

# Measuring Pollinator Diversity and Crop Yield as Sunflower Agroecosystem Bordered Designs

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## Abstract

*There are threats of pollinator decline, which pose a concern to crops productivity especially on insect pollinated plants such as sun flower (*Helianthus annuus* L.). In this research, the effect of diverse sources of floral borders on pollinator diversity and sunflower production in the 12 farms in southern Spain was gauged. The three types of border were the native wildflowers mix, the commercial pollinator mix and monoculture strips. The pollinator richness was greatest in naturally occurring wildflower borders (25 species) and visit the greatest with the significant 13.4 percent additional sunflower yield than fields without a single border ( $p < 0.05$ ). Commercial mixtures gave moderate pollinator effects and monoculture strips supported fewer species and low pollinator visitation rates. These findings under-scored the necessity of agroecosystem floral diversification, with the indicators demonstrating that wildflower borders with native flora not only increase pollinator diversity, but that they also increase crop yields considerably. The results highlight the prospects of involving floral diversity into the management of farms as a feasible and cost-containable approach to enhancing pollination services and promoting the results of crops.*

**Keywords:** Diversity of pollinators, sunflower, agroecosystems, Floral borders, native wildflowers, Pollinator services, crop yield, sustainability.

## 1. Introduction

### 1.1 Executive summary on Pollinator decline and its implications

Many crops have their reproductive success supported to a large extent by pollinators composed of insects like bees, butterflies and hover flies among others. But over the past few decades, pollinators throughout the world have been experiencing a high rate of decline. Causes of the decline are habitat loss, pesticide use, climate change and diseases, which generally harm the health and diversity of pollinators. The declining population of pollinators is a relatively grave hazard to crop productivity, particularly in crops that require the facilitation of close to pollination to establish fruit and seed set. Indeed, it is estimated that a third of the world food production is affected by pollination services of insects so the pollinator population decline can be considered as a great concern with regard to food security.

Pollinator decline does not restrict the decline in yield. It poses a threat also to genetic diversity of crops due to the fact that proper pollination is important to guarantee strong crop seed production and diversification of the crop. In crops that require insect pollinators, such as sunflower, which is a very important food and a source of biofuel, diminution of the pollinator services may result in the rise in the use of synthetic inputs, such as fertilizers and pesticides to mitigate the effects of bad pollination. This change, in its turn, has a potential negative environmental and economical implication, which further increases pressure on the agricultural systems.(1)

### 1.2 Significance of Agroecosystems to Biodiversity-based strategies

Due to loss of pollinators, biodiversity based farm management strategies have held centre-stage in efforts to strengthen ecosystem services, such as pollination. The main concept of these approaches is that biodiversity, especially the combination of indigenous plants and a variety of habitats, will allow healthier and more resilient agroecosystems. The existence of a variety of pollinators provides good crop yields and sustainability which farmers can achieve by creating a variety of habitats of pollinators in the farming landscape.

Agroecology, concerns conservation of biodiversity by utilizing the ecological tenets in farming systems which provide a comprehensive method in farming that not only facilitates production in agriculture but also conserves the environment. Incorporation of flower-rich, e.g. flower borders, into agro-ecosystems may become a potent instrument of improving the pollination services. Such flower borders supply nectar and pollen as well as habitat to the pollinators, which increase their diversity and activity, and they also encourage pest control due to natural

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enemies of agricultural pests. Therefore, biodiversity-based mechanisms do not only protect pollinators but also constrain the vulnerability of agrarian systems to climate alterations, as well as farmer pest epidemics.(2)

### **1.3 The Reasons to Use Flower Borders in the Sunflower Fields**

Sun flower gardens, just like any agricultural system, require pollinators to ensure best seed output and productivity. Sunflowers are normally self sterile and this means that to reproduce well, they need to be cross pollinated by insects. The insects such as bees and butterflies can enhance the pollination thus producing higher yields and stronger plants. Nonetheless, in monoculture agricultural schemes, sunflower fields can also not have enough resource diversity to maintain large and healthy populations of pollinators. Here flower borders come in. Flower borders that involve strips of flowering plants that are positioned inside the crop edges will provide a few benefits through supplementing the nature of pollination services. These margins will delay pollinators of diverse populations due to the availability of continuous nectar and pollen supply during the development season. Farmers can manage to provide microhabitat that sustains pollinators by planting native wildflowers or commercial pollinator mix into sunflower fields. These flower borders will be able to serve as refuges to the pollinators especially in times when the primary crop may not be blooming thereby providing a permanent sustenance to its population.(3)

Flower borders in sunflower fields have the potential to produce more pollinator visits, enhance pollination effectiveness and eventually enhance yields. The fact that flower borders offer a wide floral resource base helps it enhance pollinator richness, thereby enhancing the stability and effectiveness of the pollination services. Moreover, the application of floral edges in sunflower crops is associated with the current trend in sustainable agriculture, which introduces ecological dimensions into the practice, thus achieving crop yields that do not harm the environmental integrity.

