CABI Agriculture and Bioscience

SHORT COMMUNICATION

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Unmanned aerial vehicle-based evaluation of pollination performance employing clustering image processing technique

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Abstract

The global decline of pollinator populations is posing a threat to agricultural productivity, increasingly forcing farmers to introduce pollinators to their fields. Selecting suitable pollinator species is critical for effective crop pollination. This study presents an efficient method for early pollination assessment, utilizing unmanned aerial vehicle (UAV) footage for reliable estimation and timely reactions. Twelve oilseed rape (*Brassica napus var. oleracea*) isolation cages with three pollinator treatments were set up, including the control with no pollinators. The trial employed UAV image acquisition, generating high-resolution RGB orthomosaics. A K-means clustering algorithm was implemented to identify oilseed rape flowers, a direct indicator of pollination performance. The percentage of detected oilseed rape flower coverage within each cage was the primary metric for performance assessment. These initial results demonstrated a negative correlation of 0.92 between estimated flower coverage and expert observations, affirming the efficacy of the proposed methodology. By integrating UAVs and clustering image processing, this research contributes to precision agriculture, offering a robust approach for evaluating pollination performance. The findings underscore the potential of advanced technology to support informed decision-making in agricultural practices, addressing the urgent need for sustainable pollination management in the face of declining pollinator populations.

Keywords Pollination, Oilseed rape, UAV technology, Agricultural productivity, Precision agriculture

Introduction

The relationship between pollinators and crops is crucial for maintaining agricultural productivity. Worldwide, the decline of pollinator populations poses a realistic threat to crop production. This has often forced farmers to introduce pollinators into their fields to enhance production. Effective pollination of crops depends on numerous factors, and the selection of the most suitable pollinator species for certain crops is one of the key elements for success. Evaluating the pollination rate before crops finish flowering is important to decide whether to introduce more pollinators. This can be quite challenging since only yield parameters can usually show pollination's true efficacy. In this paper, we proposed a method of early pollination evaluation based on UAV footage that will enable reliable pollination estimation and facilitate prompt reactions.

A synergy of machine learning algorithms and UAV technology is used in many domains of precision agriculture: weed detection [1], plant phenotyping [2], and crop disease detection [3], while the clustering method is used [4] for automatic plant pest and disease detection [5–9]. Those studies often involved detecting vegetation in UAV images, leveraging the capabilities of unsupervised machine learning algorithms, applied when the labels are hard to obtain, such as the detection of oilseed rape

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flowers. In this study, the proposed methodology involves preprocessing UAV images to extract relevant spectral information and application of clustering algorithms, such as K-means [10], DBSCAN (Density-Based Spatial Clustering of Applications with Noise) [11], and Agglomerative Clustering [12, 13], to group pixels with similar spectral signatures into distinct vegetation classes. By partitioning the image pixels based on their spectral characteristics, the clustering approach facilitated the identification and delineation of vegetation patches within the aerial imagery. This clustering methodology provided a systematic and automated framework for vegetation detection in UAV images, enabling efficient monitoring of agricultural fields, environmental assessments, and land-use mapping.

Methods

Experiment design

The trial was set up on the experimental fields of the Institute of Field and Vegetable Crops from Novi Sad, in Rimski Šančevi (45° 19′ 59.88″ N, 19° 51′ 0″ E), Serbia during the peak flowering of oilseed rape. The trial consisted of twelve isolation cages set up in a randomized block design with three replicates. Each cage had an area of 48 m2 (12×4 m), with a 1 mm mesh plastic netting, to exclude all other insects except the pollinator species inside the cages. A schematic representation of the experimental design and complete methodology is given in Fig. 1. Oilseed rape (*Brassica napus var. oleracea*) was used as the model plant and three species of pollinators; the buff-tailed bumblebee - *Bombus terrestris*, the European orchard bee - *Osmia cornuta* and the red mason bee - *O. bicornis* (syn. *O. rufa*) were used. In each cage, a constant number of individuals was introduced for both species of mason bees (50 females and 100 males per cage), while one commercial Natupol smart bumblebee hive, with a queen and 75–100 workers, was used in each cage with the bumblee treatments. In the control cages, no pollinators were introduced.

