Modeling the impact of pollinator biodiversity on the resilience of agricultural ecosystems

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Abstract. This study focuses on examining the factors that influence the yield of wild blueberries (Vaccinium spp.), taking into account ecological and agronomic aspects. In the context of climate change and declining pollinator populations, food security has become a pressing issue. Successful pollination determines the quantity and quality of harvests, including berries. The research utilized data on the habitat characteristics of blueberries, including pollinator density (honeybees, bumblebees, wild bees) and climatic conditions (temperature, precipitation). Statistical methods, such as correlation and factor analysis, were applied to identify relationships between yield and the influencing factors. The results showed that high blueberry yields are associated with the presence of pollinators and climatic conditions. Positive correlations were observed between seed quantity and yield, as well as negative correlations between clone size and fruit set. These findings underscore the importance of pollinator diversity and optimal climatic conditions. The study highlights the need to preserve pollinator biodiversity and optimize agronomic practices in the face of climate change. The results can be used to develop recommendations for improving blueberry cultivation methods and increasing yields.

1 Introduction

In recent decades, there has been increasing concern about the sustainability of agriculture and the preservation of biodiversity. Food security is becoming an ever more pressing issue in the context of climate change and declining pollinator populations. Pollination plays a key role in ensuring high yields of many agricultural crops, including berries, fruits, and vegetables. In this context, wild blueberries (Vaccinium spp.) represent a significant crop, both from an economic perspective and for the ecosystems in which they grow.

The yield of blueberries depends on many factors, including climatic conditions, pollinator density, and the characteristics of the plants themselves. Honey bees, bumblebees, and wild bees play a crucial role in the pollination process, directly affecting the quantity and

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quality of the yield. It is also necessary to consider that climatic factors, such as temperature fluctuations and precipitation levels, can significantly influence the growth conditions and fruiting of blueberries.

The relevance of this research lies in the understanding of how these factors affect the yield of wild blueberries, which can contribute to increasing the efficiency of their cultivation and improving agronomic practices. The goal of this work is to analyze data on pollinator density, climatic conditions, and plant characteristics to identify the key factors affecting blueberry yield. The analytical methods employed will allow for an assessment of the degree of impact of various factors and provide recommendations for optimizing the growing conditions of this important crop.

2 Materials and methods

Several statistical methods were used for data analysis. Correlation analysis was employed to identify relationships between variables. This method allows for the determination of the degree and direction of the association between factors, such as temperature, pollinator density, and the number of rainy days, and their impact on blueberry yield. Factor analysis was used to simplify the data structure by highlighting key latent factors that influence yield. This dimensionality reduction method groups correlated variables into a few factors, aiding in a better understanding of their impact on the response variable.

Linear regression was applied to create a model of yield dependence on various factors, such as weather conditions and pollinator populations. This method enables the assessment of how each factor affects yield and forecasts it based on existing data. To evaluate the quality of the models, information criterion analysis (AIC, BIC) was used, which helps compare different models and select the one that best explains the data with the fewest parameters.

3 Data structure

The dataset describes various factors affecting wild blueberries, including environmental characteristics and pollinator density in the field.

1. Row# – the row number in the dataset (observation identifier).
2. Clonesize (m^2) — the average size of blueberry clones in the field. This measurement reflects the area occupied by individual blueberry bushes growing in one spot and may influence plant productivity.
3. Honeybee (bees/m^2/min) — the density of honeybees per square meter per minute. This indicator estimates the number of honeybees involved in pollinating blueberries in the field, which is important for successful fruit formation.
4. Bumbles (bees/m^2/min) — the density of bumblebees per square meter per minute. Bumblebees are also important pollinators of blueberries, and their presence in the field can significantly affect yield.
5. Andrena (bees/m^2/min) — the density of Andrena bees. This genus of wild bees can contribute to pollination, especially in areas where they are common.
6. Osmia (bees/m^2/min) — the density of Osmia bees. These bees are often used for pollinating agricultural crops and can be important pollinators for blueberries.
7. MaxOfUpperTRange (°C) — the maximum temperature of the upper limit of the daily air temperature range during the flowering period. This indicator is important for determining the temperature conditions under which blueberry flowering occurs.
8. MinOfUpperTRange (°C) — the minimum temperature of the upper limit of daily air temperature during the flowering period. It helps to assess the minimum temperature values that may affect the processes of pollination and blueberry growth.