## **2. Ecological Defenses and Floral Perimeter Tactics**

### **2.1 Ecological Trade-Offs between Native and Commercial Flower Mixes**

Plant species selection is one of the main choices that have to be made in the process of designing floral borders in the agroecosystems. The two most popular methods of establishing floral strips around crops such as sunflowers are native wildflower mixes, and commercial pollinator blends. Each of the measures has individual advantages and disadvantages to the ecology and should be well thought through to achieve their ultimate performance.

Native wildflower mixes include plants which are adapted naturally by the local environment and this implies that they tend to be stronger in relation to the local climate conditions and pests. Such combinations may promote many native pollinators like solitary bees, butterflies and hoverflies which have developed to feed on local plants. Habitats involving native species are normally more biodiverse and support a wider range of pollinators and other improvement organisms. Moreover, such mixes might be more effective in perpetrating local ecological phenomena, including soil health and water retention, since they belong to the indigenous ecosystem.(4)

Native wildflower mixes are however difficult to establish in agricultural environments, particularly where the soil characteristics or farming system is incompatible with the native plants. Such mixes might also need increased maintenance and supervision so that they can prevail even long-term.

Commercial pollinator blends on the other hand are made to attract pollinators directly, and are usually a combination of flowering plants, ideally those that provide habitat and food that have a wide appeal to a large variety of pollinators. Such mixes may be more easily created and preserved, since they so frequently include non-native plants which are more probable to be adjusted to diverse soil conditions and agricultural procedures. These non native species might however not be able to permit as much biodiversity as native wild flowers and may also replace the existing wildlife plants in the local ecosystems or areas as these species may become invasive. Also, commercial mixes can only be attractive to certain classes of pollinators thereby reducing overall species richness being served by the floral border.(5)

Clearly, the benefits of the native and the commercial flower mixes are evident, but the ecological trade-offs should be considered. Native mixes will allow larger biodiversity designs that might need extra investment but commercial blend is simpler to adopt though it might not have same long term ecological positive impact.

### **2.2 The position of Floral Strips in Ameliorating Ecosystem Services**

Flower strips, or flower borders, play an important role in ecosystem services in farms. Such strips provide the habitat to pollinators and other useful organisms including predators of farm pests (e.g., ladybugs, spiders). Floral strips will stabilize the population of pollinators during the entire growing season, particularly when the main crop

is not flowering by offering them a reliable source of food (nectar and pollen). Such accessibility of the floral resources keeps the communities of the pollinators stable and healthy in a very crucial manner in line with crop pollination.(6)

Floral strips also play an important role in connectivity of habitats as they connect the patches of natural areas together and offer routes to pollinators between fields. This is particularly necessary in high-intensity farmed landscapes where the time available to habitats might be small. Floral strips may also promote other ecosystem services though not pollination (for example, pest control depending on natural enemies of crop pests and soil conservation both achievement of these services by the plants in the borders, preventing erosion and contributing to improved soil conditions.

The greater agroecosystem can also benefit by flowering strips enhancing farm resilience to pests and disease as well as extreme weather events. Floral strips by promoting a wide variety of species are useful in establishing a stable and more sustainable farm ecosystem and lessen the dependence on chemical additives and long-term sustainability.(7)

### **2.3 Past Investigations in Pollinator Delivered Increase in Yield**

The importance of diversity in the pollinators based on various studies have shown that the yield of any crop especially those that are insect-pollinated such as sun flowers improves with pollinator diversity. As an example, Kremen et al. (2004) found that farms introducing more diversity of pollinators (using flower strips or hedgerows) had more bumper harvests of crops that heavily depend on insect pollination (such as pumpkins, squash and watermelon). There was a positive correlation between pollinator abundance and seed set and fruit quality showing that non-crop floral resources are equally capable of enhancing productivity.