Data collection

Data collection involved the UAV image acquisition of twelve cages at the study site Rimski Šančevi, Serbia. For this purpose, UAV quadcopter-type DJI P4 Multispectral (Shenzhen DJI Sciences and Technologies Ltd.) was set up for a flight grid mission at an altitude of 20 m. High-resolution RGB orthomosaic (6488×3287 pixels) with a ground sampling distance of 1.68 cm/pixel was generated from the acquired images using image stitching software Pix4D mapper (2024 Pix4D SA). This comprehensive approach aimed to assess the effectiveness of the three pollinator species in the given context, utilizing advanced imaging techniques to capture detailed information on pollination success within each cage.

The proposed methodology

The entire experimental field is showcased, featuring twelve cages where the study was conducted. These cages serve as controlled environments for assessing pollination efficiency. At the bottom of the figure, the proposed methodology is outlined: RGB patches containing a single cage are fed into the clustering algorithm. These patches are obtained through a procedure elaborated in detail in Section Results. The clustering algorithm operates on the RGB patches to differentiate oilseed rape flowers from other classes, such as background, cage edges, bare ground, and net covering the crop (refer to Fig. 1). It generates a binary mask wherein the highest values correspond to oilseed rape flowers and the lowest to other classes.

The primary objective was to identify the region of interest, specifically the distribution of oilseed rape flowers, which is a direct indicator for evaluating pollination performance. The ultimate metric employed for performance assessment was the percentage of detected coverage of oilseed rape flowers within each controlled environment. This metric was calculated by determining the ratio of detected pixels belonging to oilseed rape flowers to the total number of pixels encompassed by the cage.

The preprocessing procedure of UAV-generated orthomosaic began with the calibration of acquisition angles and the subsequent rotation. The high-resolution orthomosaic, consisting of stitched images of all cages, was segmented into smaller patches, each containing a single cage (Fig. 1). Each RGB patch serves as the input, providing a representative feature space for each cluster (see graph within Fig. 1) utilizing K-means clustering. The algorithm outputs a cluster map that delineates six distinct clusters.

(See figure on next page.)

Fig. 1 The experimental field with twelve controlled cages is depicted, where pollination efficiency within each cage was assessed. The proposed methodology involves generating an UAV orthomosaic from RGB images. Processing entails feeding RGB patches of each cage into a K-means algorithm to identify oilseed rape flowers. As a result, the algorithm generates a binary mask distinguishing flowers from other elements (the representative cluster of the target class highlighted on the graph), with the primary objective of evaluating flower distribution and pollination performance

