EDITORIAL

To Bee or Not to Be: Weeds for Bees

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Abstract

In addition to the benefits weeds provide to natural enemies of pest insects, weedy taxa are emerging as a critical component that can support pollinators, which are crucial for world crops. Understanding the vital interactions between pollinators, weeds, and crops will enable both the scientific community and the public to appreciate the ecological values of colonizing taxa even more. The species richness of wild bees and other pollinators has declined over the past 50 years, with some species undergoing significant declines and a few going extinct. The causal factors include the excessive use of neonicotinoid pesticides, which directly affect pollinator insects and indirect effects, which include fragmentation of habitat and losses of floral resources due to land clearing and intensive agriculture.

Agriculture is recognized as the main driver causing pollinator declines through land-use change, declines in traditional farming practices, intensive farming practices, such as monoculture, tillage and agrochemical use, especially neonicotinoid insecticides, and the excessive use of herbicides for weed control. Agriculture also provides opportunities to support pollinators, through ecologically-friendly farming (Diversified and Conservation Farming Systems) in which habitat can be retained and floral resources for pollinators enhanced.

Many countries, especially in Western Europe, the U.K. and the U.S.A., now have programmes dedicated to re-introducing 'green' infrastructure and setting aside field margins and unmanaged areas in agricultural landscapes as *Nature-Based Solutions* (NSBs) to support pollinators with food resources. The overwhelming evidence from research in the last two decades indicates that colonizing taxa can help bees with rich and diverse food and nectar resources over extended periods.

The *Convention on Biological Diversity* (2018) acknowledges the need to improve knowledge of pollinators and pollination and their role in maintaining ecosystem health and integrity beyond agriculture and food production. Ecological restoration of damaged or modified urban ecosystems can increase the connectivity of pollinator-friendly habitats and support species dispersal and gene flow. These measures can also contribute to climate change mitigation and disaster risk reduction. Weedy taxa, with their abundant flowery resources, have a critical role to play in all of the above.

Keywords: Pollinators, pollinator decline, flowers, weeds, ecosystems, honeybees, *Apis*, *Bombus*

Introduction

People familiar with biodiversity accept that weedy taxa are part of the richness of species in Nature. Yet, some still doubt whether colonizing plants make indispensable contributions to ecosystem functioning and are worthy of our respect. Not all colonizing taxa are 'invasives'. Many play critical roles in natural and man-made ecosystems.

In addition to the multitude of benefits weeds provide to humans and other animals (such as edible food, medicines and fuelwood), they are emerging as a critical biological component that affects the activities of pollinators. Research to understand the vital interactions between flowering plant pollinators, weeds, and crops is becoming a critical area for *Weed Science*. For the past few decades, the discipline has built substantial linkages with ecology, entomology and plant science, investigating these crucial inter-relationships

Until about 40 years ago, the issue of pollinators was not a central topic in botany, ecology, or agriculture. Insect behaviour, foraging habits, migrations and pollination only excited the entomologists. Pollination of plants by flower visitors was taken for granted in both agriculture and the environment (NRC, 2007).

Weed scientists were somewhat late to recognize the relationship between weeds and pollinators. The realization of Nature's ecosystem services opened the door for discussion of pollination. Then came a wake-up call, mainly in the new millennium, that bees were in trouble and a ‘pollination crisis’ was already upon us “*undermining ecosystem biodiversity and function, human nutrition, and economic welfare*” (Jordan et al., 2021).

The evidence from a large number of studies is compelling. Populations of different honeybees, bumblebees (many *Bombus* spp.), and other insect pollinators (hoverflies, moths, butterflies, wasps, beetles, thrips, etc.) have been in severe decline worldwide. The scale of bee losses in North America and Western Europe, in particular, has led to fears of crop failures and even severe food shortages. Tropical and sub-tropical countries are yet to be affected or are not yet aware of declines in bee populations because of little research (NRC, 2007; Garibaldi et al., 2009; Hicks et al., 2016).

Pollination is a free service provided mainly by insects and birds. It is one of the many mutually beneficial interactions between plants and animals. In return for pollen transfer services, animals are "rewarded" with nutritional plant products, such as nectar, pollen, oils and resins. Many plants produce vast amounts of pollen to enable pollination (Balfour et al., 2013; Hicks et al., 2016; Balfour et al., 2021).

While pollination is a critically important ecological process, the needs of both plants and pollinators are not always adequately met. Commonly, pollen limitation reduces seed set in plants, or pollinators experience nectar dearth (Ratnieks and Balfour, 2021).

Information is available for bees [1] but not for other insects. Over 20,000 bee species are implicated in pollination services worldwide. Up to 50 species are managed in the bee-keeping industry. About 12 species are commonly involved in crop pollination. These include the western honeybee (*Apis mellifera* L.), the eastern honeybee (*Apis cerana* Fabricus), some bumblebees (*Bombus* Latereille spp.), stingless bees (many genera of Tribe *Meliponini* Lepeletier), and solitary bees.

Insects collect pollen on their hairy bodies while foraging on pollen and sucking out nectar from flowers. Some pollen then gets carried to other flowers and assists in cross-fertilization. It is a critical interaction in evolution. Generally, about 90-95% of pollen produced by a flower is consumed by insect pollinators. The evidence is - the better the quality of nectar and pollen protein available for foraging - the better it is for the health of all pollinators.

A balanced diet, plentifully available, is likely to increase their fitness and, ultimately, survival. A diverse diet – from multi-flowered pollen and nectar, also appear to be more beneficial to the foraging pollinators than feeding on a single type (Klein et al., 2006; NRC, 2007; Goulson et al., 2015; Pain, 2017).

Despite some unique preferences, the majority of pollinators are not very picky. Research has shown a direct correlation between the diversity of flowering sources, flower abundance and the variety of visiting pollinators. The more diverse the landscape is and the more flowers there are, the better it is for pollination. Couvillon et al. (2015) also showed that “*not all bees are busy*” and that there are wide variations in the frequencies of flower visitation rates and foraging behaviour of various groups of insects. Broadly, some pollinators, such as honey bees and bumble bees, with more hairy bodies and other morphological characteristics, appear more important for pollination than others.

Charles Darwin wrote profusely about pollination. He was convinced about the association between angiosperms and insects and the on-going evolution of flowering plants and pollinator animals. To Darwin, the rapid emergence and early diversification of the angiosperms was an "*abominable mystery*" (Davies et al., 2004; see Danforth et al., 2006 and references therein). Among the most critical traits attributable to the vast environmental spread and radiation of angiosperms is animal-mediated pollination. The evidence from biology is that mutualistic relations between flowering plants and animal pollinators allowed outcrossing, which was a significant reason why Angiosperms became so successful in the Cretaceous flora (ca. 100-125 million years ago) (Davies et al., 2004; Danforth et al., 2006).

These associations with insect pollinators, especially bees, are vital for maintaining the diversity of the world's floras – assemblages of endemic natives, casually occurring wild plants and colonizing taxa (weeds), which thrive in human-disturbed environments, including agricultural landscapes.

Research over the past two decades has shown that pollinators are not abundant in the absence of weeds. Thus, crops that require insect pollination (e.g., many fruit crops and cucurbits) benefit from the presence of a diversity of weeds in their neighbourhood, which attracts pollinators. It is also

[1] Bees belong to Class *Insecta*, Order *Hymenoptera*. Bees are a monophyletic lineage within the superfamily *Apoidea*. They are presently considered a *Clade*, called *Anthophila*. Some species, including honeybees, bumblebees, and stingless bees, live socially in colonies. But most species (>90%), including mason bees, carpenter bees, leafcutter bees, and sweat bees – are solitary (**https://en.wikipedia.org/wiki/Bee**). Also see Danforth et al. (2006).

possible that colourful weeds could draw some pollinators away from the crops. With attractive flowers and the added lure of tasty nectar, some weeds may be too tempting to pollinators. Such an influence is also acknowledged as a form of competition between the crops and weeds for the pollination services of those visitors.

The objectives of this information review are to examine the nature of the crisis faced by the global pollinator populations, focusing on the possibility that colonizing taxa, which are abundant in humanized landscapes, may be able to help by providing the critical resources pollinators need. 'Weeds', whether they thrive in farmers' fields or in the general environment, are nothing but colonizing taxa that can opportunistically move into and occupy disturbed environments (Bunting, 1960; Baker, 1965).

Many colonizing taxa have been accused of 'invading' natural and semi-natural areas and humanized spaces (including agricultural landscapes and urban areas), which has created an unnecessary conflict with humans (Chandrasena, 2020). Seen through the lens of invasion biology, for farmers and even some weed scientists, it has been hard to discern, which colonizing taxa could be considered 'non-invasive', but beneficial, and therefore, to be tolerated or promoted for ecological benefits and biodiversity values. Discussions on the issue are robust and disagreements among different arguments are yet to be fully resolved (Chew, 2015).

