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Exploring the Multi-dimensional Impact of Insects on the Green Revolution

Abdul Hamid Nazari[1], Zal Khan Abdullah[2] and Mohammad Yar Malakza[3]
[1,2]Department of Plant Protection, Faculty of Agriculture, Helmand University, Afghanistan
[3]Department of Agronomy, Faculty of Agriculture, Helmand University, Afghanistan
Email: nazarihamid40@gmail.com (corresponding author)

ABSTRACT

The Green Revolution marks a significant era of agricultural advancement in the mid-20th century, playing a vital role in addressing global food security challenges. While the contributions of crop breeding, mechanization, and agrochemical use to this movement are well-recognized, insects' complex and varied impact remains less explored. This paper highlights insects' diverse roles during this transformative period. Drawing on a range of scientific research, scholarly publications, and online scientific databases, this review examines insects' beneficial and detrimental influences on the Green Revolution. Pollinators like bees and butterflies supported crop fertilization, boosting yields and preserving genetic diversity. At the same time, pest insects pose serious threats to crop productivity, often resulting in considerable losses if uncontrolled. Developing and applying insecticides were pivotal in mitigating these risks and safeguarding crops against destructive pests. Insects also shaped the ecological balance within agricultural systems; predatory insects, like ladybugs and lacewings, naturally controlled pest populations, reducing dependency on synthetic insecticides. Decomposers, such as dung beetles, contributed to nutrient recycling and soil health, indirectly supporting crop growth. However, the Green Revolution's reliance on high-yielding crop varieties and intensive farming practices unintendedly affected insect populations and biodiversity. The widespread adoption of monocultures and heavy pesticide use led to habitat loss and a decline in insect diversity, which may disrupt ecosystem services and affect long-term sustainability. Understanding the multifaceted role of insects in the Green Revolution is essential for guiding sustainable agricultural practices in the future.

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Introduction

In 1968, William Gourd introduced the term "Green revolution" to depict a transformative process that drives enhancements in agricultural productivity. The global population is estimated to exceed nine billion by the year 2050. Underdeveloped countries are anticipated to experience the majority of this population, which are already facing significant challenges in meeting their food needs (Benbi, 2017). The Green Revolution brought about a substantial increase in crop productivity by implementing various measures. These measures included expanding the cultivated land area, adopting double-cropping practices to grow two crops annually, utilizing high-yielding varieties (HYV) of seeds, substantial increases in the utilization of inorganic fertilizers and pesticides, the improvement of irrigation systems, and adopting enhanced farm machinery and crop protection techniques (Singh, 2000; Brainerd & Menon, 2014). Considerable resources were allocated to crop research, the development of infrastructure, the expansion of markets, and the implementation of appropriate policy support measures (Pingali, 2012). Concerted endeavors were made to improve the genetic characteristics of conventional crops. These initiatives involved selecting for enhanced yield potential, adaptability to diverse habitats, shorter growth periods, higher-quality grain, resistance against biotic stressors like insects and pests, and resistance against abiotic stressors like aridity and flooding (Khush, 2001). Following the green revolution, the production of cereal crops experienced a threefold increase, while the cultivated land area only expanded by 30%. This remarkable achievement was witnessed globally, with a few limited exceptions. Moreover, the Green Revolution positively affected poverty alleviation and increased economic food prices (Pingali, 2012). Research studies have shown that in the absence of the green revolution, there would have been an estimated decline of around 11-13% in caloric availability (Johan & Babu, 2021).

Insects are significant in global food production, contributing approximately 15% to 30% of the total output (Roubik, 1995). Flower visitation has been observed across various insect orders. Still, only four stand out for their significant role in regularly pollinating flowers and engaging in mutualistic relationships with crops. The four orders are Coleoptera (beetles), Diptera (flies), Lepidoptera (butterflies and moths), and Hymenoptera (ants, bees, and wasps). Additionally, some thrips species, which consume pollen, may act as pollinators, while certain stoneflies (Plecoptera) and true bugs (Hemiptera) explore flowers to feed on pollen and nectar. Furthermore, specific lacewing (Neuroptera), Scorpionfly (Mecoptera), and caddisfly (Trichoptera) species consume nectar. However, further research is necessary to establish whether most of these less well-known flower visitors serve as pollen vectors (Inouye & Ogilvie, 2001). Honey bees are the main pollinators for many flowering plants worldwide, crucial contributors to the pollination of around 66% of the world's 1500 crop species. This contribution by honey bees accounts for 15-30% of global food production (Ollerton et al., 2011). Honeybees have shown their efficacy in pollinating diverse types of crops, such as oilseeds, forage, fiber, and cereal crops (Halder et al., 2019).