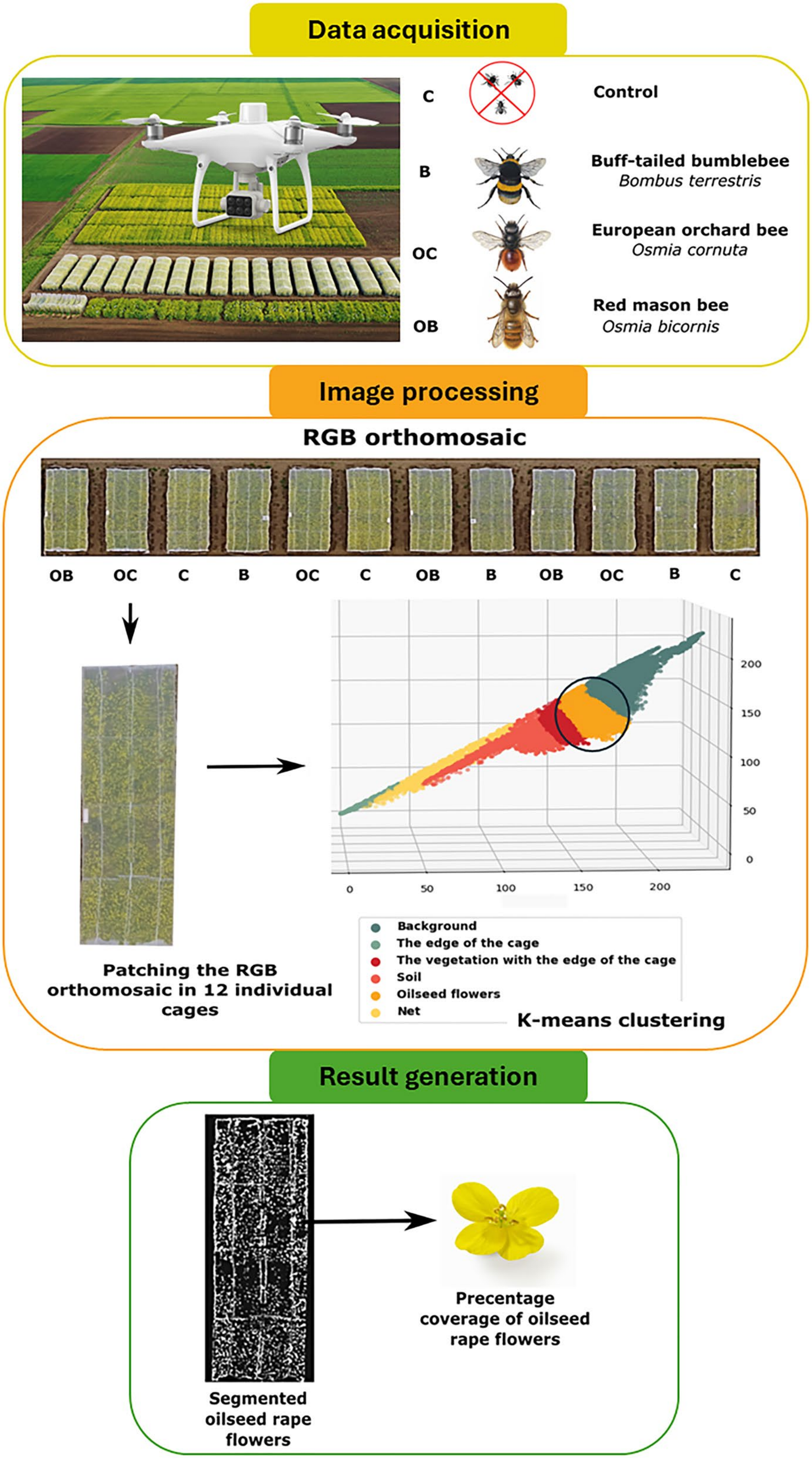

Fig. 1 (See legend on previous page.)

The iterative decision-making process involves identifying the appropriate cluster with particular emphasis on the second, third, and fifth clusters. Additional image arithmetic subtraction operations among these clusters focus on comparing and highlighting differences between clusters and regions of interest. It results in the precise detection of oilseed rape flowers (The binary representation in Fig. 1). This obtained result is prioritized for evaluating the percentage of oilseed rape flowers within each cage, contributing to the final evaluation metric.

The ultimate metric employed for performance assessment was the percentage of detected coverage of oilseed rape flowers within each controlled environment (cage). This metric was calculated by determining the ratio of detected pixels belonging to oilseed rape flowers to the total number of pixels encompassed by the cage.

Results

The results obtained from the K-means algorithm demonstrated the highest negative correlation of 0.92 between the estimated coverage of oilseed rape flowers and the observed alterations noted by experts.