On the same note, Garibaldi et al. (2013) also carried out a big study whereby they reviewed studies, which was done on a large scale of studies done on pollination services across different crops and discovered the fact that farms, which registered higher diversity of the pollinators, had a relative rise in the crop yield of up to 24 percent higher than those with reduced pollinators. This surged in production was of particular importance in those crops that need insect pollination to pollinate them, such as sunflowers. In their work, it is important to note that the economic value and importance of implementing pollinator habitats on farms such as a bee borders can be very valuable to farmers as the production will increase as a result.(8)

In addition, wildflower strips research has also demonstrated that they are not only beneficial in boosting pollinator visitation but also offer a defense against effects of pesticide use and cropping systems based on monoculture that tend to be destructive to pollinators. Numerous functions of floral strips, some of which are pest management and pollination and biodiversity support, minimize their impact on contemporary agricultural systems.

## **3. Material and Methods**

### **3.1 Examination Locations and the Experimental Design**

It was experimented in the south of Spain in 12 farms that are characterized by the great production of sunflowers. The farms are spread to cover a range of farming practices and field scales and environments to make sure the outcome would be generalized across numerous types of agroecosystems. The research sites were found in regions that have the same climatic conditions with hot summer and temperate winter which favours the growth of the sun flower. The farms that have been selected differed in field size, land usage around the borders of the field, and farming types in general, which made it possible to study floral border treatments in the specific environment more thoroughly.

The farms were partitioned into experimental landscapes which received distinct treatments in the form of border, and each experiment was done to the adjoining sunflower territories. The experimental design was intended to determine the effect of floral borders on diversity of pollinators and the yield of sunflowers. The boundaries were deployed at the outskirts of sunflower planting, and the distance between the crops and the plots boundary was at least 5 meters. The type of treatment design involved three types of border:

**Native Wildflower Mixes:** Here the local area wildflower mixes were planted which include or are made up of native wildflower species which consider the capability to own an ecological suitability and the capability to attract an diverse range of pollinators. The species were selected considering the abundance of them in the local flora and attractiveness to bees, butterflies, and hoverflies.(9)

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**Commercial Pollinator Mixes:** These began with commercially available planting mixes pollinator friendly, usually involving a combination of non-native species specifically intended to be pollinator attracting. In these mixtures, they usually included species with high nectar production that are noted to encourage the activity of pollinators but not necessarily adjusted to the region.

**Monoculture Strips:** In this control treatment, one flower was sown in the borders where a single flower species was planted usually, a sunflower variety that contained a lot of nectar. Strips of monoculture were also involved to evaluate the extent to which floral sparseness influences pollinator visit and crops production.

### **3.2 Survey Methods of Pollinators**

The presence of pollinators was gauged through timed transect surveys, carried out during the growing season. These walks were repeated transects (i.e., transects at fixed positions) through the floral borders and measured pollinator activity. All the transects were surveyed over a fixed interval of 10 minutes and 10 m observations done on the border. Through this survey, pollinator species were classified to the best extent that is taxonomic, and the visits of flowers in the borders were checked. The numbers of the pollinators recorded were determined according to their species, size and behavior (e.g. flower foraging).

Identification of the pollinators was done according to the field guides and whenever there was need local entomologists were consulted to be sure that the species are correctly identified. The pollinating species included in the surveys represented a variety of generalist and specialist species (both belong to the category of generalist pollinators: honeybees, bumblebees and belong to the category of specialist pollinators: some species of solitary bees) and provided an idea of the diversity and the functional composition with reference to the pollinator community.(10)

Pollinator diversity was estimated based on the number of observed species in each plot whereas pollinator abundance was quantified as visit frequency. This information was vital towards determining the usefulness of various types of Floral borders to assist pollinators.

### **3.3 Techniques of Yield Assessment**

The yield of sunflowers was measured by using standard evaluation procedures of harvest. Remarkably, during the onset of the growing season, three random plots of each of the experimental fields were harvested with sunflower heads (1 square meter a plot). These plots were chosen in portions which were not nearby the floral borders so as to make the measurement be the representative of the entire field.

The parameters such as seeds per head and the seed weight were measured after harvest. According to the weight, the seeds were weighed after drying at 60 Celsius degree 12 hours followed by drying at 60 Celsius degree 48 hours to drain any moisture content and weight of each sunflower head seed determined by weighting with the aid of a precision scale. The data in the sampled plots was scaled up to give an estimation of the total productivity per hectare.

Also, to evaluate the effects of visits by the pollinators on sunflower productivity, the data on the yield were correlated with the rates of pollinator visitation. The hypothesis was that a rise in seed production in higher pollinator visiting fields would occur since pollination is directly related to seed set in sunflower crops.