Beneficial Insects in the Green Revolution

Biotic communities are essential to fulfill environmental functions and provide valuable ecological services (Naeem et al., 2012). Insects are incredibly diverse and successful organisms, with over one million identified species, and their total count has been approximated by several million species that have yet to be discovered. They inhabit nearly every corner of the Earth, from the highest mountains to the deepest oceans. They are distributed across various habitats, such as forests, pastures, deserts, wetlands, and urban areas. One of the critical reasons for insects' success is their ability to occupy various trophic niches. They display a remarkable range of feeding habits, including herbivory (feeding on plant material), carnivory (preying on other animals), scavenging, and detritus feeding (consuming decaying organic matter). This diversity in feeding strategies allows insects to exploit a wide array of food resources, contributing to the stability and functioning of ecosystems (Gullan and Cranston, 2014). Insects profoundly impact ecosystem dynamics and processes due to their large numbers and incredible diversity. They contribute to maintaining the balance and functioning of ecosystems through the various ecological services they provide (Samways, 1993; Kim, 1993). The ecological importance of insects is often overlooked due to their common perception as pests or potential pests. However, insects play critical roles in ecosystems through various ecological functions, including pollination, ecosystem cycling, decomposition, and predation/parasitism (Jankielsohn, 2018).

Insect as Pollinators

Insects have a substantial influence on both the quality and quantity of crops. Within agricultural and horticultural contexts, insect pollinators perform an essential function by transferring nectar and pollen from one flower to another. This practice is essential for successfully pollinating various crops, including cucurbits, citrus, pomegranate, and fig. These horticultural crops, highly dependent on cross-pollination, require pollinator insects to augment crop yield and quality through their intervention (Haldhar et al., 2018). Research indicates that approximately 84% of the 300 commercial crops are pollinated by insects. Honey bee pollination plays a crucial role in successfully pollinating certain crops Table. 1. Honey bees have been observed to contribute significantly to the increased yield of crops such as apple, niger, onion, and faba bean, with reported improvements ranging from 33% to 84% (Bareke & addi, 2019). The data presented in Figure 1 shows the overall economic worth of crop production that relies on honey bee pollination, encompassing the top 20 crops. The data indicates that apples, almonds, macadamia nuts, melons, and cherries substantially rely on honey bee pollination. According to a study by Stein et al. in 2017, bees' pollination of cotton and sesame resulted in an enhancement in both the quality and quantity of the crops. In cotton, bee-mediated outcross pollination led to significant improvements in yield, ranging from 27% to 31%. In a research investigation carried out by Vinícius-Silva et al. in 2017, it was observed that the seed weight and number in tomato fruits increased because of the movement of pollinators such as *Aphis mellifera*, *Trigona spinipes*, and *Exomalopsis analis*, as compared to self-pollination (Pollination without insects). In a study conducted by Garratt et al. in 2018, it was observed that insect pollination resulted in a significant improvement in yield, specifically a 40% increase in *Brassica napus*. Almonds (*Prunus dulcis*) are a cross-pollinated crop and require pollinators due to their self-incompatibility. The primary pollinators for almonds are honey bees (Connel, 2000). The researchers observed a considerable increase in fruit setting, with approximately 60% higher rates, and a 20% boost in kernel yield among trees pollinated by bees, compared to trees that did not receive bees as pollinators.

Furthermore, the study indicated that honey bee pollination increased the production of oilseed rape (*Brassica napus*), Strawberry (*Fragaria x ananassa*), field bean (*Vivia faba*) and buckwheat (*Fagopyrum esculentum*). A study carried out by Padamshali and Mandal in 2018 in West Bengal demonstrated the significant impact of honey bees on enhancing onion yield. Seeds obtained from self-pollinated crops exhibited a higher germination percentage (76%) compared to seeds obtained from non-insect-pollinated crops (14%). In a study by Shakeel and Inayatullah in 2013, it was reported that nine species of bees and flies played a beneficial role in foraging and visiting canola crops, increasing the crop's yield.