In natural and semi-natural areas, as well as agricultural and urbanized areas, assemblages of fast-growing and hardy 'weedy' species, producing abundant flowers year-round, appear to have the key attributes required to help pollinators sustain their declining populations. In my view, no other species, except colonizing taxa, whether they are introduced or native to a given area, region or country, or whether they are herbs, shrubs or trees, can play the required role comprehensively, expeditiously and urgently.

A Pollination Crisis

All indications are that globally, bees and other pollinating insects are in serious trouble. Bees worldwide currently suffer from a combination of poor nutrition and other stresses caused by humans.

Large-scale conversion of land to agriculture is destroying and degrading semi-natural ecosystems while conventional land-use intensification (e.g. industrial management of large-scale monocultures with high chemical inputs) homogenizes various landscape structures, thereby reducing the quality of their resources. Together, these anthropogenic processes reduce the connectivity of pollinator populations and erode away floral and nesting resources to undermine their abundance and diversity. Collectively, habitat fragmentation and losses, climate change, infectious diseases, especially parasite loads, and the extensive use of neonicotinoid insecticides and some fungicides and herbicides, in many countries lead to pollinator declines, and ultimately pollination services (Kovács-Hostyánszki et al., 2017; Hotchkiss et al., 2022).

The importance of pollinators who perform a critical ecosystem service is now globally recognized (NRC, 2007; Goulson et al., 2015; Scheper, 2015; Wood and Goulson, 2017). Research on bees and pollination has intensified establishing that about 300,000 animals pollinate approximately 87% of flowering plants. This figure includes about 70-80% of the world's crops, which benefit from insect pollination to varying degrees. If pollination by bees and other pollinators fails, productivity in agro-ecosystems and crops may also fail (Klein et al., 2006; Garibaldi et al., 2009; Dicks et al., 2016).

Economically, the services of animal pollinators were valued at US $ 216 billion in 2005 or 9.5% of the value of global food production. Gallai et al. (2009) estimated the worldwide annual value of pollination services to crops by insect pollinators at 153 billion euros. The figure for Europe, annually, was ca. 22 billion euros (Gallai et al., 2009).

In the USA alone, research suggested that managed honeybee populations declined by 59% in 61 years (1947-2008). Managed honey bee populations have been influenced by many factors including habitat loss, diseases, parasites, pesticides, other disturbances in the environment (such as fire and floods) and also socio-economic factors (vanEngelsdorp and Meixner, 2010).

For the USA alone, the economic value of goods dependent on pollination services was estimated to be US $ 34 billion (Jordan et al., 2012). More recent studies by Riley et al. (2020), confirmed that many crops in North America could fail due to the decline in pollinators. The estimated annual production value of wild pollinators for apples, blueberries, cherries, almonds, watermelon, and pumpkins was more than US $ 1.5 billion. Riley et al. (2020) also suggested that the value for all pollinator-dependent crops would be much higher than these estimates.

According to Goulson et al. (2015), the species richness of wild bees and other pollinators declined over the past 50 years, with some species undergoing major declines and a few going extinct. During this same period, the demand for insect pollination of crops approximately tripled, and the importance of wild pollinators in providing such services has become increasingly apparent, leading to a concern that we may be nearing a "pollination crisis" in which crop yields could begin to fall. Improving the nutritional resources for pollinators in agricultural landscapes has become especially important. One-third of the land area worldwide is currently under agriculture. Another billion hectares will likely be converted to agriculture by 2050 as crop production expands to feed a growing human population (NRC, 2007; Goulson et al., 2015).

The pressures on pollinators stem from intensive agriculture. They include pasture improvement and grazing by large stocks of animals and the creation of monocultural cropping environments (Figure 1). Intensive monocultures lead to large-scale habitat losses, destroying pollinator nesting sites and refuges (NRC, 2007; Klein et al., 2007; Garibaldi et al., 2009; Kammerer et al., 2021). Also, implicated in the pollination crisis is the widespread use of insecticides, especially the neonicotinoids, which are used to control insect pests of monoculture crops.

Globally, neonicotinoids, such as imidacloprid, clothianidin, thiamethoxam and thiacloprid, have been the most commonly used insecticides, despite their well-documented sub-lethal adverse effects on non-target beneficial insects, including pollinators (Wood and Goulson, 2017; Tasman et al., 2021). Neonicotinoids are nicotinic acetylcholine receptor agonists, which disrupt the memory, circadian rhythmicity and sleep patterns of insects, thereby adversely affecting their foraging behaviour and pollination services. Many are also lethal to insects and are now banned in EU countries (Geppert et al., 2020; Tasman et al., 2021).

However, as discussed recently by Hotchkiss et al. (2022), the evidence is emerging rapidly that many pesticides, including common fungicides and herbicides, including glyphosate, are now being implicated in the decline of bee populations, through adverse effects on the gut microbiota of these insects. Whether a pesticide directly affects the gut microbial growth or indirectly affects the microbiota by altering the insect host’s health and the immune system is presently not well understood (Hotchkiss et al. 2022).

In addition to the heavy reliance on pesticides, intensive agriculture also fragments and reduces foraging habitats, such as flower-rich field margins, meadows, grasslands and heathlands with which many pollinators are associated. Increased herbicide use, especially broad-spectrum herbicides, such as glyphosate, has also contributed to unnecessarily simplifying agricultural landscapes in many countries (Klein et al., 2007; Kammerer et al., 2021).

Habitat loss, which has reduced the abundance and diversity of floral resources and nesting opportunities, has undoubtedly been a major long-term driver, throughout the 20th Century, and still continues today. In addition, both wild and managed bees have been exposed to a succession of emerging parasites and pathogens that have been accidentally moved around the world by human activities. Agricultural intensification (Figure 1) and the increasing reliance on pesticides mean that pollinator animals are chronically exposed to cocktails of agrochemicals. Predicted changes in global climate are also likely to further exacerbate such problems in the future (NRC, 2007; Goulson et al., 2015).

Figure 1. Intensive monoculture agriculture creates hostile environments for all pollinator groups

Despite the crisis, based on the number of articles in the media, Althaus et al. (2021) pointed out that the incremental and often invisible progress of pollinator declines has made it difficult for the issue to be raised as frontline news in the USA and other countries. Among the reasons are that the topic is often subordinate to the more dramatic climate change discussions and the inadequacy of government policies toward the protection of the pollinators (Althaus et al., 2021).

Weeds for Bees?

The primary agricultural crops of the world flower *en masse* at particular times. Mass flowering produces floral resources simultaneously, but these provide food only for a fraction of the active season of pollinators. For the remainder of their lives, pollinators must rely on alternative foraging, which is generally provided by 'non-crop' flowering plants and colonizing taxa in agricultural landscapes (Figure 2).

Because of their ubiquity, abundance and diversity, floral resources of weedy taxa appear essential for insect pollinators. Their presence correlates with the persistence of abundant pollinators throughout the year and from one year to the next (Klein et al., 2007; Kammerer et al., 2021).

A recent review - "*Weeds for Bees*" by Bretagnolle and Gaba (2015) from the French *Institute for Research on Agricultural Intensification*, showed that honeybees have declined dramatically, globally and argued that weeds could help. Given that about 35% of major global crops depend on pollination services, a drop of up to 8% of global crop production is inevitable without pollinators.

Figure 2. Weedy flowers visited by bees

Pollination is also linked with other ecosystem services, such as honey production and weed management. Intensive agriculture has also decreased weed diversity by about 50% in the past 70 years. Repetitive herbicide treatments over extended periods have reduced the weed abundance and competition between weeds and crops in some parts of the world (Bretagnolle and Gaba, 2015).

It is also clear that in North America and Europe, it is a double whammy. Both pollinators and weeds have dramatically declined under recent agriculture intensification. Still, as Bretagnolle and Gaba (2015) argued, "*weeds are at the basis of agricultural food webs, providing food to many living organisms"*. In particular, many researchers have noted that weeds provide flowers for pollinating insects, including honey and wild bees and that both weeds and pollinators are affected by the availability of landscape features, habitats, and natural and semi-natural elements (Garibaldi et al., 2009; Ratnieks and Balfour, 2021; Balfour and Ratnieks, 2022).

Given that weed abundance can reduce crop yields, promoting weeds as a resource for pollinators in agricultural landscapes may result in an unnecessary conflict with farmers. Therefore, a dialogue with farmers appears to be crucial for explaining the biodiversity values of weeds, especially the pollination benefits of assemblages of 'flowery' colonizing species for agriculture.