9. AverageOfUpperTRange (°C) — the average value of the upper limit of daily air temperature. The average temperature helps to understand the overall climatic conditions during flowering.

10. MaxOfLowerTRange (°C) — the maximum temperature of the lower limit of the daily air temperature range. These are the highest temperature values during cooler times of the day that may influence flowering.

11. MinOfLowerTRange (°C) — the minimum temperature of the lower limit of daily air temperature. This indicator reflects the lowest temperatures that can slow down or disrupt the processes of pollination and blueberry growth.

12. AverageOfLowerTRange (°C) — the average temperature of the lower limit of daily air temperature, which provides insight into how cold the flowering period was.

13. RainingDays (days) — the total number of rainy days during the flowering season. Precipitation can affect pollinator activity and the pollination process.

14. AverageRainingDays (days) — the average number of rainy days throughout the flowering season, which helps assess how wet the weather conditions were during this period.

Overall, the data include both biological and climatic factors that can influence the pollination process and, consequently, the yield of blueberries.

4 Results

For statistical analysis, the data were divided into 11 groups based on yield levels. Figure 1 presents the data for the group. Figures 2-4 display data on average temperature metrics within the group, while Figures 5 and 6 show the average number of observed bees for each group. Figure 7 provides average rainfall data. Figures 8 and 9 present metrics directly related to agriculture.

It is evident that with an increase in average yield, there are notable changes in other parameters, which may indicate existing relationships. For example, the average size of the clonesize metric tends to decrease with increasing yield, suggesting that higher yields may be achieved with smaller pollinator colony sizes.

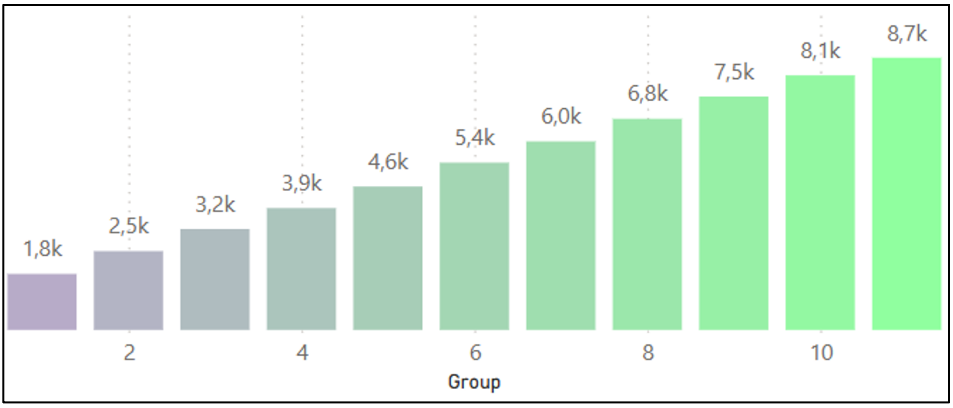
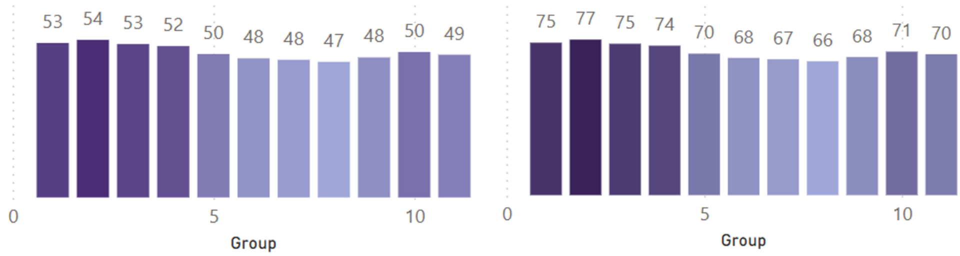


Fig. 1. Average yield metrics in groups.