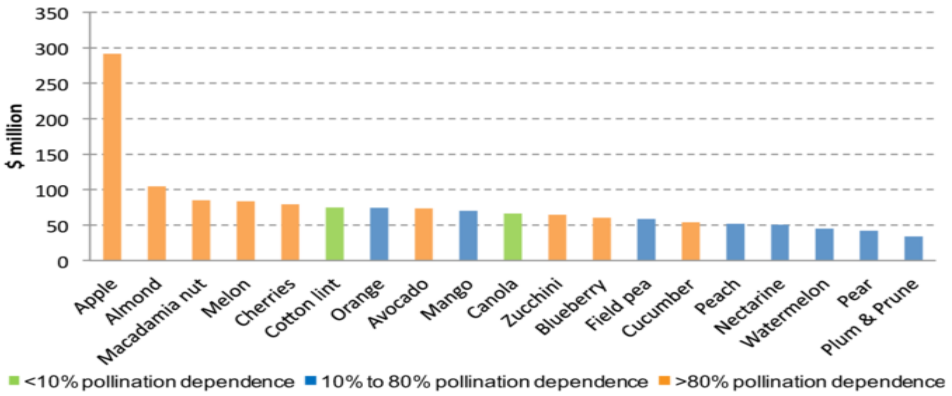
In Kota, Rajasthan, a separate study investigated the impact of honey bees on mustard yield during the 2013-14 and 2014-15 seasons. The study involved three pollination modes: bee, open, and pollinator exclusion (no pollinators). During both seasons, bee pollination demonstrated a substantial increase in yield compared to the pollinator exclusion treatment. During the 2013-14 season, the mustard harvest was recorded as 1785 kg/ha in the bee-pollinated treatment, 2040 kg/ha in the open-pollinated treatment, and 1509.38 kg/ha in the pollinator exclusion treatment. These results highlight the positive influence of bee pollination on the yield of mustard crops compared to the other treatments. Similarly, the yields were 1875 kg/ha, 2068.75 kg/ha, and 1577 kg/ha, respectively, during the 2014-15 season (Patidar et al., 2017). A study conducted by Sihag in 1986 at Hisar, India, revealed the significant role of bees as primary pollinators in enhancing seed rates in umbelliferous and cruciferous crops. Insects, including bees, contributed to a remarkable 1.8-fold increase in seed yield. In the Northwestern Himalaya region of India, honey bees were found to play a crucial role in promoting higher seed production in broccoli, Chinese cabbage, and German turnip crops. During the 2006-07 and 2007-08 seasons, the seed productivity of Chinese cabbage, German turnip, and broccoli in the natural pollination condition was recorded as 187 kg/ha, 143 kg/ha, and 439.30 kg/ha, respectively. However, when honey bees were specifically pollinated, the seed yield increased to 212.85 kg/ha, 187 kg/ha, and 181.20 kg/ha, respectively (Sushil et al., 2013).

Table. 1. Percentage of crop production dependent on honey bee pollination

Crop	Dependence (%)	Crop	Dependence (%)	Crop	Dependence (%)
Almond	100	Grapefruit	72	Peanut	2
Apple	81	Kiwifruit	72	Pear	45
Apricot	56	Lemon & Lime	18	Plum & Prune	63
Avocado	90	Lucerne seeds	90	Pumpkin	10
Bean-Soybeans	5	Lupin	10	Raspberry	90
Blueberry	90	Macadamia nut	81	Rockmelon	90
Canola seed	90	Mandarin	27	Strawberry	4
Canola	14	Mango	72	Sunflower	90
Cherries	81	Nectarine	48	Watermelon	63

Cotton lint	8	Orange	27	Zucchini	90
Cucumber	90	Papaya	16	Vegetable seed	90
Field pea	45	Peach	48		

Source: ABARES calculations based on Cook et al. (2007); Cunningham, FitzGibbon & Heart (2002); Gordon & Davis (2003); Keogh, Robinson & Mullins (2010); Monck et al. (2008); and Morse & Calderone (2000).



Note: Value of production dependent on honey bee pollination is the product of annual crop value and the percentage of crop dependent on honey bee pollination.