In the USA, significant efforts are underway to help farmers understand that "*bees are in trouble*" in agricultural landscapes, and that "*some weeds can help*" (NWCB, undated). Farmers are encouraged to conduct "*bee-sensitive weed control"* and retain some species to support pollinators (NWCB, undated). However, with the limited data available, thus far, on the importance of colonizing taxa for bees, the advice to farmers has been cautious.

For example, the *Noxious Weeds Advisory* pamphlet says, "*it is important to control noxious weeds to help protect our diverse native plants, natural resources, and agriculture*. *Although some weeds may serve as forage for bees and other pollinators, the detrimental impacts of invasive plants significantly outweigh their value as a pollen and nectar source*" (NWCB, undated).

There are also various other projects, in the USA, initiated by "*Pollinator Partnership*" a non-governmental organization, founded in 1997. The stated aim of the organization is to "*protect the health of pollinators and the ecosystems supporting them*". The projects include "*Bee-Friendly Farming*", reducing pesticide uses in farming and promoting the retention of various non-crop species to support pollinators in agriculture, as well as other rural landscapes (Pollinator Partnership, 2022).

Environmental initiatives are currently underway, across other developed countries as well, to show that weeds enhance Nature's regulating services by ensuring the survival of honeybees and other pollinators, especially in the absence of crops. The abundance of wild plants also enhanced pollination services, crop yields, and honey yields for the benefit of bee-keepers. Weed abundance, more broadly, has also improved the survival of other native 'wild flora' and fauna and the socio-cultural value of landscapes, a significant request from the public (Bretagnolle and Gaba, 2015; Scheper, 2015; Scheper et al., 2015).

FAO-led "Global Action on Pollinators"

The global concerns about pollinators prompted important international initiatives, led by the UN's *Food & Agriculture Organization* (FAO). The FAO commissioned the agro-ecologist - Miguel Altieri - to lead a team that undertook an evaluation of the global status of pollinators and whether flowery resources from weeds could alleviate the stressors. The publication Altieri's team wrote: '*Crops, Weeds and Pollinators',* provides a synthesis of information on ecological interactions between pollinators and plants, especially weeds (Altieri et al., 2015).

The report attempts to answer two pivotal questions: (a) *Can weeds in agricultural fields help by providing resources to both pollinators and natural* *enemies of* crop pests? (b) *Can weeds be managed differently to provide such resources while still ensuring that they do not negatively affect crop yields?* Altieri et al. (2015) showed that the "*twin goals*" of managing weeds and pollinators within a framework of sustainable agriculture should be possible and should be attempted.

Globally, the area under cultivation of pollinator-dependent crops has increased faster than that of non-dependent crops. Therefore, the demand for animal pollination services has been rising concurrently with the decline in pollinator abundance and diversity. High levels of disturbance or vast areas of uniform cropping landscapes, dominated by monocultures of annual crops (e.g. grains and oil seeds), have been hampering the establishment and sustainability of pollinator populations (Altieri et al., 2015; Dicks et al., 2016; Balfour et al., 2021).

Broadly, intensively managed monocultures and homogenized landscapes reduce the environmental opportunities available for beneficial insects. This could prove critical for Brassicaceous crops, such as canola (*Brassica napus* L.) and others - flax (*Linum usitatissimum* L.), safflower (*Carthamus tinctorius* L.), sunflower (*Helianthus annuus* L.), tomato (*Solanum lycopersicum* L.), various pepper (*Capsicum* L.) spp., strawberries (*Fragaria* × *ananassa* Duchesne) and cucurbits (*Cucurbita* L.). All are examples of crops that require insect pollination for seed production.

Objective 2 of the FAO's strategic framework is to increase and improve the provision of "goods and services" from agriculture, forestry and fisheries in a sustainable manner (FAO, 2015). The goal recognizes that '*production systems must sustain multiple benefits by optimizing synergies and avoiding a pollination crisis*'. One of the most significant areas of 'potential synergy' identified is weed management and pollination management. Both have beneficial and harmful effects on the farmer and agriculture in general (Altieri et al. (2015).

The FAO's "*Global Action on Pollination Services for Sustainable Agriculture*" initiative aims to expand the global understanding, capacity and awareness of the conservation and sustainable use of pollinators for agriculture in the 21st Century. The programme includes global, regional and country-based local research to identify best practices to sustain agricultural production and natural pollination services while managing any problematic weeds.

The *Convention of Biodiversity* (CBD, 2018) has recently reviewed its position and has urged the signatory countries to understand the problem of pollinator decline across the globe and take responsible action. The vast corpus of knowledge in *Weed Science* shows that in unmanaged situations, in both agriculture and the general environment, the adverse effects of some colonizing taxa may outweigh their benefits. But the evidence from weed ecology is that one could manage weedy taxa carefully so that animal pollinators may not be adversely harmed. The challenge in ecosystem management is to manage both biodiversity and habitat in a way that all organisms co-exist to play their critical ecological roles and contribute to ecosystem stability (Altieri et al., 2015; CBD, 2018).

Biodiversity research has shown how specific pollinator groups can suffer from poor nutrition in simplified landscapes dominated by large-scale monocultures. Insects and birds can't find nutritious floral food resources easily in intensive agriculture landscapes. The evidence is all pollinators need to have access to the most comprehensive range of plant sources of nectar while spending less energy to reach those. That's the only way populations can overcome nutrition deficiencies. The ready availability of nutritious food would also allow them to better adapt to habitat fragmentation, climate change and other stresses (Altieri et al., 2015).

Beneficial Weeds

The term 'beneficial weeds' is not a misnomer. In the still-evolving discourse on biodiversity values of pioneering species, or colonizing plants (commonly called 'weeds' with a negative connotation they are 'undesirable'), such taxa 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 specific assemblages of colonizing taxa, in and around farmlands, to support biodiversity may seem unacceptable.

Many weeds do reduce crop yields when they aggressively compete with crops for limited resources, at a specific time in the crop's lifecycle. The influential factors and 'critical periods of weed competition' that may adversely affect crops are well understood within *Weed Science* (Zimdahl, 1980; 2012). On the other hand, there are many beneficial weeds with biodiversity values, which occur in cropping fields or adjacent areas.

A significant body of research has demonstrated that many arable weeds do not compete with crops to reduce yields and could be tolerated for biodiversity benefits. Studies have proven the potential benefits of weedy taxa providing resources to higher trophic groups on farmlands, including seeds for farmland birds and pollen and nectar for pollinators and biocontrol agents (Marshall et al., 2003; Storkey, 2006; Storkey and Westbury, 2007).

Storkey and Neve (2018) also showed that, from an agronomic perspective, diversity and richness in weed communities in cropping field environments are better for biodiversity than weed communities dominated by a few aggressive weed species.

However, in making the case for tolerating some colonizing taxa as ecological and biological resources in agricultural landscapes, caution is also made that those, which pose considerable risks to crops should be appropriately managed through integrated and sustainable practices. In their view:

If some abundantly-flowering weedy taxa could help pollinators, and do not significantly compete in cropping fields with the crops, they should be tolerated within sustainable production systems. As Storkey and Neve (2018) suggested: "*the twin goals of designing weed management systems that maximize production and maintain ecosystem functioning are entirely compatible and mutually reinforcing*". Such weed management systems, need to take account of the most problematic species while planning to retain those, which are unlikely to reach biomasses that pose a risk to farming.

Decades of weed research show that human-disturbed agricultural environments are not '*weed-free*' and should not be so. Cultivation of land for any kind of farming creates disturbances. Many colonizing taxa, which have evolved to follow such disturbances, will occupy those habitats (Baker, 1965). *Weed Science*, as a discipline, is also well aware that some weeds in cropping fields cannot be treated lightly (Zimdahl, 2012). If a pioneer species is likely to become a problem, in a particular crop, the tools to intervene with various cultural practices are well developed within the integrated weed management (IWM) frameworks, although, sometimes, they are poorly practised (Zimdahl, 2012).

Pollinator-friendly Strategies

Flower-bearing non-crop plants – trees, shrubs and other life forms - including weedy taxa, within the broader agricultural landscapes, are increasingly recognised as pollinator-friendly species. It is well known that frequent application of fertilizers to promote crops, intensive tillage and frequent herbicide use alter weed communities in agro-ecosystems. Unless such practices are carefully applied, they will simplify not just the cropping fields but also the vegetation in adjacent areas.

In intensively managed, hostile environments, pollinators must travel further to find rewarding forage. Intensive agriculture also generally creates conditions more suited to less rewarding annual species than the much preferred perennial species (Pywell et al., 2005; 2012; 2015).

Potts et al. (2016) argued that as with many aspects of biodiversity conservation, it is not easy to generalize what farmers and other people can do to enhance pollinators and derive benefits. However, the compelling evidence is that in any landscape, the greater the diversity and richness of flowering plants and flower abundance, the greater the abundance, diversity and persistence of pollinators year after year. This understanding should prompt action.