Data on temperature ranges, such as MaxOfUpperTRange, MinOfUpperTRange, and AverageOfUpperTRange, show a tendency for maximum temperatures to decrease as crop yields increase. This may suggest that cooler temperature conditions can be favorable for achieving high yield levels. Such temperatures are likely to provide optimal conditions for plant growth, reducing heat stress and promoting the efficient use of resources such as water and nutrients. This conclusion could be useful for developing crop management strategies in the context of climate change.



(a) (b)

Fig. 2. Average values of metrics in groups: a) AverageOfLowerTRange, b) AverageOfUpperTRange.

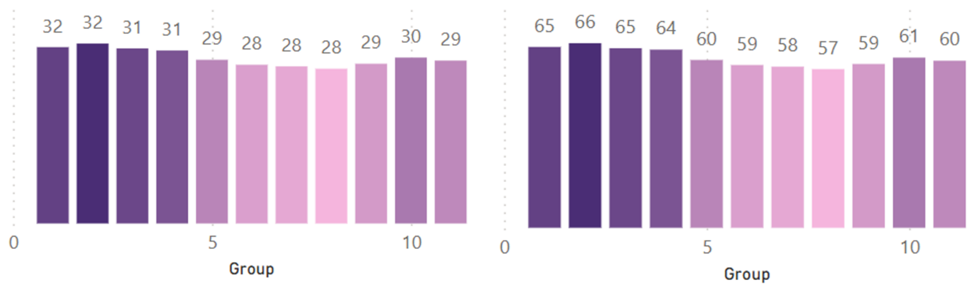


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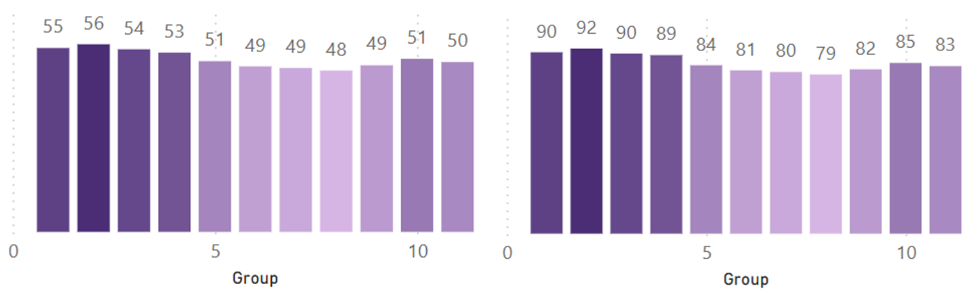
Fig. 3. Average values of metrics in groups: a) MinOfLowerTRange, b) MaxOfLowerTRange.



(a) (b)

Fig. 4. Average values of metrics in groups: a) MinOfUpperTRange, b) MaxOfUpperTRange.

The abundance indicators of different bee species also change depending on yield levels. In particular, the proportion of honeybees and bumblebees (Bombus) decreases as crop yields increase, while the populations of andrenids (Andrena) and osmiids (Osmia) also show a similar trend, but at a lower level. This may indicate a decline in pollinator biodiversity at high yield levels, which could be related to a decrease in the diversity of resources for feeding and nesting. The reduction in key pollinator species may have long-term impacts on ecosystem services, necessitating further study to understand the relationship between agricultural practices and biodiversity conservation.

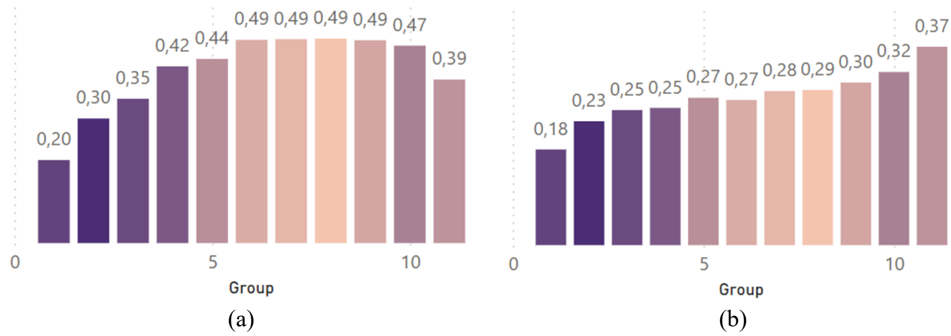


Fig. 5. Average values of metrics in groups: a) andrena, b) bumbles.