(Source: Hafi & Hafi, 2012)

Figure 1. The economic value of production is dependent on pollination for the top 20 crops in Australia.

Insects as Biocontrol Agents

Several beneficial insects are highly significant as natural enemies. Lacewings, similar to lady beetles, are known to prey on aphid colonies. They also consume scales, mites, and mealybugs. Stink bugs, despite being considered damaging insect pests, can serve as valuable predators due to their varied eating behaviors, which differ among species. Lady beetles exhibit frantic searching behavior and quickly bite their prey, allowing them to consume a wide range of small insects regardless of their developmental stage. While aphids are their primary food source owing to their diminutive size, ladybeetles also consume whiteflies, mealybugs, scales, mites, beetle grubs, small caterpillars, and a variety of insect eggs. Among mites, a few species, like spider mites, are harmful pests to crops, while others are valuable. Phytoseiid mites are particularly important among beneficial mites since they prey on plant-feeding mites and small organisms like thrips and insect eggs (Nazir et al., 2019). Predators and parasitoids, inhabiting upper trophic levels as consumers at the secondary or tertiary level, are crucial in regulating the population growth of primary consumers and phytophagous organisms. They act as natural controls for herbivorous insects, especially those with the potential to become pests (Van Lenteren, 2012). The insect orders Odonata (dragonflies) and Neuroptera (lacewings and ant lions) consist entirely of predatory types. In the Hemiptera, Diptera, Hymenoptera, and Coleopteran orders, a significant percentage of species are predators, either during their larval stage or throughout their larval and adult stages. Table. 2 displays the effective natural enemies found in agri-horticultural ecosystems, including their respective families, host ranges, and feeding sites.

Table. 2. Efficient arthropod predators for controlling major insect pests in different crops

Natural enemy	Pest	Crop
The ladybird beetles *Menochilus sexmaculatus*, *Brumoides suturalis*, *Harmonia dimidiate* and *Coccinella septempunctata* and green lacewings, *Chrysoperla zastrowi sillemi*	Aphids; Aphis *craccivora*, *Myzus persicae*, *Lipaphis erysimi* (Hemiptera: Aphididae) and Leafhoppers; *Empoasca kerri*, *E. facialis*, *E. fabae* (Hemiptera: Cicadellidae) etc.	Vegetables, Fruits, Pulses, Oilseeds
Predatory mites such as *Phytoseilus persimilis* and several species of *Amblyseius spp*.	Spider mite; *Tetranychus spp*. (Acari: Tetranychidae)	Tomato, Brinjal, Sweet Peppers, Cucumber
Cryptolaemus montrouzieri, *Scymnus spp*.	Mealy bugs, *Paracoccus marginatus* and *Phenacoccus solenopsis*, green shield scale: *Pulvinaria psidii* (Hemiptera: Pseudococcidae), etc	Brinjal, Okra, Tomato, Papaya, Guava, Sapota, Lemon
Coccinellids *Chilocorus nigrita* and *C. circumdatus*	Green scale, Coccus *viridis* (Hemiptera: Coccidae) on acid lime and white scale *Aulacaspis tubercularis* on mango (Hemiptera: Diaspididae)	Acid lime, Mango
Predatory mirid bugs, *Nesidiocoris tenuis*	Tomato pinworm, *Tuta absoluta* (Lepidoptera: Gelechiidae), etc.	Tomato, Potato, Pepper
Predatory anthocorid bugs, *Orius sauteri*	Thrips; *Thrips palmi*, *Frankliniella occidentalis* etc.	Brinjal, Sweet pepper, Cucumber

Source: Halder et al., 2018; Seni & Chongtham, 2013; Waterhouse & Sands, 2001

Insects as Nutrient Recyclers

The presence of insect herbivores can significantly modify the quality, quantity, and timing of plant debris inputs, thereby hypothetically exerting substantial impacts on ecosystem recycling (Mattson & Addy, 1975). Belovsky and Slade conducted a study and discovered that grasshopper herbivory increased plant richness, primarily through the greater accessibility of nitrogen (Belocsky & Slade, 2000). Phytophagous insects play a crucial role in driving ecosystem processes by converting living plant biomass into various forms such as frass, greenfall, and throughfall (Hunter, 2001). Additionally, they can contribute to a substantial portion of the nitrogen and phosphorus fluxes from above-ground to belowground within ecosystems (Metcalfe et al., 2014).