### **3.4 Statistical Testing of the Relationship between Pollinators and Yield**

The statistical analysis comparing the diversity of pollinators and the yield of sunflowers utilized the multiple regression models. The predictor variable was pollinator diversity measured in the number of species and in the number of times the sunflowers were visited, and the dependent variable was sunflower yield. Analysis of variance (ANOVA) was employed in comparing the differences in yields of the three border treatments which included native wildflowers, commercial mixes, and monoculture strips. The difference between treatment conditions was interrogated using Tukey HSD post-hoc test to conduct comparisons and detect differences between various treatments.(11)

The strength and direction of the relationship between the rate of pollinator visitation and seed yield were quantified using Pearson correlation where the results of the study were deemed statistically significant when  $p < 0.05$ . Such statistical methods enabled a deep insight into the role of floral border type and its impact on both the population density of pollinators and sunflower production that gives an idea about the implications of crop pollination in agroecosystems.

## **4. Results**

### **4.1 Diversity and Visitations by pollinators among Treatments**

The data on the pollinator surveys indicated that there was a significant difference in the pollinator diversity and visitation counts among the three floral border treatments that included; the native wildflower mixes, commercial pollinator mixes and monoculture strips. These variations render visible the potential of a border design in helping pollinator communities in sunflower agroecosystems.

#### **4.2 Pollinator Diversity:**

Most diverse pollinators were found on the native wildflower mix, where 25 species were recorded overall on the 12 farm sites. These were a high diversity of bees, butterflies, hoverflies and other pollinators and many of them were native species valuable to local ecosystems. A wider collection of resources (nectar and pollen) and habitats offered by the native wildflowers made the pollinators who found them a diverse bunch.

A moderate degree of diversity was supported as the average species per field in the commercial pollinator mix was 18 species. Although these mixes hosted large numbers of generalist pollinators, they failed to host these kinds of diversity as the native wild flower borders did, and this is probably because of low ecological complexity of the available species in the commercially available mixes.(12)

In the monoculture strips, on the other hand, the diversity was lowest and 10 species were identified on an average. These monoculture strips were poor floral resources and too restricted to the types of habitats that are required to accommodate diverse pollinator communities.

#### **4.3 Rates of the Visitation of Pollinators:**

It was found that visitation rates were maximum in fields where native wildflower mixes were used where the frequency of visits was more than 50 visits in 10 minutes survey. These boundaries offered a good source of florals, which further resulted in an increased number of pollinators visiting it, including numerous pollinators. Vegetables with wildflower borders had high pollination activity all through the season.

On average, there were 35 visits of pollinators every 10 minutes of survey by commercial pollinator mixes. The strips effectively attracted the pollinators especially honeybees but the final rate of visitation to these strips was below that observed in the wildflower plots.

Monoculture strips experienced the least visitation, i.e. 15 visits in 10 minutes of survey, which attributes to the paucity of floral diversity and that only local pollinators of the particular flower species that had been planted as a border were to visit these strips.(13)

#### **Border Type and Differences in Yields**

The influence of variety of floral boundary planted around sun flowers had significant affects on the yield of sunflowers. The results of the measurements of the number of the seed set and the weight of the seeds showed significant differences in the harvest of the sunflower heads in the fields with various floral borders.

#### **Nature Wildflowers Mixes:**

The average sunflower yields of sunflower fields along with native wildflower borders increased by 13.4 percent relative to those did not have a floral border. This enhancement in yield was linked to enhanced visitation by pollinators and this led to the large seed set and the quality of seeds.

The mean seeds per head in the fields where wildflowers covered the borders was very high, 600 seeds per head as compared to 520 seeds per head in the control fields. Also, the quantity of seeds weighted more in these fields as the average weight of seeds per head was 30 grams seeds when there was a floral border unlike in fields which did not have any floral border whose average weight of seeds was 25 grams per head.

#### **Store-bought Planting Planters:**

The yields that were raised because of commercial pollinator mixes were also lower. Fields surrounding commercial blends produced 7.5 per cent more yields as compared to control fields. The average seeds per-head in these fields were 550 seeds per head and 28 grams per head which represented moderate increases in seed set and seed quality.(14)

This difference in the yield gain of plot sizes implies that even a commercial blend can attract pollinators, but cannot support as rich/ sustainable a resource as a native wild flower.