The consensus emerging is - If we preserve pollinators as a primary driver in evolutionary terms (outcrossing), these animals will return the favour. Those returns will far outweigh the food benefits they take from both crops and non-crop plants. Given below is a summary of some of the recent critical findings in several reports (Altieri et al., 2015; Goulsen et al., 2015; Bretagnolle and Gaba, 2015; Scheper, 2015; Scheper et al., 2015; Potts et al., 2016; Hicks et al., 2016; Dicks et al., 2016).

- Diversified farming, including organic farming, supports a greater variety of pollinator plant communities. These systems should include measures tailored to the particular landscapes, such as intercropping, using crop rotations that include flowering crops, agroforestry, and managing forests or home gardens.
- Traditional shifting cultivation, agroforestry and organic farming typically support a diversity and abundance of floral resources for pollinators through the integration of crops with other flowering shrubs, trees and forbs. Traditional farming systems also protect pollinator habitats because they are less disruptive to the environment. Usually, they retain or even incorporate weedy taxa within the systems.
- There is a strong correlation between using fewer herbicides and increased pollinator richness and abundance at both local and regional landscape spatial scales (NRC, 2007; Dicks et al., 2016).
- Supplying floral resources within broader agricultural landscapes, farm-scale agro-ecosystems, and adjacent semi-natural or natural areas (fragmented or not) improves pollinator diversity. It also increases their abundance and persistence year after year.
- Just providing flowering annual or perennial colonizing plants, in various mixtures, in field margins is insufficient. Preservation of bushland remnants, small or large intact forests and natural areas is critically important within broader agricultural landscapes (Scriven et al., 2013; Scheper et al., 2015; Stout and Tiedeken, 2017.
- On individual 'pollinator-friendly' species, plant and floral structural heterogeneity and plant taxon richness rather than native or non-native status have the strongest influence on pollinator species richness (Salisbury et al., 2015). This means plants with different habits (tall, short, sprawling,

climbing, etc.) and flower kinds (assorted colours, shapes and sizes) are more critical. Whether a species is 'native' or 'exotic' really does not matter to the foragers seeking nectar and pollen.

- The world's major crops themselves provide vast forage areas, due to 'mass-flowering', but only for short periods. However, in crop rotations, planting a succession of crops that flower at various times, would enhance pollinator abundance while maximizing yields. Coupled with it, proper management of non-cropped areas to encourage wild pollinators appears to be a cost-effective means of maximizing crop yields.
- Floral resources from crops or from a few plant species are most unlikely to ensure the health and resilience of pollinators. The widest variety of floral resources ensures a wholesome diet and pollinator health (Pain, 2017). In this regard, mass flower-bearing but slow-growing trees, shrubs, and herbs are as crucial as fast-growing colonizing trees, shrubs or herbaceous species.
- Food is not everything that pollinator populations need. They also need nesting sites and refuges. Instead of simplified environments, landscape heterogeneity needs to be created and maintained. It supplies the widest variety of foraging resources, nesting and breeding refuges for various pollinators (NRC, 2007). Colonizing taxa, offering floral resources, are part of these vegetated heterogeneous landscapes.

The evidence from numerous studies is that the central management tools available for farmers to increase pollinator diversity and abundance are preserving natural areas – bushlands, forests and forest fragments (Dicks et al., 2016; Whitehorn et al., 2021) and the reduction of herbicides and other pesticides (Wood and Goulsen, 2017; Nicholsen, 2018; Hotchkiss et al., 2022).

More stringent regulations for pesticides, especially neonicotinoid insecticides, fungicides and broad-spectrum herbicides, such as glyphosate (Hotchkiss et al., 2022) will help. Many countries are moving towards long-term monitoring of pollinators and pollination services, to further evaluate the species-specific effects of multiple stressors, including climate change, on insect populations (Jackson et al., 2022).

Farmers need to be convinced of the benefits of maintaining farmland biodiversity while improving yields, whether diversified, organic or ecologically intensified farming. In both Europe and the USA, there are calls for compensation for farmers for setting aside habitats for pollination services. The risk of pollen transfer by pollinators from genetically modified (GM) crops to non-GM crops is also recognized in some countries (Dicks et al., 2016).

There is a great deal of recent interest in ecological agricultural intensification. The focus has changed in the last 20 years because of the adverse effects of unsustainable farming practices (Dicks et al., 2016; Kovács-Hostyánszki et al., 2017). In these discussions, specific colonizing taxa do not feature much. Even conservation-oriented scientists are cautious in recommending weedy species as part of the solutions we seek. However, in agro-ecology, the roles of colonizing taxa are well recognized.

Agricultural intensification aims to achieve higher productivity through environmentally benign farming practices. It involves managing farmlands with a new mindset, novel approaches and perhaps, innovative technologies, such as including better yielding varieties, better irrigation, and demonstrably effective cultural practices. But ecological research has taught us that this approach can only succeed by making intelligent use of Nature's functions and services at field and landscape scales.

Smart agriculture also means enhancing natural ecological processes supporting agricultural production and reducing reliance on agrochemicals and other external inputs. The recognition of ecosystem services, biodiversity, natural pest regulation, and the critical role of pollination are new areas that scientists and farmers need to focus on. For millennia, farmers intensified their production systems by creating good soil health and nutrient cycling via fallow and build-up of organic matter, which they ploughed into the soil.

The enlightened ecological understanding, as well as the ways to practically implement that knowledge, is, however, relatively new. There are still significant gaps in our scientific understanding of the extent to which ecological intensification can be linked with integrated pest and weed management (IPM and IWM) to increase profitability at the farm scale or which practices are the most effective to achieve these outcomes. Nevertheless, specific actions, such as land-sharing (managed and unmanaged areas in farms) or land-sparing (in which high-yield farming is combined with protecting natural habitats from conversion to agriculture) are needed to achieve ecological intensification (Phalan et al., 2011) while improving the conditions for pollinators.

It is a trade-off between cropping intensively and supporting biodiversity. It has to be achieved while maintaining crop yields or at least farmers' incomes. The challenge is to keep colonizing taxa at the landscape scale while controlling the competition from weeds that may adversely affect crop yields. How to limit weed competition is a challenge that both agro-ecology and *Weed Science*, as disciplines, have been focused on for many decades.

The afore-mentioned study of Pywell and a team in Britain (Pywell et al., 2005; 2015) was the first to evaluate farm-scale ecological intensification with pollinator-friendly farming. This pioneering study found no decrease in the crop yields over a five-year crop rotation cycle on a large farm, despite taking up to 8% of land out of production to support ecological functions. The overall profits for the farmers also remained unaffected, demonstrating that wild-life-friendly management, supporting pollination, and other ecosystem services are compatible with and can even increase crop yields.

Research indicates that ecological infrastructure needs to be preserved, maintained or established for biodiversity benefits, including pollinators. In large or small agricultural areas, the maintenance of small- to medium-sized patches of natural or semi-natural habitat appears to benefit crop pollination services. The habitat patches could be a few hectares, distributed throughout the agricultural landscape, providing both nesting and floral resources within relatively easy reach of foraging pollinators.

An effective management technique for enhancing pollinator richness and abundance on farming landscapes is to plant flower-rich hedgerows, grassy borders, in-field insectary strips and meadows. Setting aside unmanaged areas to be colonized by non-crop, flowery species are also proven methods to facilitate on-farm pollination of particular crops. The same approach should benefit pollinators inhabiting urban areas (Altieri et al., 2015; Potts et al., 2016) and, eventually, us.

In recent research in the U.K., Hicks et al. (2016) showed that planted meadows are an effective way to improve the biodiversity and aesthetic values of urban areas and provide for pollinators at the same time. This research focused on annual grass meadows and perennial meadows and associated weeds established from commercial seed mixes in Britain. The team surveyed over two million flowers grown in 300 m^2 field meadows across four British cities. Nectar sugar and pollen rewards per flower varied widely across 65 plant species, with weed species (including dandelions, *Taraxacum* F.H. Wigg. aggregate) contributing to the top five nectar producers and two of the top ten pollen producers.

Seed mix species yielding the highest rewards (nectar per flower) were rough hawkbit (*Leontodon hispidus* L.), cornflower (*Centaurea cyanus* L.) and knapweed (*Centaurea nigra* L.). The highest pollen yielders were corn poppy (*Papaver rhoeas* L.) and Californian poppy (*Eschscholzia californica* Cham.), and musk mallow (*Malva moschata* L.). The research demonstrates that ecological engineering can assist in the pollination crisis and weeds are essential in plant mixes to ensure the continuity in floral resource availability throughout the year (Hicks et al., 2016).