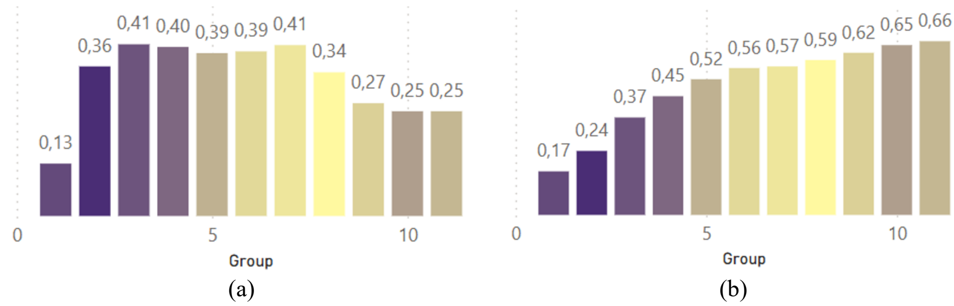


Fig. 6. Average values of metrics in groups: a) honeybee, b) osmia.

Parameters related to precipitation, such as RainingDays and AverageRainingDays, play an important role as they can influence water availability and overall conditions for plant growth. In this case, it is observed that the number of rainy days increases with higher crop yields, which is likely associated with improved water management and more favorable conditions for crop growth. Increased precipitation may contribute to better soil moisture, positively affecting root development and nutrient uptake. However, it is important to consider that excessive rainfall can lead to issues such as soil waterlogging or increased disease risk, so a balance between precipitation levels and plant needs is necessary for optimal yields.

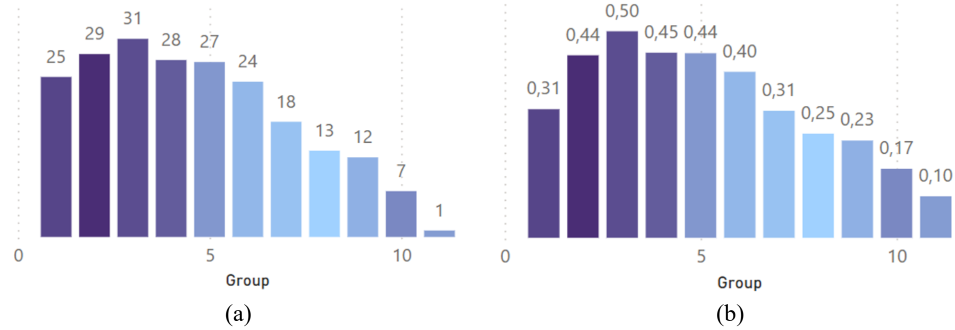
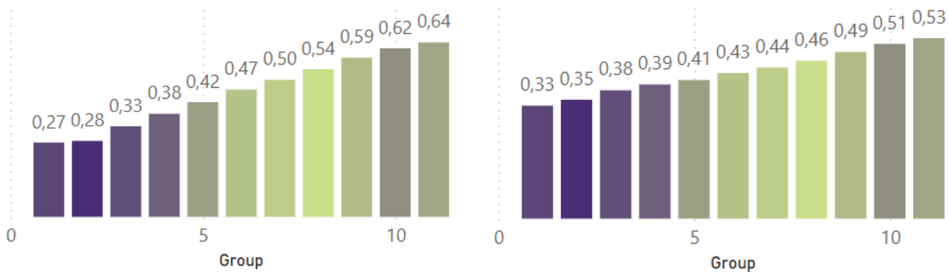