Insects as Decomposers

Insects, including dung and carrion, play a significant role in the crucial ecosystem process of decomposing organic waste. Dung beetles, with approximately 4000 documented species, are particularly important contributors to the decomposition of manure (Scholtz & Mansell, 2017). Dung beetles enhance soil health by increasing the content of important nutrients like nitrogen, phosphorus, potassium, calcium, magnesium, and total proteins (Macfadyen et al., 2015). Dung beetles also contribute to the carbon cycle by reducing greenhouse gas (GHG) emissions, decreasing approximately 7% to 12% (Nichols et al., 2008). Termites, flies, beetle larvae, and ants are important agents in cleaning plant debris, breaking it down for subsequent decay by microorganisms. In particular, ants and termites, as soil macroorganisms inhabiting arid and warm regions, play a pivotal role in improving the accessibility of mineral nitrogen within the soil (Evans et al., 2011). Carrion is a nutrient for insects, with flies and beetles playing major roles as insect detritivores (Merritt & De Jong, 2015). Calliphorid flies are the initial colonizers of cadavers, pioneering the start of a dynamic sequence of arthropod species succession that inhabit the decaying remains. This succession can involve as many as 100 species from various insect families (Farwig et al., 2014; Richards & Goff, 1997). The decomposition efficiency is determined by the specific function contributed by a particular species rather than its abundance. A study by Farwig et al. in 2014 demonstrated that the decomposition proportion of carrion is influenced by the composition of insect scavenger assemblages rather than the number of individuals present.

Detrimental Insects in the Green Revolution

In agricultural systems, insect pests are a leading cause of crop production and storage damage. There are over 10000 insect species, 30000 weed species, 100000 diseases caused by fungi, viruses, bacteria, and other microorganisms, and 1000 nematode species that contribute to the damage inflicted upon food plants worldwide (Hall, 1995; Dhaliwal et al., 2007). As farming technology has progressed and agricultural practices have evolved, the intensity of pest issues has significantly changed. Nevertheless, it is noteworthy that only a small fraction of the identified pest species, specifically below the 10 percent mark, are typically recognized as significant pests (Dhaliwal et al., 2010).

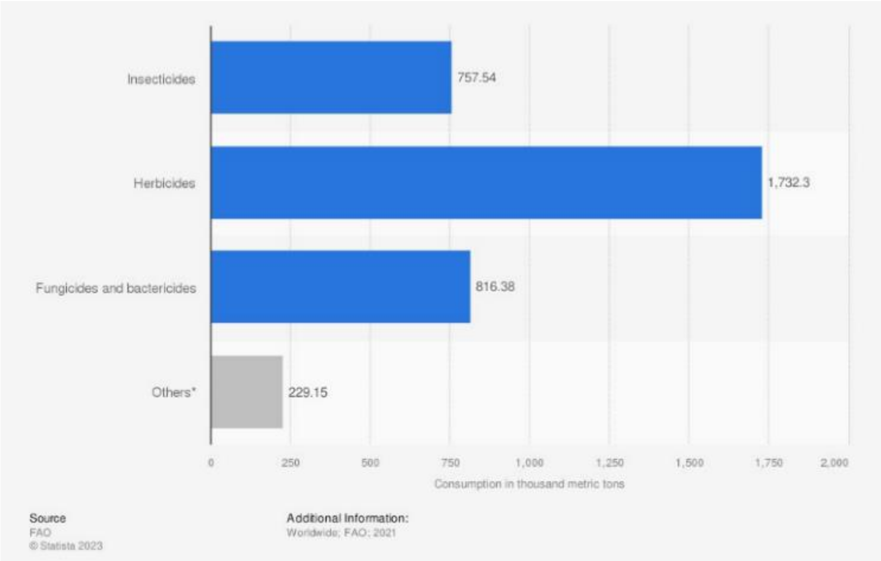
Insects undeniably possess unparalleled adaptability, surpassing all other animal groups in sheer numbers. Many insects play a vital role in both human societies and the environment. However, it is essential to acknowledge that certain insect pests can cause harm to humans, farm animals, and crops through their destructive behaviors (Williams, 1947).