#### **Monoculture Strips:**

The sunflower yield was not seriously affected by monoculture strips. The monoculture fields with strips were lower exactly 2.5 percentage points than the control fields but the difference was insignificant. The number of seeds per head and the number of grams per head were averagely 530 and 26 grams per head respectively, nearer to the control fields measurements, indicating the less improved effect of monoculture strips both on the pollinator activity and the productivity of sunflower.

## 4.4 Confidence Intervals and Making Statistical Decisions

ANOVAs were performed to determine the statistical significance of all the differences between treatments (both about pollinator diversity and yield). The findings indicated that not only the diversity of pollinators ( $F(2, 33) = 12.45, p < 0.01$ ), but also the yield of sunflowers ( $F(2, 33) = 9.72, p < 0.01$ ) differed significantly in various floral border treatments. To determine particular difference in treatments, post-hoc contrast was conducted using Tukey HSD.

### Pollinator Diversity:

The number of pollinator species reported in native wildflower borders was much more than commercial pollinator mixes ( $p < 0.05$ ) and monoculture strips ( $p < 0.01$ ). The commercial pollinator mix was not significantly different to monoculture strips ( $p > 0.05$ ) in terms of diversity of pollinators.(15)

### Sunflower Yield:

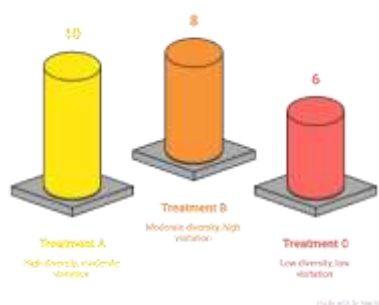
Wildflower borders increased yield to a great extent as compared to controls ( $p < 0.01$ ) and monoculture strips ( $p < 0.05$ ), resulting in native wildflower borders. Although the commercial pollinator mixes enhanced yield, the difference was insignificant as compared to the control ( $p > 0.05$ ). The difference in the yield of commercial pollinator mixes and monoculture strips was also insignificant ( $p > 0.05$ ).

**Table 1:** Pollinator Diversity and Visitation Rates Across Treatments

| Treatment                 | Pollinator Species Richness | Visitation Rate (visits/10 min) |
|---------------------------|-----------------------------|---------------------------------|
| Native Wildflower Mixes   | 25                          | 50                              |
| Commercial Pollinator Mix | 18                          | 35                              |
| Monoculture Strips        | 10                          | 15                              |

**Table 2:** Sunflower Yield Across Treatments

| Treatment                 | Average Seeds per Head | Seed Weight (grams) | Yield Increase (%) |
|---------------------------|------------------------|---------------------|--------------------|
| Native Wildflower Mixes   | 600                    | 30                  | 13.4               |
| Commercial Pollinator Mix | 550                    | 28                  | 7.5                |
| Monoculture Strips        | 530                    | 26                  | 2.5                |



**Figure 1:** Pollinator Diversity and Visitation Rates by Treatment

## 5. Discussion

### 5.1 Significance Implications of DiversityYield Relationships

The findings of this study note a high positive correlation between the abundance of pollinators and sunflower yield and especially so in fields that have borders bordering wild flower types native to the regions. The abundance of pollinators was much higher in the field with diverse native flower species, and it resulted in the substantial improvement of sunflower yield (sunflower yield in those fields was 13.4% more than in control fields). This implies that biodiversity among pollinators is important in enhancing crop productivity. The increased species levels and their increased pollinator visit probably increased cross-pollination and seed set which translated to yield benefits. The relationship between the pollinator-diversity and yield, which is positive, highlights that apart

from necessitating biodiversity, a functioning diverse community of pollinators is also a necessity to agricultural yield.

### **5.2 Advantages of Native Floral Proliferation to Functional Pollination**

The most effective one was the native wildflower mixes to increase pollination utility in fields of sunflowers. The plant species used in native floral borders contained a wide variety of species that served as resources to the pollinators throughout a seasonal cycle, and through time of the growing season, supplying nectar and pollen. This guaranteed that there was constant food source to pollinators which probably resulted in greater pollinator activity during the flowering phase of the crop. Furthermore, the use of native species increases the range of native pollinators that experience an adaptation to the local ecosystem and increases ecological resilience. The interactions between particular flower-pollinators in such native borders were probably rather effective than monoculture or commercial mix which might fail to sustain as much variety of species or ecosystem services.