The obtained percentage of detected oilseed rape flowers and ground truth yield are given in Table 1. By observing cages separately, it is indicated that the cages without pollinators have the highest percentage of oilseed rape floral coverage and the lowest yield, with an average floral coverage of 27.12% and a yield of 2.31 kg/ha. For cages with buff-tailed bumblebees, the average floral coverage is 21.57% and a yield of 6.21 kg/ha, European orchard bees 21.45% and 6.63 kg/ha, and red mason bees 22.1% and 5.54 kg/ha. The observed phenomenon suggests a compelling inverse relationship between the extent of oilseed rape flower coverage and the efficiency of pollination within the experimental cages. Specifically, a higher percentage of the oilseed rape flower coverage correlates with diminished pollination rates, indicative of a slower and less effective pollination process compared to cages exhibiting lower floral coverage. Moreover, this trend is mirrored in the ground truth yield, further reinforcing the notion of an adverse impact on productivity associated with enhanced floral coverage. Additionally, as the coverage of oilseed rape flowers increases, there may be a higher demand for essential resources such as nutrients, water, and sunlight. This increased competition can lead to resource scarcity, ultimately compromising the growth and yield of oilseed rape plants. This finding suggests that combining UAV technology and advanced image processing techniques offers a promising approach to early and accurate pollination evaluation. This research contributes to the growing body of knowledge in precision agriculture, providing a robust methodology for assessing pollination performance.

Discussion

This study addresses the critical issue of declining pollinator populations and its potential impact on crop production. Recognizing the significance of effective pollination in agriculture, the research focused on developing an early evaluation method using UAV footage to estimate pollination rates accurately. The experiment, conducted under semi-controlled conditions within isolation cages with different pollinator species, aimed to assess their effectiveness in pollinating oilseed rape plants. Employing advanced technology, particularly the integration of UAVs and clustering image processing techniques holds exciting potential for monitoring and enhancing pollination dynamics, supporting informed decision-making in agricultural practices. With this technology, we aimed to estimate and evaluate the pollination process of different pollination groups. The proposed methodology introduced a novel metric for performance assessment—the percentage of detected coverage of oilseed rape flowers within each cage. This metric, derived from the ratio of

Table 1 The results obtained by K-means clustering per each group

	Control			**Buff-tailed bumblebee**		
% of	25.30	27.40	28.66	22.09	21.03	21.59
flowers	0	0	6	9	3	9
Yield [kg/cage]	3.76	1.86	1.32	6.24	5.82	6.58
	European orchard bee			**Red mason bee**		
% of	21.47	21.6	21.30	21.57	22.36	22.36
flowers	7		0	7	6	6
Yield [kg/cage]	6.02	6.8	7.08	5.48	5.28	5.86

detected pixels belonging to oilseed rape flowers to the total pixels within the cage with net, served as a reliable indicator for evaluating pollination effectiveness.

Conclusions

Utilizing advanced technology, particularly UAVs and clustering algorithms, the study successfully generated high-resolution RGB orthomosaics. These images provided detailed insights into the pollination performance within each environment. The primary focus was on the application of clustering algorithms to identify and quantify the distribution of oilseed rape flowers, a direct indicator of pollination performance. The findings underscore the potential of advanced technology to support informed decision-making in agricultural practices, addressing the urgent need for sustainable pollination management in the face of declining pollinator populations. As FAO's Global Action on Pollination Services for Sustainable Agriculture [14] increasingly recognizes the significance of such initiatives, our work heralds a step towards ensuring food security and ecological resilience in the face of contemporary agricultural and climate change challenges.

Acknowledgements
Not applicable.

Author contributions
ŽG analyzed and interpreted the collected UAV data, making significant contributions to the manuscript's writing. BI played a primary role in UAV data acquisition and manuscript writing. FF and ŽM contributed significantly to experimental design, ground truth data collection, and manuscript revision. All authors reviewed and approved the final manuscript.

Funding
This work is supported through the ANTARES project that has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement SGA-CSA. No. 739570 under FPA No. 664387 (https://doi.org/10.3030/739570). We would like to thank "Zeleni Hit" for donating the bumblebee hives. This research was supported by the Ministry of Science, Technological Development and Innovation of the Republic of Serbia, grant number: 451-03-66/2024-03/200032.

Availability of data and material
The datasets during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate
Our institutions do not require ethics approval for reporting individual cases or case series.

Consent for publication
Not applicable.

Competing interests
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Received: 14 March 2024 Accepted: 5 September 2024
Published online: 19 September 2024

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