One of the primary areas of interest in agricultural research revolves around exploring the correlation between biodiversity and pest management. As natural habitats are transformed into agricultural landscapes, there is a potential decline in the provision of crucial ecological services (Kremen et al., 2004). Ecosystem services encompass a range of ecological processes, including pest control, that enhance and support human well-being (Daily, 1997). Various pest control methods are utilized, encompassing cultural, mechanical, biological, and chemical control. In particular, biological pest control entails harnessing natural predators or organisms to manage pest populations (Huang & Yang, 1987). Pests are living organisms that cause physical harm to humans, animals, and crops. Put, pests can be well-defined as any creature with the ability to cause damage to cultivated plants. Insect pests, in particular, can harm agricultural productivity, market accessibility, the natural ecosystem, and our way of life (Mansosathiyadevan et al., 2017).

Role of Pesticides in Mitigating the Risk of Devastating Pests

If pesticides were not utilized, there would be a 78% decrease in fruit production, while vegetable production would experience a 54% decline, and cereal production would decrease by 32% (Lamichhane, 2017). Insects contribute to a 15% loss in crop yield, while pathogenic microorganisms and weeds individually account for 13% of the damage, and postharvest pest infestation results in an additional 10% loss. Pesticides play a crucial role in mitigating these losses. Without pesticides, food production would decline, leading to soaring food prices. Reduced production and higher prices would diminish the competitive edge of farmers in global markets for key commodities. By preventing or reducing agricultural losses caused by pests through pesticides, yields are improved, ensuring a steady supply of affordable agricultural produce for consumers. Pesticides find wide-ranging applications beyond what is commonly known to the general public. Just as pests in farming and public health contexts result in undesirable consequences like losses, spoilage, and damage, they can also adversely affect human activities, infrastructure, and common materials when these organisms are not controlled. Such adverse effects are effectively prevented by pesticides' significant and frequently overlooked contribution. As a result, the benefits of pesticides extend to various stakeholders, not only farmers or consumers but also society as a whole. For instance, without intervention, trees and vegetation growing beneath power lines can lead to power outages. Effectively using herbicides resolves this problem, guaranteeing unimpeded access for maintenance and repair purposes. Along highways, highway maintenance teams utilize herbicides to manage flora, enhancing safety by improving visibility for car drivers and allowing water to drain more proficiently during heavy rainfall or flooding. Additionally, herbicides are used to manage invasive weeds in parks, wetlands, and natural areas, contributing to preserving their ecological integrity.

Insecticides are utilized to prevent insect contamination. Grocery stores also employ pesticides to regulate insects and rodents lured by food and food waste. According to a study by Davis et al. in 1992, nearly all families (97.8%) utilized pesticides annually, with approximately two-thirds using more than five times yearly. The primary context for family pesticide usage was within the household, with roughly 80 percent of families employing pesticides once annually in this setting. Following that, approximately 57% of families used herbicides to manage yard weeds. A notable proportion of families, about 33%, also utilized pesticides in their gardens or orchards. Figure. 2. illustrates global pesticide consumption by type in the agricultural sector in 2021 (in 1000 metric tons). The positive impact of pesticides on our quality of life, property protection, and environmental well-being is evident. However, quantifying the non-monetary benefits associated with pesticide use poses challenges. Policymakers have grappled with the dilemma of assigning monetary values to intangible factors such as aesthetic quality, the preservation of endangered species, and peace of mind (Damalas, 2009).



(Source: Statista, 2023)

Figure 2. Agricultural consumption of pesticides worldwide in 2021, by type (in 1000 metric tons)