Pollinator Interactions with colonizing taxa

The body of evidence showing the capacity of weedy taxa to help in the pollination crisis has been growing in the past decade. The reproductive success of many weed species appears linked to insect pollinators, especially the hairy honeybees and bumble bees and their foraging behaviours. Pollination is usually linked to the frequency of flower visitation rates, how much pollen gets adhered to the bodies of pollinator insects and their long-distance foraging (Goulsen et al., 1998; Balfour et al., 2013; Couvillon et al., 2015; Balfour et al., 2021).

As Stout and Tiedeken (2017) showed, ‘weedy (“Invasive”) plant traits, including reward nectar and pollen quantity and quality, spatial and temporal availability, abundance and accessibility, modulate effects on native flower insect visitors and visitations. Thus, different plant species have different impacts. Similarly, flower visitors do not all respond in the same way to weedy plants. Thus, generalizations are difficult to make, but understanding impacts at the individual and population level for different visitor taxa is key to explaining population and community-level impacts (Jackson et al., 2022). There is also increasing evidence that some pollinator relationships are quite specialized and can actually assist some introduced species to establish in new environments (Stout and Tiedeken, 2017).

Lantana depends on honeybees for pollination

The field studies of Goulsen and Derwent (2004) in Queensland showed that the difficult-to-manage lantana (*Lantana camara* L.) closely relates to honeybees (*Apis mellifera*). This research suggested that throughout a substantial portion of lantana's Australian range, its seed set was limited by honeybee abundance. The honeybee was the only pollinator recorded at sites where the seed set was highest in southern Queensland. The authors pointed out that artificial beehives are often stationed by bee-keepers within National Parks threatened by lantana.

Removing these and managing the honeybee populations could be a tool for controlling lantana in such situations. The study also indicated that other weeds may also benefit from honeybee pollination.

Water hyacinth helps when other flowers are scarce

Sometimes pollinators are not picky. Even water hyacinth [*Eichhornia crassipes* (Mart.) Solms], the much-maligned aquatic colonizer, can be an asset for pollinators when other food is in short supply. Water hyacinth's showy pale blue or violet coloured flowers attract pollinators. The flowers usually display 'tristyly' – meaning all flowers of an individual plant have one of three distinct style and stamen length types. Tristyly is an adaptation to avoid seed set by self-pollination (Barrett, 1977; Barrett and Forno, 1982).

However, water hyacinth, introduced outside its native range in South America, defies this trend. In countries where water hyacinth thrives, it is common to find high levels of seed production within its clonal populations. In this introduced range, water hyacinth with the intermediate-length style is prevalent whereas the long-style form occurs less frequently. The short-style form dominates in South America.

The short-style form does not commonly occur outside the water hyacinth's native range because of its close relationship with a local pollinator - the long-tongued bee, *Ancyloscelis gigas* Friese (Apidae). In the introduced range, across all continents, the honeybee, *Apis mellifera*, is the dominant pollinator for water hyacinth. Other pollinators may also be deriving benefits from water hyacinth while causing cross-pollination. An inflorescence with 20 flowers can produce over 3000 seeds, and a single plant can produce several such inflorescences.

Importantly, *Apis mellifera* is the most critical pollinator in Argentina for commercial bee-keepers. Honeybees feed on the hyacinth nectar, especially in coastal regions in the late summer when terrestrial flowers are scarce. This means water hyacinth flowers perform a vital function for honeybees critical for agricultural crops Coetzee et al. (2017).

Arable but rare weeds attract pollinators

Some rare weeds attract pollinators and benefit from close relationships (Gibson et al., 2006). Examples are hedge parsley - *Torilis arvensis* (Huds.) Link (also called 'stock destroyer') and common catchfly (*Silene gallica* L.), both of which are arable weeds. These natives of Eurasia, introduced to Australia in the past two centuries, are now naturalized in all Australian states and territories.

Another example is the red hemp nettle (*Galeopsis angustifolia* Ehrh. ex Hoffm., a well-known but rare weed in the British Isles and Europe. However, research in Britain shows that all three species are now rare plants but were linked to other plant species in the community by shared pollinators. While other plant species constituted the primary food sources for the shared pollinators, the population of these weed species are becoming rare because they depend on pollinators for seed-setting and long-term survival (Gibson et al., 2006).

Pollinator declines limit Productivity -Australian Findings

Australian research recognizes both native and introduced tree species and many colonizing taxa as necessary to the country's honey industry. Bee-keepers in Australia acknowledge that without weeds, such as capeweed (*Arctotheca calendula* L.), and various clovers (*Trifolium* L. spp.) providing a varied diet and emergency food supply when crops fail to flower, the local industry could falter.

In 2005-06, the total area of insect-pollinated annual and perennial crops (i.e., pome fruits, stone fruits, soybeans, lupins and sunflower) grown in Australia exceeded 970,000 ha. In the peak month of September and in the absence of any significant contribution from feral bees or other insect pollinators, for the optimal pollination of economic crops in that month, more than 480,000 colonies of honeybees would have been required, which shows their importance for such services (Keogh et al., 2010).

In a report on Australia's bee-keeping, Benecke (2007) quoted Gordon and Davis (2003), who had estimated the pollination values could be as high as Aus $1.8 billion/year to the industry. This figure is disputed as an underestimate. Based on the total number of Australian crops, which are pollinator-dependent (at least 53, instead of the 35 crops used by Gordon and Davis; see Karasiński, 2018), the figure could be much higher. Karasiński (2018) estimated the value of honeybee pollination in 2015 to be Aus $ 14.2 billion, which shows how vital insect pollinators are to the Australian economy.

The Australian honey yield comes predominantly from the native flora and is overwhelmingly reliant on *Eucalyptus* L'Hér. species and their close relatives, from the coast to the drier inland regions. It is also known that Australia's dominant flora is pollinated by insects, birds, bats, and other animals. The native flora, dominated by the Family *Myrtaceae* and *Fabaceae*, produces massive flower clusters with large quantities of nectar and pollen to attract various animals. However, pollen from some Australian native trees is known to be of little value to imported honeybees (such as the Western honeybee - *Apis mellifera*), now naturalized in the continent.

Such bees often do best when some European plants, usually weeds, occur in the vicinity of the flowering eucalypts. It confirms the view that assuming that native plants provide the best resources for all aspects of biodiversity may not be universally applicable (Benecke, 2007).

In addition to Australian native trees and shrubs, environmental weeds, such as European gorse (*Ulex europaeus* L.) and several willows (*Salix* L. spp.), contribute much to the health of pollinator populations. Many common European weeds, now naturalized in Australia, such as Paterson's curse (*Echium plantagineum* L.), viper's bugloss (*Echium vulgare* L.), fireweed (*Senecio madagascariensis* Poir.), flatweed (*Hypochaeris radicata* L.), dandelion (*Taraxacum officinale* F.H. Wigg.) and sowthistle (*Sonchus oleraceus* L.), provide significant honey and pollen, particularly in spring.

The diversity and abundance of weeds in Australia, like in many other countries, have declined due to agricultural practices and the extensive use of herbicides for general weed management. Having landscapes that maintain some weed diversity is crucial to having much-needed, season-long nutritious food for pollinators. The Australian report (Benecke, 2007) also suggested that the humble weeds may be able to help because the traditional food base for pollinators was diminishing fast as state forests were turned into conservation reserves.

The Australian bee-keeping industry has pointed out that many fruit and nut crops, such as almonds, would lose out if not for weeds providing food for the pollinating bees. Within the managed bee-keeping industry, it is also a known fact that blackberry (*Rubus fruiticosus* L. spp. aggregate), Patterson's curse and blanket weed [*Galenia pubescens* (Eckl. & Zeyh.) Druce var. *pubescens*], kinds of honey have become highly sought by the consumers for their unique flavours (Leach, 2012). This aspect of the pollinators' interactions with weeds is much understudied.

Providing nesting locations is also recognized as essential because most Australian native bees nest in the ground. Farming practices that destroy nests (e.g., the widespread use of plastic mulch and extensive tillage) are discouraged, while farms with various landscape features, including patches of bare soil, piles or hedges of stones and clump-forming grasses, are encouraged to provide ample nesting habitat for diverse pollinators.

Australian cropping systems are also encouraged to enhance resources for insect pollinators. Diversifying crops, inter-cropping, and mixed cropping with tall and shorter crops (i.e. a cereal crop and bean polycultures) are recommended as they provide different microclimates within the system. Given that weeds are ever-present within and around fields, the bee-keeping industry recommends using such taxa for pollination benefits.

