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PHENO_MAIZE: UAV-BASED HIGH-THROUGHPUT FIELD PHENOTYPING IN TEMPERATE MAIZE BREEDING

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Abstract

High-throughput field phenotyping (HTFP) has become an important approach for improving the efficiency and objectivity of phenotypic evaluation in modern plant breeding. Within the PHENO_MaizE project the practical application of UAV-based RGB phenotyping in temperate maize breeding under field conditions is investigated. The project integrates repeated drone imaging, extraction of image-derived traits, and predictive modeling in order to evaluate the potential of digital phenotyping for the selection of superior maize genotypes. Experimental material includes maize inbred lines and their corresponding testcrosses evaluated across multiple environments in Serbia. UAV surveys conducted during the growing season will enable monitoring of temporal crop development and extraction of traits such as plant height, canopy cover, vegetation indices, and growth dynamics. The research within the project will also assess the potential of phenomic prediction models for estimating important agronomic traits, including grain yield, flowering time, and grain moisture at harvest. Special emphasis is placed on developing a practical, cost-effective, and scalable HTFP framework adapted to medium-sized breeding programs. The expected outcomes may support wider implementation of digital phenotyping and data-driven selection strategies in maize breeding.

Key words: high-throughput phenotyping, UAV, maize breeding, RGB imaging, phenomic prediction, digital phenotyping

Introduction

Maize (*Zea mays* L.) is one of the most important field crops worldwide due to its high productivity, broad genetic diversity, and diverse utilization in food, feed, and industrial production. Modern maize breeding programs are focused on developing hybrids with improved yield potential, stability, and tolerance to biotic and abiotic stresses under increasingly variable environmental conditions. Efficient phenotypic evaluation therefore remains one of the key components of successful breeding programs.

Conventional field phenotyping is largely based on manual measurements (Chen et al., 2026) and visual scoring of agronomic traits. Although widely used, these approaches are labor-intensive, time-consuming, and difficult to apply efficiently in large breeding populations. Manual measurements may also introduce subjectivity and limit the number of traits and

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developmental stages that can be evaluated during the growing season.

Recent advances in remote sensing (Feng et al., 2021) technologies and unmanned aerial vehicles (UAVs) have enabled the development of high-throughput field phenotyping, which allows rapid, non-destructive, and objective assessment of crop performance under field conditions. UAV-based platforms can generate large amounts of spatial and temporal data throughout the growing season and provide detailed information on crop growth, canopy structure, and plant development dynamics. Among different sensing approaches, RGB imaging (Feng et al., 2021) represents one of the most accessible and cost-effective solutions for breeding applications because of its relatively simple data acquisition and processing requirements.

In recent years, UAV-based HTFP has become increasingly important in plant breeding and precision agriculture. Image-derived traits obtained from UAV surveys have shown considerable potential for evaluating plant architecture, vegetation dynamics, stress responses, and yield-related characteristics in maize and other crops. Furthermore, integration of phenotypic data with statistical and machine learning (Crossa et al., 2024; Farooq et al., 2024) approaches has opened new possibilities for predictive breeding and phenomic selection (Crain et al., 2018).

The PHENO_MaizE project was established with the aim of investigating the practical application of UAV-based high-throughput field phenotyping in temperate maize breeding. The project combines repeated RGB-UAV imaging, extraction of image-derived traits, and predictive modeling in order to evaluate the potential of digital phenotyping for improving breeding efficiency and selection accuracy under field conditions.

Project concept and objectives

High-throughput field phenotyping enables the evaluation of plant traits directly under field conditions, where crops are exposed to natural environmental variability throughout the growing season. This is particularly important in maize breeding, where genotype performance strongly depends on environmental conditions and genotype-by-environment interactions. Compared with conventional phenotyping, HTFP allows efficient extraction of image-derived traits such as plant height, canopy cover, vegetation indices, and temporal growth dynamics, which are difficult to measure manually in large field experiments.

The main goal of PHENO_MaizE is to optimize the use of UAV-based HTFP within the maize breeding program of the Maize Research Institute Zemun Polje (MRIZP). The project uses MRIZP breeding material as a model system for testing whether drone-derived phenotypic information can improve the speed, precision, and scalability of field evaluation. The concept of the project is based on repeated imaging of breeding trials during the growing season, automated extraction of plot-level traits, and their use in predictive models for agronomically important traits (Figure 1).