Impact of Green Revolution Practices on Insect Populations and Biodiversity

Arthropods, a diverse group of organisms including insects, spiders, and crustaceans, have thrived for over 400 million years and have withstood major extinction events like the Permian and Cretaceous extinctions (Kim, 1993). Insects have demonstrated remarkable accomplishments in their species diversity and population numbers, making them the major contributors to species richness among terrestrial arthropods (Samways, 1993; Stork et al., 2015). Insects comprise approximately 66% of the known species on Earth and comprise over three-quarters of the world's current biodiversity (Zhang, 2011; Kim, 1993). The number of known insect species is estimated to be around 1 million. However, it is important to note that only approximately 7% to 10% of all insect species have been scientifically described (Zhang, 2011). Stork et al. (2015) suggest that the overall number of insect species could range from 2.6 million to 7.8 million, with a mean estimate of around 5.5 million species. In terms of individual insects, the estimated range is between 1018 and 1019 individuals. When it comes to biomass, insects also hold a position of dominance, with an estimated ratio of 150 to 1500 kilograms of insects for every human being (Dicke, 2017). The insect kingdom is classified into 30 different orders, and the most diverse group among them is the Beetles (Order: Coleoptera). Beetles, in particular, make up approximately 40% of all identified arthropod species, with an estimated count of 1.5 million beetle species (Stork et al., 2015). The abundance of beetle species can be attributed to several factors, including the fact that many modern lineages originated in the Jurassic period. Beetles have also displayed high lineage survival rates and have diversified into various niches, successfully utilizing all parts of plants for their survival and adaptation (Farrel, 1998; Hunt et al., 2007; Jankielsohn, 2018).

The diversity of species within a field is recognized to influence trophic relations and biological control significantly (Andow, 1991). Andow (1991) conducted a comprehensive review that analyzed 209 published studies to explore the connections between vegetation diversity and species of phytophagous arthropods. Out of the 287 phytophagous species identified in these studies, about 52% had lower abundance in diversified agroecosystems than monocultures, whereas approximately 15% displayed higher densities in diversified systems. Monocultures, such as crop fields consisting of a single plant species, often struggle to support effective biological pest control due to limited resources available for natural enemy populations. However, increasing field diversity through intercropping, cover cropping, or even tolerating weeds can increase biological control and decrease the injury caused by insect pest attacks. This hypothesis has been extensively investigated through numerous studies, all of which have consistently shown that increased crop diversity significantly reduces pest damage (Nickel, 1973; Norris & Kogan, 2005; Perrin, 1977; Risch, 1983; Vandermeer, 1989). Several hypotheses have been put forth to shed light on the potential mechanisms that explain the interactions between within-field diversity and the occurrence of pest damage. The "enemy Hypothesis" initially formulated by Pimentel (1961) and later expanded upon by Root (1973), suggests that the reduced population of herbivores in intercropped fields can be attributed, at least in part, to the enhanced attractiveness of intercrops for more abundant and effective predator and parasitoids. This increased attractiveness is likely because of the availability of greater resources and habitats compared to monocultures. Tahvanainen and Root (1972), followed by Root (1973), proposed another hypothesis known as the "Resource Concentration Hypothesis." Based on this hypothesis, the likelihood of phytophagous creatures discovering their plant host, staying on it, and successfully reproducing is higher in monocultures than in mixtures of multiple species. In monocultures, the resources needed by herbivores are concentrated on a single plant species, whereas in mixed-species environments, the resources are diluted among multiple plants. This hypothesis is supported by the idea that herbivores may experience chemical or physical confusion in mixed-species settings as they encounter mixed cues, as proposed in Vandermeer's "Disruptive Crop Hypothesis" (1989).

Additionally, introducing a secondary crop within or near the main crop can result in high herbivore densities on the secondary crop, consequently reducing the prevalence of phytophagous on the primary crop. This phenomenon is known as the "Trap Crop Hypothesis," as proposed by Vandermeer (1989). However, it is essential that increasing within-field diversity does not always guarantee improved pest control. Higher diversity may sometimes exacerbate pest-related issues (Andow, 1991). Alternatively, increased within-field diversity can either facilitate or impede the activity of beneficial insects (Andow & Risch, 1985). Higher within-field diversity can amplify interspecific competition or intraguild predation among beneficial insects (Broatch et al., 2010).

Results

1. Maintaining certain species of weeds at manageable levels within crop fields is important to sustain pollinators' survival. These weeds provide food resources and refuge for pollinators.

2. Formulating strategies that effectively control weeds is essential to minimize their competition with crops and disruption of cultural practices. Determining economic thresholds for weed populations and factors that impact the balance between crops and weeds, particularly cropping systems, is necessary.
3. Further investigation is needed to enhance our understanding of beneficial weed species and how to promote them to attract pollinators without negatively impacting crop yields.
4. In regions where intensive farming is practiced, numerous non-cultivated spaces such as field margins, field edges, paths, headlands, fence lines, rights of way, and adjacent uncultivated patches of land play a vital role as sanctuaries for pollinators.
5. Maintaining and restoring hedges and other flora at the margins of fields is crucial for providing habitat for pollinators.
6. Implementing effective management practices for non-cultivated areas to promote the presence of wild pollinators can prove to be a cost-efficient strategy for optimizing crop productivity.

