EDITORIAL

Weeds and Biodiversity: Some Reflections

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Published: 30 December 2021

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…".*
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> *"…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 <u>all</u> 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-

[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.

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[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.

[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.

Acknowledgements

I thank Robert Zimdahl for reviewing the essay and providing valuable input, improving it.

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