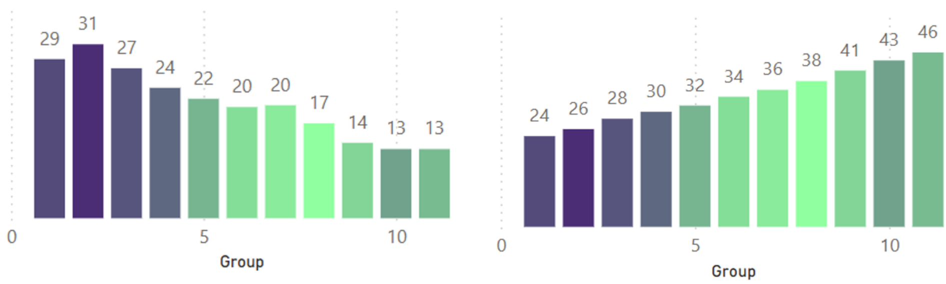
Fig. 7. Average values of metrics in groups: a) RainingDays, b) AverageRainingDays.

The analysis of other variables, such as fruitset, fruitmass, and seeds, can provide additional insights into plant performance and crop quality. These indicators reflect not only the plants' ability to set fruit and produce seeds but may also be closely related to the abundance and activity of pollinators, as successful pollination directly affects the number of set fruits and their weight. Furthermore, these indicators can vary depending on weather conditions, such as precipitation and temperature, which influence the processes of growth and fruit ripening. A comprehensive analysis of these factors can help better understand how the interaction between biotic (e.g., pollinators) and abiotic (e.g., climate) factors impacts the final productivity and quality of crops.



(a) (b)

Fig. 8. Average values of metrics in groups: a) fruitset, b) fruitmass.



(a) (b)

Fig. 9. Average values of metrics in groups: a) clonesize, b) seeds.

During the analysis of the relationship between crop yield and various factors, correlation coefficients were calculated to show the degree and direction of the linear relationship between the variables.

The most notable correlation is the positive correlation between yield and the number of seeds, reaching a value of 0.941. This indicates that an increase in the number of seeds is associated with an increase in yield. Additionally, the relationship between yield and fruit mass is also significant, with a correlation coefficient of 0.912. This suggests that heavier fruits contribute to higher yields.