Conclusion

The Green Revolution, which began in the mid-20th century, was a period of significant agricultural advancements that aimed to increase crop yields and alleviate global hunger. While insects are often associated with crop damage and pests, they also play diverse and important roles in the Green Revolution. Here are some key findings on the diverse roles of insects in this agricultural transformation:

1. Pollination: Insects, particularly bees, are crucial pollinators for many crops. They facilitate the transfer of pollen from the stamen to the pistil of plants, allowing for fertilization and subsequent fruit or seed production. Insect pollination enhances the production and quality of different plants.
2. Biological Pest Control: Insects contribute to pest control in agricultural systems through biological means. Predatory insects, including ladybugs, lacewings, and parasitic wasps, feed on agricultural pests such as aphids, caterpillars, and mites. These beneficial insects help suppress pest populations, reducing the need for chemical pesticides.
3. Decomposition and Nutrient Cycling: Insects, particularly detritivores like beetles and termites, play a crucial role in decomposing organic matter and recycling nutrients. They feed on dead plant and animal material, accelerating decomposition and releasing essential nutrients into the soil. This nutrient cycling is critical for maintaining soil fertility and productivity in agricultural ecosystems.
4. Research and Education: Insects have been extensively studied in the context of the Green Revolution, leading to a better understanding of their ecological roles and interactions with crops. This knowledge has contributed to improving integrated pest

management strategies, sustainable agriculture practices, and educational initiatives to raise awareness about the importance of insect conservation and biodiversity.

Recommendations

It's important to note that while insects provide numerous benefits, they can also pose challenges as agricultural pests. Implementing sustainable and integrated pest management approaches that balance the ecological roles of insects while minimizing crop damage is critical for the success of the green revolution and future agricultural systems. Balancing pest management with preserving beneficial insects and biodiversity is crucial for establishing sustainable and resilient food production systems. Individuals, farmers, policymakers, and organizations need to act to accomplish this delicate balance. Here is a call to action outlining key steps:

1. Integrated Pest Management (IPM): Promote the implementation of IPM strategies that prioritize biological control techniques, like the use of beneficial insects, traps, and crop rotation, alongside judicious pesticide application. Encourage farmers to implement monitoring systems to assess pest populations accurately and determine appropriate intervention thresholds.
2. Education and Awareness: Raise awareness amongst farmers, agricultural professionals, and the general public about the significance of beneficial insects and biodiversity in agriculture. Emphasize the role of pollinators, natural pest controllers, and soil organisms in sustainable food production. Provide educational resources and training programs to support the implementation of biodiversity-friendly practices.
3. Habitat Conservation: Preserve and restore natural habitats within and around agricultural landscapes. Create wildflower strips, hedgerows, and insect-friendly corridors to provide food, shelter, and nesting sites for beneficial insects. Encourage the establishment of protected areas and conservation programs specifically targeting insect diversity and ecosystem health.
4. Reduced Pesticide Use: Encourage the responsible and judicious use of pesticides by promoting alternatives and innovative pest management techniques. Develop and promote low-toxicity and selective pesticides that have minimal impact on beneficial insects. Provide incentives and support for farmers to transition to organic and agroecological farming practices that minimize pesticide use.
5. Research and Innovation: To develop sustainable and effective pest management solutions, invest in research and innovation. Support studies on beneficial insects' ecology, behavior, and interactions to improve their conservation and integration into agricultural systems. Foster collaborations between researchers, farmers, and industry experts to develop and disseminate best practices.
6. Policy Support: Advocate for policies prioritizing biodiversity conservation and sustainable pest management in agriculture. Encourage governments to provide

incentives, subsidies, and regulations that promote adopting biodiversity-friendly practices. Support the development of comprehensive and science-based policies that consider the long-term ecological impacts of agricultural practices.

7. Collaboration and Partnerships: Foster collaboration among farmers, researchers, policymakers, conservation organizations, and industry stakeholders. Facilitate knowledge sharing, exchange of best practices, and joint initiatives to promote sustainable pest management and biodiversity conservation. Encourage public-private partnerships to drive innovation and implementation at scale.

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