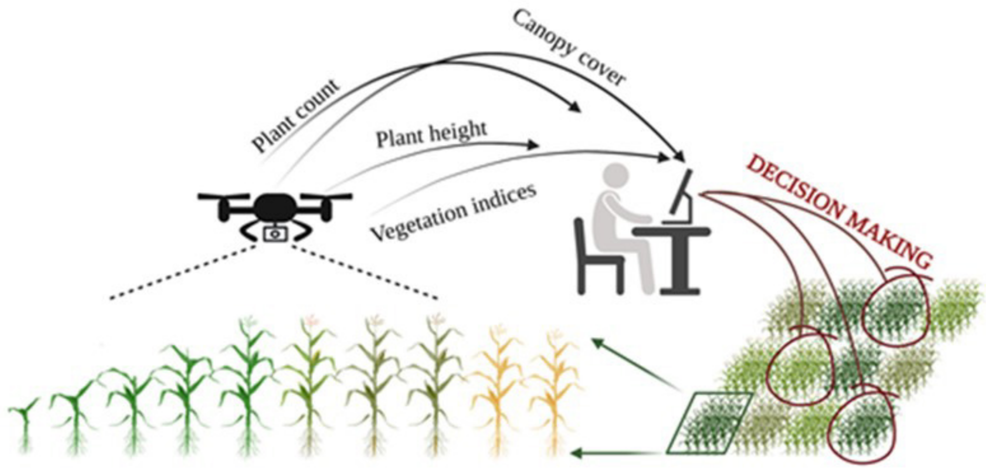


Figure 1. PHENO_MaizE concept
Grafikon 1. PHENO_MaizE koncept

The project addresses several practical questions relevant to maize breeding: whether UAV-derived data can partially replace selected manual measurements (Chen et al., 2026); how accurately image-derived traits can predict grain yield, flowering time, and grain moisture at harvest; which traits and growth stages provide the highest predictive value; and how such methodology can be implemented in breeding programs with limited technical and financial resources. A central idea of the project is not to develop a technologically complex system that is difficult to apply in routine breeding practice, but rather to establish a practical and reproducible workflow based primarily on RGB imaging (Feng et al., 2021) and open-source analytical tools. Such an approach is expected to make digital phenotyping more accessible to medium-sized breeding programs and to support gradual integration of data-driven decision-making into maize improvement.

Plant material and field experiments

The project includes two groups of maize inbred lines and their corresponding testcrosses. The first group consists of 100 doubled haploid (DH) lines derived from a biparental population developed by crossing two yellow dent MRIZP commercial inbred lines belonging to the Iowa Stiff Stalk Synthetic (BSSS) heterotic group. The second group includes 100 selected MRIZP commercial inbred lines, promising recombinant inbred lines, and several ex-PVP lines incorporated into the MRIZP breeding program. These materials mainly represent BSSS and Iowa Dent genetic backgrounds and cover medium-early to late maturity groups under Serbian growing conditions.

Testcrosses are produced using a commercial MRIZP tester from the opposite heterotic group. The selected tester has stable agronomic performance and is routinely used in the MRIZP breeding program. In total, 400 genotypes, including inbred lines and their testcrosses, will be evaluated using UAV-based RGB imaging (Feng et al., 2021) and conventional field measurements.

Field experiments are organized across multiple environments in Serbia. The first year of the project included two locations, while an additional environment is being included in the second year. This experimental design will enable evaluation of prediction models across different environmental conditions and provide a basis for testing model robustness when year and location effects are considered.

UAV-based RGB phenotyping workflow

The methodological framework of PHENO_MaizE is based on unmanned aerial systems equipped with RGB imaging (Feng et al., 2021) technology. Experimental fields will be monitored repeatedly during the growing season using a DJI Mavic 3M drone. Flights will be performed at selected developmental stages, from early vegetative growth to physiological maturity, in order to capture temporal changes in crop development (Picture 1).