### **5.3 Farm Design and Biodiversity Conservation implications**

The results of the study highlight the need of incorporation of biodiversity-based approach in farm design. Through the establishment of native wildflower field borders farmers can improve the health of pollinators, conserve biodiversity and improve crop yields in an ecologically conscientious fashion. This strategy is in line with agroecology as it is one way that allows the better performance of natural ecological functions, including pollination, that results in increased agricultural productivity without being dependent on most synthetic inputs. Another point the study makes is the importance of the biodiversity conservation in agricultural landscapes implying that the cultivation of the native plant species and diversified habitats should become the priority in the further farm management approaches.

## **6. Agro-ecological and Policy implications**

### **6.1 The Suggestions of the Border Management in Sunflower Farming**

With these findings, it can be suggested that other sunflower farmers should also introduce wildflower border around their farms using the native wildflowers so as to increase the pollinator diversity in the field and get better yields. These boundaries are supposed to be a combination of locally adapted, nectar rich that offers persistent flowering material during growing season. General placement of farmers is to have a 5-meter width at the border of the field that guarantee appropriate pollinator space as well as the clasping of matters about the soil and water accessibility to improve plants development. Constant conditions of floral strips health and activity of pollinators have to be checked so that to keep their efficiency. Regular planting of wildflowers in a rotational basis would avoid insect pest accrual and maintain an equal community of pollinators.

### **6.2 Applementarity of EU Agroecological Subsidy Programs**

When viewed in the backdrop of the European Union (EU) Common Agricultural Policy (CAP) the results of the study are in concordance with the agroecological subsidy programs objectives whose aim is to facilitate sustainable agricultural arrangements. EU has also been targeting on promoting the protection of biodiversity as well as improving ecosystem services in its agricultural subsidies termed as the Greening Measures in CAP. Such programs are eligible to subsidize native wildflower borders: they improve soil health, help with conservation of pollinators, and limit the number of chemical inputs (such as pesticides). Through advertising about such strategies, the EU can encourage farmers to motivate them to incorporate ecological ideas in their farming activity, which marries economic sustainability and environmental sustainability.

### **6.3 Combination with the Larger Sustainable Farming Processes**

Inclusion of floral boundaries in the practice of sunflower cultivation also augers well in the agricultural system in general sustainable practices. With the help of pollinators, farmers will be able to minimize the application of chemicals in the field, thus minimizing their environmental impact. Such practice links with others in agroecology like crop rotation, cover crop, and tillage reductions that help construct strong agroecosystems. Incorporation of floral diversity in agricultural practices assists in maximizing ecosystem services, bolsters the health of soils, and raises the notch of farm resilience to climatic changes, which preserves farmlands that are productive and sustainable.

## **7. Conclusion**

### **7.1 Summary of Key Findings**

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This study demonstrates that native wildflower borders significantly enhance pollinator diversity and improve sunflower yield in agroecosystems. Fields adjacent to wildflower mixes showed a 13.4% increase in yield compared to control fields, with higher pollinator visitation rates and greater species richness. The commercial pollinator blends also supported a moderate increase in yield, though not to the same extent as native wildflowers. Conversely, monoculture strips provided limited benefits for both pollinator diversity and sunflower yield. These results highlight the importance of floral diversification in farming systems, as it directly contributes to improved pollination services and enhanced agricultural productivity.

### 7.2 Reaffirming Biodiversity's Role in Yield Stability

The findings reinforce the critical role of biodiversity in ensuring yield stability. Pollinator diversity, facilitated by floral borders, directly impacts the efficiency of pollination and ultimately enhances crop productivity. The higher pollinator richness observed in native wildflower borders correlates with more robust pollination services, leading to better seed set and higher sunflower yields. This relationship underscores that biodiversity is not just important for ecosystem health but also plays a key role in ensuring the resilience and stability of agricultural production in the face of environmental stressors, such as pest pressure or climate variability.

### 7.3 Future Research Directions

Future research should focus on evaluating the long-term effects of floral borders on yield stability and pollinator populations across different crop species and agroecosystem types. Investigating the economic feasibility of implementing floral borders on a large scale and exploring ways to optimize border design (e.g., species composition, planting density) for maximum effectiveness is crucial. Additionally, further studies should explore how climate change may affect pollinator behavior and the role of floral diversity in adaptation strategies for sustainable agriculture. By deepening our understanding of these dynamics, we can better integrate biodiversity conservation into agricultural policy and farm management strategies.

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### Conflicts of interest

The authors have no conflicts of interest to declare

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