Indicators	andrena	AverageOfLowerTRange	AverageOfUpperTRange	AverageRainingDays	bumbles	clonesize	fruitmass	fruitset	honeybee	MaxOfLowerTRange	MaxOfUpperTRange	MinOfLowerTRange	MinOfUpperTRange	osmia	RainingDays	seeds	yield
andrena	1,00	-0,03	-0,03	0,05	0,03	-0,01	0,10	0,12	0,18	-0,03	-0,03	-0,03	-0,03	0,38	0,04	0,11	0,16
AverageOfLowerTRange	-0,03	1,00	1,00	-0,01	-0,01	0,03	0,06	-0,13	0,00	1,00	1,00	1,00	0,99	-0,06	0,00	-0,03	-0,18
AverageOfUpperTRange	-0,03	1,00	1,00	-0,01	-0,02	0,03	0,06	-0,13	0,00	1,00	1,00	1,00	0,99	-0,06	0,00	-0,03	-0,18
AverageRainingDays	0,05	-0,01	-0,01	1,00	0,06	-0,02	-0,45	-0,50	0,00	-0,01	-0,01	-0,01	0,00	0,10	0,89	-0,47	-0,53
bumbles	0,03	-0,01	-0,02	0,06	1,00	0,01	0,34	0,29	0,08	-0,02	-0,02	-0,02	0,00	0,26	0,03	0,36	0,30
clonesize	-0,01	0,03	0,03	-0,02	0,01	1,00	-0,46	-0,55	0,78	0,03	0,03	0,03	0,03	-0,13	-0,02	-0,50	-0,52
fruitmass	0,10	0,06	0,06	-0,45	0,34	-0,46	1,00	0,93	-0,33	0,06	0,06	0,06	0,04	0,32	-0,44	0,96	0,91
fruitset	0,12	-0,13	-0,13	-0,50	0,29	-0,55	0,93	1,00	-0,34	-0,13	-0,13	-0,13	-0,15	0,30	-0,48	0,94	0,97
honeybee	0,18	0,00	0,00	0,00	0,08	0,78	-0,33	-0,34	1,00	0,01	0,01	0,00	0,00	0,09	0,00	-0,36	-0,31
MaxOfLowerTRange	-0,03	1,00	1,00	-0,01	-0,02	0,03	0,06	-0,13	0,01	1,00	1,00	1,00	0,98	-0,07	0,00	-0,03	-0,18
MaxOfUpperTRange	-0,03	1,00	1,00	-0,01	-0,02	0,03	0,06	-0,13	0,01	1,00	1,00	1,00	0,99	-0,07	0,00	-0,03	-0,18
MinOfLowerTRange	-0,03	1,00	1,00	-0,01	-0,02	0,03	0,06	-0,13	0,00	1,00	1,00	1,00	0,99	-0,06	0,00	-0,03	-0,18
MinOfUpperTRange	-0,03	0,99	0,99	0,00	0,00	0,03	0,04	-0,15	0,00	0,98	0,99	0,99	1,00	-0,04	0,00	-0,05	-0,19
osmia	0,38	-0,06	-0,06	0,10	0,26	-0,13	0,32	0,30	0,09	-0,07	-0,07	-0,06	-0,04	1,00	0,07	0,34	0,36
RainingDays	0,04	0,00	0,00	0,89	0,03	-0,02	-0,44	-0,48	0,00	0,00	0,00	0,00	0,00	0,07	1,00	-0,46	-0,51
seeds	0,11	-0,03	-0,03	-0,47	0,36	-0,50	0,96	0,94	-0,36	-0,03	-0,03	-0,03	-0,05	0,34	-0,46	1,00	0,94
yield	0,16	-0,18	-0,18	-0,53	0,30	-0,52	0,91	0,97	-0,31	-0,18	-0,18	-0,18	-0,19	0,36	-0,51	0,94	1,00

Fig. 10. Correlation coefficients.

The correlation coefficients also revealed strong relationships among various characteristics related to growth conditions. For example, the relationship between average rainy days (AverageRainingDays) and the total number of rainy days (RainingDays) was 0.893, confirming the similarity of these indicators.

Negative correlations are also noteworthy. Significant negative values were observed between clone size (clonesize) and fruit set (fruitset), where the coefficient was -0.547. This may indicate that an increase in clone size is associated with a decrease in fruit set. A similar trend is observed in other combinations, such as clone size and yield, where the coefficient is -0.516.

Important negative correlations are also seen between yield and the number of rainy days, as well as between yield and average rainy days. This may suggest that excessive precipitation can adversely affect the final yield. For example, the correlation coefficient between yield and the number of rainy days is -0.507.

Finally, strong relationships were noted between certain factors related to climatic conditions, such as minimum and maximum temperatures. These correlations indicate that they may play an important role in determining yield and other plant characteristics.

The analysis results reveal a complex network of relationships between yield and various agronomic, climatic, and ecological factors. These data may serve as a basis for further research and practical recommendations for improving yield.

In the conducted factor analysis, five factors affecting characteristics related to yield and external conditions were identified. Each of these factors, based on the coefficients, defines various aspects of influence on the plants. The factor loadings are presented in Figure 11.

The first factor appears to be related to temperature conditions, as evidenced by the high coefficient values for variables concerning the upper temperature range (MaxOfUpperTRange, MinOfUpperTRange, AverageOfUpperTRange). These variables have coefficients close to one, indicating their strong influence on the first factor. Notably, the variable clone size (clonesize) does not show a significant contribution to this factor, which may suggest that temperature conditions are more significant for other characteristics.