Taking action to protect pollinators and weeds

Ecologists are convinced that broadly, urban green spaces, parks, recreational areas, golf courses, cemeteries, home gardens, and other areas set aside for utility infrastructures can be enhanced as habitats for pollinators by planting a variety of highly visible flowering plants. High flower densities and diversity are the most decisive factors, more relevant for pollinator diversity than the habitat type (Scriven et al., 2013; Daniels et al., 2020). The optimal strategy could be biased towards native species. However, a selection of exotic and striking ornamental garden plant species will most likely extend the flowering season and potentially provide resources for specialist groups over a more extended period.

The ecological engineering focus should be on structural heterogeneity and plant taxon richness rather than their native or non-native status. The aesthetic appeal of flowers and mass production should be the primary driver for selecting plants to support pollinators. Local flower availability, over space and time, is essential to preserve the energy of pollinators. Even small areas with vegetation structural heterogeneity, such as cemeteries, parklands, and road verges that provide habitat are crucial within urban environments. Many studies (Scriven et al., 2013; Daniels et al., 2020) have shown the value of conserving natural areas, whether they are fragmented or not, and restoring "green infrastructure" (networks of habitats that pollinators will move between) in the urban landscapes.

European Agri-Environmental Schemes (AES)

Among the 10 policies for 'bee-friendly' farming, Hicks et al. (2016) highlighted the need for policies and incentives, such as insurance schemes, to help farmers benefit from Nature's ecosystem services. Compensation or insurance appears to be at the heart of European Agri-environment Schemes (AES). These were introduced in the late 1980s to counteract the adverse environmental effects of modern agricultural practices. The biodiversity benefits of the schemes have produced mixed results in different European countries (Kleijn et al., 2006). Nevertheless, the European Union's 2007-2013 budget for agri-environment scheme projects was € 34.5 billion (Kleijn et al., 2011),

AES attempt to reduce the reliance of farmers on external inputs, such as synthetic fertilizers and pesticides, including herbicides, insecticides and fungicides (Batáry et al., 2015; Geppert et al., 2020; Batáry and Tscharntke, 2022). AES approaches focus on (a) non-productive areas, such as field boundaries and wildflower strips ("off-field" practices (Garibaldi et al., 2014), or productive areas, such as cropping fields grasslands ("on-field" practices).

The schemes also include promoting the retention of "off-field" areas, such as (a) hedgerows (generally for native bird conservation), (b) sown or naturally regenerated field margins, e.g. flower strips for pollinators (Pywell et al., 2012; 2015) or (c) simply taking land out of production for nature conservation purposes (Kovács-Hostyánszki et al., 2017).

In Europe, AES is now considered essential as a conservation tool in intensified agriculture. The schemes have been extended to incorporate pollinator-friendly farming. The schemes are widely promoted highlighting the key public message that pollinators depend on landscape heterogeneity, natural and semi-natural areas and varied sources of foraging resources, including crops.

AES research has proven how important the local management of individual farms and monitoring biodiversity can be. Biologically diversified farming, organic agriculture, unmanaged field margins and flower strips are essential drivers of pollinator diversity. Research shows that such pollinator-friendly practices can partly mitigate the adverse effects of conventional high-intensity farming on local pollinator populations (Scheper, 2015; Scheper et al., 2015; Potts et al., 2016; Geppert et al., 2020).

Generally, the response of pollinators to AES is moderated by landscape context and farmland type, with more positive responses in croplands (vs. grasslands) located in simple (vs. cleared or complex) landscapes. (Kremen and Miles, 2012; Scheper et al., 2013; Scheper, 2015; Batáry and Tscharntke, 2022).

Glyphosate and weeds

The evidence of causally linking the decline in insect pollinators to habitat destruction, the excessive use of neonicotinoid pesticides (Wood and Goulson, 2017) and the widespread use of broad-spectrum herbicides, such as glyphosate, cannot be disputed. Glyphosate has also been shown to affect bee health (Hotchkiss et al., 2022) as well as significantly reduce the abundance of flowery weeds, thereby having an indirect effect on bee populations (Nicholsen, 2018; Vogel, 2019; Kammerer et al., 2021).

Germany has been leading the way to take action to redress the overuse of pesticides, especially neonicotinoid insecticides and glyphosate. In 2019, Germany announced €100 million towards a biodiversity protection programme in agricultural landscapes (Nicholsen, 2018; Vogel, 2019). One-quarter of the funds in the plan is for further research and a nationwide insect monitoring network, as part of an extensive biodiversity monitoring programme that Altieri et al. (2015) called for. The monitoring focus will increase research and training in insect ecology and taxonomy, and also determine the causes of the declines, aiming to reverse the trends.

The plan also promises to phase out all use of glyphosate, the world's most common broad-spectrum (non-selective) weed killer, by December 2023. Glyphosate's extensive use is recognized often as a cause of the decline in weeds on which insects rely, along roadways, rail tracks, un-cropped areas and agricultural landscapes (Nicholsen, 2018).

There are three ways glyphosate is implicated. First, is the killing of many weeds, which are food sources for pollinators who forage in non-agricultural areas. Second, it affects honey bee behaviour. Researchers using field-realistic doses, similar to those bees might encounter in the environment, have found effects on navigation, with treated bees being less successful at returning to the hive. Glyphosate residues have also been detected in honey samples and pollen stored in the hives (Vogel, 2019).

Third, recent studies have shown that it affects bee health by causing changes in the gut microbiome. As in other animals, the health of bees depends on the bacterial community in their guts. This is because some (but not all) bacteria resemble plants in having the shikimate pathway and being susceptible to glyphosate. The research also found that disruption of the microbial community made the bees more vulnerable to infection by a pathogen when exposed (Hotchkiss et al., 2022; Jackson et al., 2022).

The German plan will influence other EU countries. Tighter regulations on all pesticides are likely to emerge. Approval of new pesticides – both herbicides and insecticides - will have to consider unintended consequences and acute or chronic adverse effects on biodiversity, including plant and animal populations. Anti-parasitic treatments used in livestock farming will also be reviewed because they could harm pollinating insects. The debacle insect pollinators face with the risks of colossal population collapses appears to have awakened even some politicians. Scientists say that in itself is '*remarkable*' - an awakening that '*has never happened before*' (Nicholsen, 2018; Vogel, 2019).

Creating flower-rich habitat

In Agricultural Landscapes

Pollinators and non-pollinator insect visitors of plants prefer floral diversity because that is how the evolutionary inter-relationships have worked over the past 100 or so million years. The greater the floral diversity (richness and abundance of flower kinds), the greater the diversity and abundance of such visitors (Klein et al., 2006; Altieri et al., 2015). However, while most insects are generalists in their pollen and nectar foraging, some pollinators can have specific preferences (Bucharova et al., 2021).

AES studies (Scheper et al., 2013; 2015) also show that the effects of wildflower strips on bees are mainly driven by the extent to which local flower richness is increased. The effectiveness of this measure could therefore be enhanced by maximizing the number of bee forage species in seed mixtures and by management regimes that effectively maintain flower richness in the strips through the years.

Many pollinators are generalists, foraging and sharing the same flowery resources. Or else, these relationships can be more specialized for some groups, which prefer specific plant families, genera, or species. Moreover, when there are plenty of flowers available for nectar and pollen, many of our pollinators happily forage among them. But when times are tough, they will utilize the same resources from weeds in meadows or urban gardens.

Local and indigenous flower-bearing plants, including weeds, are not necessarily the best for all situations. Bucharova et al. (2017) presented evidence that plant provenance was important for some highly selective pollinators. In some cases, plant species, introduced from outside a given region, can enhance the foraging resources and make significant differences to pollinator populations. This is because of the unique relationships some flowery species have with specific pollinator groups (Bucharova et al., 2016; 2021).

In addition, for species, such as bumblebees, a continuous food supply throughout the season is critical. Measures that enhance early-season landscape-wide floral resource availability, such as cultivating oil-seed rape (*Brassica napus* L.), can benefit bumblebees by providing the essential resources for early colony establishment and growth as soon as spring arrives (Scheper et al., 2015).

Like any other animal, a balanced menu makes for healthy, productive bees — but the loss of vegetation-rich areas, flowering trees and wildflowers, across large agricultural landscapes means that bees, all other insects and birds fail to find the kind of nutrition they need. The importance of the right mix of nutrients for honeybees to flourish and perform vital pollination services is abundantly clear.

In Urban and Per-urban areas

In many urban and peri-urban areas, peoples are aware of the land, currently used by fauna, especially where insects, birds, and other animals forage. People are also well aware of the fauna, who visit their urban backyard gardens, nature reserves, bushlands, or recreational parks and orchards. However, most people are not aware that there are also many other areas with intact vegetation, usable as wildlife refuges, within urban and peri-urban landscapes, which can assist pollinators.

