4-chloro-2-fluoro-3-methoxyphenyl)-5-fluoropyridine-2-carboxylic acid
halosulfuron	3-chloro-5-[[[[(4,6-dimethoxy-2-pyrimidinyl) amino] carbonyl] amino] sulfonyl]-1-methyl-1H-pyrazole-4-carboxylic acid
imazethapyr	2-[4,5-dihydro-4-methyl-4-(1-methylethyl)-5-oxo-1H-imidazol-2-yl]-5-ethyl-3-pyridinecarboxylic acid
metsulfuron-methyl	2-[[[[(4-methoxy-6-methyl-1,3,5-triazin-2-yl) amino] carbonyl] amino] sulfonyl] benzoic acid
oxadiargyl	3-[2,4-dichloro-5-(2-propynyloxy) phenyl]-5-(1,1-dimethylethyl)-1,3,4-oxadiazol-2(3H)-one
pendimethalin	N-(1-ethylpropyl)-3,4-dimethyl-2,6-dinitrobenzenamine
penoxsulam	2-(2,2-difluoroethoxy)-N-(5,8-dimethoxy [1,2,4] triazolo[1,5-c] pyrimidin-2-yl)-6-(trifluoromethyl) benzene sulfonamide
pyroxasulfone	3-[[5-(difluoromethoxy)-1-methyl-3-(trifluoromethyl) pyrazol-4-yl] methyl sulfonyl]-5,5-dimethyl-4H-1,2-oxazole
quinclorac	3,7-dichloro-8-quinolinecarboxylic acid
triclopyr	[(3,5,6-trichloro-2-pyridinyl) oxy] acetic acid
2,4-D	(2,4-dichlorophenoxy) acetic acid

Book Review

Weeds and Weed Seeds of South-East Asia
With Special Focus on Thailand

Hirohiko Morita



A superior book for Weed Science in the tropics entitled “Weeds & Weed Seeds of Southeast Asia With Special Focus on Thailand (A5, 280 pages, ISBN 978-967-18186-0-2)” was published by Dr. Siriporn Zungsontiporn, a weed scientist in Thailand. She is a specialist in weed diversity and invasive alien plants, who worked for Weed Science Research Group (WSRG), Plant Protection Research and Development Office, Department of Agriculture, Thailand. Siriporn has been an active member of APWSS for many years.

Her co-authors are Dr. Soetikno Sastroutomo, a plant ecologist, well experienced in plant quarantine and protection Projects of ASEANET for many long years, based in Malaysia. Other cpo-authors are Ms. T. Jongukthai, Ms. A. Promma and Ms. M. Noomdee, weed scientists of WSRG, DOA, Thailand, and from the ASEAN Network on Taxonomy (ASEANET www.aseanet.org) in 2020. The authors explain the purpose and foundation of the book as follows: “

> *“...There was little incentive for farmers or extension officers to pay close attention to the identity of the weeds when the preferred management practice was simply to apply of a broad-spectrum herbicide.” And*
>
> *“…The book is based on surveys and research that has been conducted for many years in Thailand by the first author, Dr. Siriporn Zungsontiporn assisted by her team (third to fifth authors) from the Weed Science Research Group (WSRG), Department of Agriculture (DOA), Thailand.”, respectively...”*

The descriptions include 101 weed species, 29 species of grasses, nine species of sedges, 60 species of broad-leaved weeds and three ferns. Botanical names, synonyms, common names, local names, native ranges, plant habits, status in Southeast Asia, status in Thailand, pathways, distribution, native vs introduced, and seed characteristics are among the details of each species.

“New weeds in Thailand”, such as *Cyperus entrerianus*, *Cleome chelidonii*, *Digera muricata*, *Marsilea scalaripes*, *Mikania micrantha* etc. which Dr. S. Zungsontiporn identified, are included.

These are in addition to the conventional weed species given in “MAJOR WEEDS IN THAILAND illustrated by colour” from National Weed Science Research Institute Project by JICA, Japan and DOA, Thailand in 1984 and 1994.

Precise stereo-microscope images of seeds, achenes, spikelets and other features make the book especially valuable, described as “*one of the very effective ways of spreading weeds is through contamination of batches of seeds imported from other countries for planting directly in the fields or in the greenhouse*.”.

This book will contribute certainly to the development of weed science and management not only in Southeast Asia but also in the Asian-Pacific region. Furthermore, the next volume of this book is expected because much other information on “New Weeds in Thailand” might be accumulated by the authors.

Anyone who wants to purchase this publication should contact the second author, Dr. Soetikno S. Sastroutomo (ssoetikno@gmail.com), by e-mail.