Indicators	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5
andrena	-0,02	-0,01	0,07	-0,14	0,88
AverageOfLowerTRange	1,00	0,00	0,01	0,00	-0,02
AverageOfUpperTRange	1,00	0,00	0,01	0,00	-0,02
AverageRainingDays	-0,01	0,95	-0,04	0,07	0,09
bumbles	-0,01	0,04	0,07	0,92	0,02
clonesize	0,02	0,00	0,94	-0,01	-0,08
fruitmass	0,07	-0,59	-0,51	0,50	0,24
fruitset	-0,12	-0,62	-0,55	0,42	0,24
honeybee	0,00	-0,02	0,90	0,09	0,20
MaxOfLowerTRange	1,00	0,00	0,01	-0,01	-0,02
MaxOfUpperTRange	1,00	0,00	0,01	-0,01	-0,02
MinOfLowerTRange	1,00	0,00	0,01	0,00	-0,02
MinOfUpperTRange	0,99	0,02	0,01	0,00	-0,01
osmia	-0,04	0,05	-0,07	0,36	0,74
RainingDays	0,00	0,94	-0,05	0,05	0,07
seeds	-0,02	-0,60	-0,54	0,50	0,24

Fig. 11. Factor loadings.

The second factor demonstrates a high coefficient for the number of rainy days (RainingDays) and the average duration of rainy days (AverageRainingDays). This indicates that this factor is primarily related to humidity and precipitation, which can significantly influence yield. Data on rainy days correlate with other characteristics, such as fruit set and fruit mass, confirming the importance of this factor.

The third factor, based on the coefficients, is related to various types of pollinators, especially bees (honeybee) and bumblebees (bumbles). The coefficient values indicate that these insects have a significant impact on plant fruiting, highlighting the importance of pollinators for obtaining a good yield.

The fourth factor highlights the variable related to fruit set (fruitset) and also includes variables associated with climatic conditions, such as temperature and rainy days. This suggests that environmental conditions and factors related to the pollination process have a complex influence on fruit formation.

The fifth factor is also associated with temperature conditions, particularly with minimum temperature values, confirming that temperature fluctuations can impact yield. Here, it is worth noting the variables related to fruit mass and the number of seeds, which may indicate that they depend on temperature conditions.

Thus, factor analysis shows that yield and other plant characteristics are influenced by both climatic conditions and ecosystem factors, such as pollination. This data can be useful for agronomists and researchers aiming to optimize conditions for achieving maximum yield.

The next step involved building a linear regression model to assess the impact of independent variables on the dependent variable and to check the model's fit to the existing data. The analysis included evaluating key indicators such as the log-likelihood, coefficient of determination (R^2), adjusted R^2, mean squared error, as well as the results of the F-test and values of information criteria (AIC, BIC, etc.). These metrics, presented in Table 1, allow for assessing the model's quality, accuracy, and significance of predictions.

The log-likelihood value of 1179.618813 indicates a good fit of the model to the data, as higher log-likelihood values suggest a better model. The coefficient of determination (R^2) is 0.964187, meaning that the model explains 96.42% of the variation in the dependent variable, which is a very high figure and indicates the model's strong explanatory power. The adjusted R^2, which takes into account the number of predictors in the model, is 0.96324, further confirming the high quality of the model.

Table 1. Regression model indicators.

Statistic	Value	Description
Model		
Constant	Included	Presence of a constant term in the regression equation
Log-likelihood	1179.618813	Measure of the goodness of fit of the model
Coefficient of determination (R^2)	0.964187	Proportion of the variance in the dependent variable that is predictable from the independent variable(s)
Adjusted R^2	0.96324	Adjusted R^2 is a modification of the R^2 that has been adjusted for the number of predictors in the model
Standard error of the estimate	0.036825	A measure of the accuracy of predictions made by the model
Degrees of freedom		
Degrees of freedom, residuals	605	
Degrees of freedom, model	16	
Hypothesis test		
F-statistic	1018.014788	A statistic used to test the overall significance of the model
p-value of the model	5.55E-16	The probability of observing a test statistic as extreme as, or more extreme than, the one that was actually observed, assuming that the null hypothesis is true
Information criteria		
Akaike Information Criterion (AIC)	-3.738324	A criterion for comparing models
Corrected Akaike Information Criterion (AICc)	-3.736695	A modification of the AIC that accounts for the number of observations and parameters
Bayesian Information Criterion (BIC)	-3.617167	A criterion for model selection that penalizes models with more parameters
Hannan-Quinn information criterion	-3.691236	A criterion for model selection