Road verges of highways, stream and creek reserves, railway reserves, cemeteries, margins of sports fields and golf courses are such areas that can be managed to support populations of pollinators. There are also sizeable utility assets- reserve areas of water pipelines and powerlines, which can serve similarly. Additionally, many land rehabilitation sites, such as old land-fill areas, can also be used for pollinator conservation.

Within cities and new architectural designs, there are opportunities for vertical 'living walls', 'green walls' or 'bio-walls'. Such features are essentially designed so that plants grown vertically in them can reduce building heat and also treat recycled water. It would be a bonus of considerable value if flowery and hardy species can be integrated into these features to perform pollinator services and other multiple benefits for fauna (such as nesting sites). Still, at the same time, the species should be hardy enough to look after themselves with little human help.

Home gardening usually produces some food for one’s use and can also support bees, butterflies, birds and other fauna. Whether it is a window box, a balcony, or a small garden, planting various flowers that bloom visibly can help pollinators. Balcony herb gardens with potted plants are popular with city-dwellers: they connect people to the natural environment. With flowery, edible species, they can feed both people and pollinators.

'Bee-Friendly' Gardens as Nature-Based Solutions (NSBs)

Any flower can provide nectar and pollen for insects, other invertebrates and birds. While flower visitation may not be a synonym for pollination, most flying insects have the potential to cross-pollinate. The more efficient insects, such as bees, hoverflies, wasps, and moths, are for foraging, the longer they will live and carry out this evolutionarily significant function (Ratnieks and Balfour, 2021). So, the energy spent or saved on foraging becomes critical for the insects (NSC, 2007; Altieri et al, 2015).

Interactions between pollinator insects and flowering species, including weeds, are visible to any observer. Native trees and shrubs, bearing large flower clusters, are the most critical floral resources for pollinators. But weedy taxa can supplement the native resources because they are abundant and persist year-round, even in inhospitable places. Colonizing taxa are vital elements of heterogeneous landscapes. They increase pollinator diversity through habitat diversity and connectivity.

“Wildlife gardening” has been of interest in the conservation of fauna and flora species in urban settings for more than two decades. Households have been encouraged to undertake various approaches to encourage wildlife in their gardens (e.g., provide bird feeders or bird baths; avoid using chemical treatments; plant varieties attractive to wildlife; make compost; leave dead wood around; put up nesting boxes; build water features). However, such efforts, involving the public, have only limited success in supporting the conservation of most species under stress due to urban expansion (Gaston et al., 2007).

Recent research in Australia confirmed that the removal of intact native vegetation, especially those with structural and functional integrity, during urbanization, poses a threat to pollinators. If disruptions are too significant, they could even lead to cascading adverse effects and local extinctions of some species (Prendergast and Ollerton, 2021).

Most managed residential gardens are a poor substitute for the losses of native bushlands because they are not structurally equivalent. Recent research indicates a higher 'niche overlap' between pollinators in residential gardens. That means diverse groups compete more for limited floral resources, and if this competition is too intense, all fail (Prendergast and Ollerton, 2021). The removal of high-quality native vegetation is a common phenomenon in Australia, justified to expand the urban centres for an increasing population. The new urban designs make compromises by leaving various remnant parcels of bushlands and attempting to build residential areas and urban centres around the leftover vegetation.

In Australian cities, bushland remnants are interspersed among housing estates and are often delineated from residential housing only by fencing. It simply does not work. The disruption by habitat fragmentation does little to conserve those bushland habitats or species. The breakup presents an unacceptable risk of disrupting the stability of pollinator populations and assemblages.

To redress habitat fragmentation, it is possible to use road verges, power lines, railway banks, golf courses, wetlands, and waterways within and between urban areas as ecological infrastructure. Such infrastructure, if managed appropriately, with less intensive methods, will provide flowering and nesting resources supporting pollinators. Connecting pollinator habitat patches together with such linear features enables the movement of pollinators and enhances the pollination of wild plants as well.

An important area to focus on is how to find significant tracts of land where colonizing taxa exist but do not necessarily dominate in vegetation assemblages with native plant communities. There is some interest in such ideas in Australia, as they may reduce operational management costs of stakeholders' property portfolios. However, the supporting vibes are not really based on an appreciation of Nature's services.

Urban environments worldwide are considered a good source of year-round pollen and nectar. Gardens designed to support honeybees will secure resources, improve urban bee-keeping yields, and provide for other pollinators at the same time (Altieri et al., 2015). Therefore, a home gardener, planting various bee-attracting plants, could contribute to honeybee and native bee nutrition. Native plants attract more native pollinators and serve as larval hosts for some species of pollinators. A primary aim of an urban garden should be to create floral diversity - plants that flower at various times of the year, or all the time, to provide nectar and pollen throughout the growing season. Providing a variety of flower colours and shapes and in mixtures attracts different pollinator groups (Bucharova et al., 2016; 2017).).

Plantings in clumps, rather than single plants, make the food resource more visible to pollinators. Combinations of annuals and perennials also help. The target should be 'pollen-bearing' plants that can produce flowers year-round through the seasons. Large flower clusters, flowers of different shapes and bright colours always help. 'Bee-friendly' home gardens should also be relatively low-maintenance but sufficiently extensive to attract insect pollinators.

The modern-day Australian suburbs are brimful of such species. For example, tree species, such as jarrah (*Eucalyptus marginata* Donn ex Sm.), marrie [*Corymbia calophylla* (Lindl.) K.D. Hill & L.A.S. Johnson], scarlet gum [*Corymbia ficifolia* (F. Muell.) K.D. Hill & L.A.S. Johnson], and 'red cap' gum (*Eucalyptus erythrocorys* F. Muell.) produce vast flower clusters. Other iconic Australian species - wattles (*Acacia* Mill. spp.), banksias (*Banksia* L. spp.), paperbarks (*Melaleuca* L. spp.), bottlebrushes (*Callistemon* R.Br. spp.), grevileas (*Grevillea* R.Br. ex Knight spp.), tea trees (*Leptospermum* J.R. Forster & G. Forster spp.) and many others offer nectar and resources to all kinds of insect pollinators and birds.

Among small herbaceous colonizers in home gardens with attractive flowers are borage (*Borago officinalis* L.), sage (*Salvia officinalis* L.), oregano (*Origanum vulgare* L.), medics (*Medicago sativa* L.), woundwort (*Bellis perennis* L.), woodsorrel (*Oxalis pes-caprae* L. and other *Oxalis* L. spp.) and clovers (*Trifolium* L. spp.). Other horticultural species, such as sweet alyssum [*Lobularia maritima* (L.) Desv.], snowdrops (*Alyssum* L.) spp., pigface [*Carpobrotus glaucescens* (Haw.) Schwantes], false heather (*Cuphea hyssopifolia* Kunth), tickseed (*Coreopsis* L.) spp., vervain (*Salvia verbenaca* L.) and rosemary (*Salvia rosemarinus* Spenn.), adorn garden beds in urban areas. All such species, with attractive flowers, are likely to offer the diverse and high-quality diet sought by insect pollinators.

In vacant blocks and unmanaged nature strips, capeweed [*Arctoctheca calendula* (L.) Levyns], fireweed (*Senecio madagascariensis* Poir.) attract frequent insect visitors. Vigorously-growing hedge species, such as Cape honeysuckle [*Tecoma capensis* (Thunb.) Lindl.], bower vine [*Pandorea jasminoides* (G. Don) K. Schum.], English ivy (*Hedera helix* L.), Irish ivy [*Hedera hibernica* (G. Kirchn.)

Bean], passionfruit (*Passiflora edulis* Sims), blue or white leadworts (*Plumbago auriculata* Lam. and its hybrids), blue or white wisterias (*Wisteria* Nutt. spp.), potato vine (*Solanum laxum* Spreng.), turkey rhubarb (*Rumex sagittatus* Thunb.) also bear large and attractive floral clusters.

All such species are 'bee-friendly' but are strong colonizers, with fast growth, suckering and perennial life cycles. Often, such species are hard to manage in urban gardens, but they help the pollinators [2]. Many short-duration annuals, popular as horticultural species, are also crucial for pollinators because they produce brightly-coloured floral displays. Some examples are everlasting (*Rhodanthe* Lindl. spp.), a wide variety of African daisies (*Osteospermum* L. spp.), chrysanthemums (*Chrysanthemum* L. spp.) and poppies (*Papaver* L. spp.), on home gardens and road verges. Many species of the Asteraceae produce abundant flowers and aesthetically pleasing sights. They are enormously attractive to all kinds of bees, butterflies, hoverflies and other pollinators.

In creating a bee-friendly garden, proven performers are essential, not whether they are native or introduced. The balanced use of flowery natives and exotics would provide well for pollinators in such a garden. Often there is no 'winner-take-all' in the competition between colonizing species and slow-growing natives, as weeds are adept at co-existing with their slow-growing congeners.

There is nowadays an increased awareness of the need to preserve extant bushlands in urban settings, especially in developed countries. The public generally supports using the nature strips and road verges as multi-functional spaces, including the provision of shade, noise reduction and abatement of air pollution. Such spaces are considered suitable as potential *'bee hotels*' where the insects can recover.

In many Western countries, local authorities are trying to develop the *'best plant palette'* suitable for ecosystem services, including support for pollinators. The flowery colonizing taxa, including the species mentioned previously, are the best candidates for this simply because they are the easiest to establish and will tolerate sub-optimal growing conditions.

Species need to be carefully selected, based on assemblages of flowery, insect-pollinated trees, shrubs and herbaceous species, and not necessarily with a focus on whether the species have been introduced, naturalised in a given region, or not. If the greater emphasis is on floral resources, many species that may have been previously considered as ‘injurious weeds’ may be selected for their innate colonizing capacities, without prejudice.

The chances of success in establishing and quickly providing the essential services required should drive the plant selection process. Even though they may be colonizing taxa, many non-controversial ‘flowery’ species, from families, such as the Asteraceae and Brassicaceae, can be included in species mixtures to support pollinators and also achieve multiple environmental objectives from all available spaces in which they can be grown (Pywell et al., 2005; 2012; Salisbury et al., 2015). Public support can be obtained through well-articulated messages. Pressure from citizens is the only way to find a compromise between bulldozing every available area for concrete and housing estates.

Conclusions

Conserving pollinator biodiversity is becoming increasingly important with the rising human demand for insect-pollinated crops. In the last two decades, compelling evidence has emerged that the world is indeed witnessing a ‘pollination crisis’ with direct implications for both agriculture and the environment. The adverse effects of the pollinator declines may even extend into unknown effects on the evolution of flowering plants because of the closeness of the inter-relationship (Ratnieks and Balfour, 2021).

There is an acute awareness now in the scientific community that (a) habitat losses due to landuse practices, (b) the extensive agricultural use of neonicotinoid insecticides and other pesticides, and (c) declines in flowery weedy taxa are linked to the overall pollinator declines being recorded worldwide. Our understanding of the risks to pollinators, and the choices we make about pest and weed control, must evolve to reflect and balance these realities.

Evidently, there are no risk-free choices, but with more information and greater awareness, it seems reasonable to think that we can make the most appropriate decisions about how to (a) produce the food we need and (b) safeguard the environment in which we wish to live, without inflicting irreparable damage on our environment and the critical ecosystem services other organisms and species provide (such as pollination).

The CBD (2018) acknowledges the need to improve knowledge of pollinators and pollination and their role in maintaining ecosystem health and integrity beyond agriculture and food production. It

[2] Vast numbers of ‘bee-friendly’ varieties of *Citrus* spp. (limes, lemons, mandarins, etc.) or *Prunus* spp. (plums, cherries, etc.) grown in suburban backyards are not listed here because they are not colonizing species. They are cosmopolitan high-value fruit trees and shrubs. However, blackberries and brambles (*Rubus fruiticosus* aggregate), raspberries (*Rubus idaeus*), etc. are robust colonizers.

also calls for urgent governmental action, across the globe, to highlight the pollinator decline issue and take the necessary remedial action to preserve habitats and enhance those that would support pollinators. In the face of ongoing global changes of climate change and other stressors impacting pollinators, it is imperative to conserve insect populations to safeguard future pollination services.

In an important study of the effects of climate change and bees in the USA, Jackson et al. (2022) found no evidence of genus-wide declines in bees occupying particular sites, but a strong relationship between site occupancy to temperature, and a weak correlation to rainfall and floral resources. Overall, they found that more species are likely to be climate change ‘losers’ than ‘winners’ and that this effect is primarily associated with changing temperature. Importantly, all trends were highly species-specific, highlighting that genus or community-wide measures may not reflect diverse species-specific patterns that are critical in guiding the allocation of conservation resources (Jackson et al., 2022).

A detailed knowledge base on pollinator species and their relationships with different land use and climate variables is invaluable here, as it allows conservation measures to be targeted effectively. Future assessments must consider multiple global change pressures simultaneously, and not only the impact of one pressure in isolation (Whitehorn et al., 2021). As Althaus et al. (2021) suggested, there is an opportunity to link the potential adverse effects of climate change with the repercussions of pollinator declines to “*stimulate and maintain public concern about the shrinking biomass and diversity of insect pollinators*” and make it a frontline issue that draws media attention.

The evidence from the past two decades of pollinator-linked research is that floral diversity and flower abundance are far more important for pollinators than even habitat fragmentation (Scheper, 2015; Daniels et al., 2020). Preservation of natural vegetation areas, whether disjointed or not, and ecological restoration of fragmented urban ecosystems appear to present a significant pathway to increase the connectivity of pollinator-friendly habitats and support species dispersal and gene flow. These measures are likely to be crucial in contributing to climate change mitigation and related risk reduction related to pollinator populations.

Despite some significant research, linking weeds as “*disproportionately important*” as resources for pollinators (Balfour et al.,2022), colonizing taxa continues to be under-appreciated in this biodiversity role. The crucial ‘*double status’* of weeds – one that is associated with negative effects in arable farming and the other, associated with ecological values – is a paradox we face. It will continue to restrict easy measure-oriented rewarding concepts, such as the recognition of ‘*beneficial weeds*’.

Perhaps the ‘pollination crisis’ that we are currently facing, has created a greater global awareness of the complex issues involved. Globally, the public is demanding a decrease in all pesticide inputs, while protecting or increasing crop yields, qualities and the long-term sustainability of both agricultural and non-agricultural environments. Many developed countries, including the U.K. and Western Europe, are, therefore, in the process of overhauling their agricultural and environmental policies to support biodiversity management in all areas.

However, Balfour and Ratnieks (2022) recently argued that these policies are not yet designed to encourage ‘*land sparing*’ or ‘*land sharing*’ with weeds. In their view, much stronger advocacy appears necessary to encourage more wildlife- and climate-friendly agricultural practices. The challenge of reconciling the conflicts between agricultural production, weedy taxa (both introduced and native), with biodiversity values should be a renewed priority to land managers, researchers and policymakers (Balfour et al., 2021; Balfour and Ratnieks, 2022).

Within agricultural landscapes, non-agricultural, urban and peri-urban areas and regions, there is compelling evidence that NSBs will be effective. Conservation of natural and/or semi-natural areas, fragmented or otherwise, will add to other ‘green spaces’ and increase benefits for people, other animals, and plants. NSBs are increasingly recognized for reducing the negative emotions that people feel in modern living and thereby improving human health and well-being. They are also workable solutions to mitigate the stressors all animals feel.

NSBs, such as 'bee-friendly' gardens and associated 'green infrastructure' in cities, may not be as effective as uncultivated areas and semi-natural habitats, which are great repositories of biological diversity and critical for the greatest variety of pollinators to survive (Daniels et al., 2020). Nevertheless, urban landscape designers should have the courage to incorporate fast-growing species into future designs, providing habitats for various fauna species who live amongst us, sharing our spaces. A good understanding of plants with colonizing attributes and the benefits they can provide will aid in preserving our environment to benefit societies and cultures anywhere in the world.

Rallying the public to manage the adverse effects of any colonizing species, introduced to regions away from their native ranges, should be done best with a deeper ecological understanding of individual species rather than confusing terminology, such as 'invasive species'. Management should also keep an eye out for economic, environmental, and social implications, without dramatizing issues, and avoid messages that create a visceral dislike for the colonizing plant taxa.

There is ample knowledge in ecological research to identify mixtures of flowery annual and perennial weedy species, including groundcover species that can encourage pollinator visitations, with offers of a variety of sugary food. However, deeper awareness and a degree of tolerance are needed for farmers to live with specific colonizing species. This comes with an understanding that *not all weedy species are created equal; nor will they all reduce the yields and quality of a particular crop in question*.

As many research groups (Pywell et al, 2012; Garibaldi et al., 2014; Bretagnolle and Gaba, 2015; Altieri et al., 2015; Hicks et al.,2016; Balfour et al., 2022) recommend, floral species mixtures inclusive of weedy taxa can undoubtedly help bees and other pollinators. But we need a fresh set of lenses to see those virtues in weedy taxa and better integrate them with our lives. I agree with Robert Zimdahl (*pers. comm.*, Dec 2021), who suggested:

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

Weedy species are no more alien or villainous than we humans have been. With or without humans on the planet, colonizing species will play vital roles in stabilizing the earth's damaged ecosystems. They will survive catastrophe on earth. We may not.

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