The mean squared error of the model's predictions is 0.036825. This low value indicates high accuracy for the model, and the residual degrees of freedom equal 605 with 16 degrees of freedom for the model, which is important for statistical tests. The F-statistic value is 1018.014788, and the p-value is 5.55E-16, confirming the high significance of the model, as the probability of it being insignificant is practically zero.

Information criteria such as AIC (-3.738324), adjusted AIC (-3.736695), BIC (-3.617167), and the Hannan-Quinn criterion (-3.691236) indicate that the model has a good fit to the data. Low values of these criteria suggest that the model is well-fitted and preferred over other possible models.

Overall, the model demonstrates high explanatory power, low prediction error, and significance of predictors, making it reliable and suitable for data analysis. The actual and predicted yield values are presented in Figure 12.

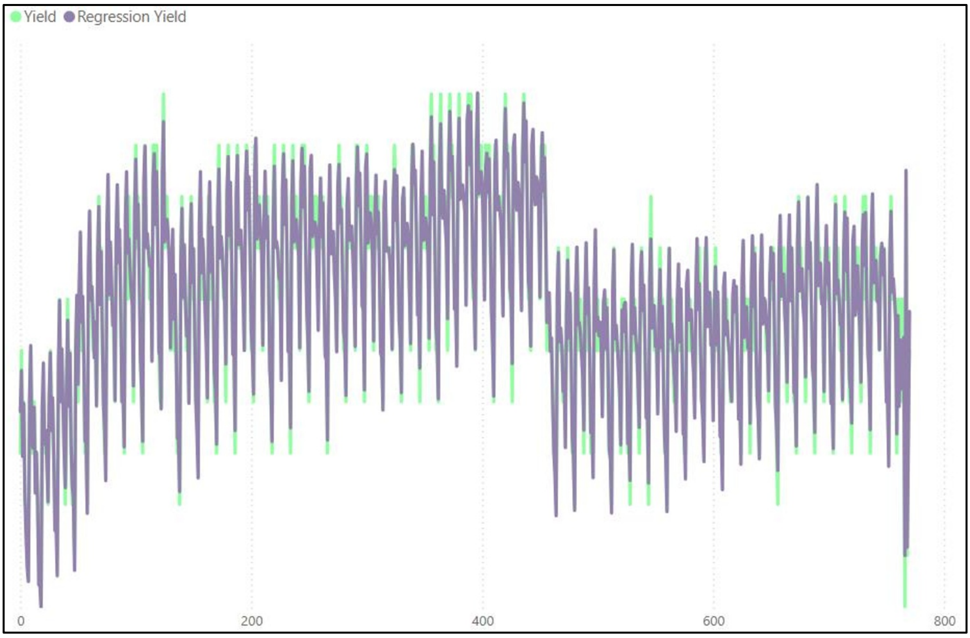


Fig. 12. Actual and predicted yield values.

5 Conclusion

This study identified significant relationships between the yield of wild blueberries and various factors such as pollinator density, climatic conditions, and the characteristics of the plants themselves. The analysis conducted established that high blueberry yields are closely linked to the presence of diverse pollinators, including honey bees, bumblebees, and wild bees. These results highlight the importance of preserving pollinator biodiversity for achieving sustainable agriculture.

Climatic conditions, such as temperature and precipitation, also significantly influenced yield. The established correlations between these factors indicate that optimizing agronomic practices in light of climate changes could lead to improved yield performance.

The results obtained can serve as a basis for further research in agronomy and ecology. They may assist agronomists and farmers in developing recommendations for optimizing conditions for successful blueberry cultivation. Thus, the investigation of factors affecting yield not only enhances agricultural efficiency but also supports efforts to protect the environment and preserve biodiversity.

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