Picture 1. DJI Mavic 3M drone
Slika 1. Dron DJI Mavic 3M

Flight missions will be planned to ensure suitable image overlap, stable illumination conditions, and sufficient spatial resolution for micro-plot experiments. The use of RTK positioning and ground control points will provide the geometric precision required for comparison of images across time points and environments. The research team will perform the flights independently, which allows full control over imaging frequency, flight parameters, and data quality.

The workflow includes field preparation, mission planning, image acquisition, photogrammetric reconstruction, generation of georeferenced orthomosaics and digital surface models, and extraction of plot-level phenotypic traits. RGB imagery and derived spatial products will be used to describe plant growth, canopy architecture, and vegetation dynamics during the season. Traits of interest include canopy cover, vegetation indices, plant height, plant number per plot, and temporal growth parameters.

Image processing and trait extraction will be performed using GIS tools and open-source analytical pipelines in R, including packages such as UASTools and FIELDimageR. The use of open-source tools is important for reproducibility and for adapting the workflow to different experimental designs commonly used in breeding programs. The resulting database will combine UAV-derived traits with conventionally measured agronomic data, enabling direct comparison between digital and manual phenotyping approaches (Figure 2).

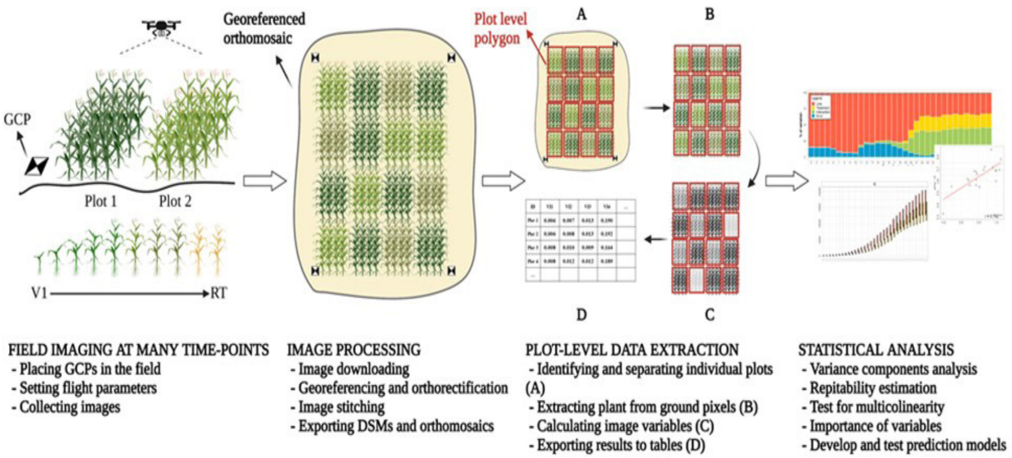


Figure 2. PHENO_MaizE workflow overview
Figura 2. Pregled PHENO_MaizE radnog toka

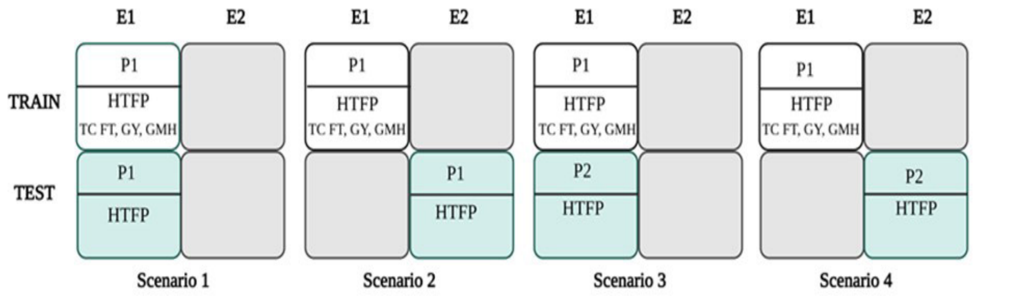
Phenomic prediction and model evaluation

A major objective of the project is to evaluate whether UAV-derived phenotypic data can be used for prediction of key agronomic traits. In this context, phenomic prediction represents an extension of genomic selection principles, where high-throughput phenotypic variables are used as predictors of breeding-relevant traits. Within PHENO_MaizE, image-derived variables will be used to develop prediction models for flowering time, grain yield, and grain moisture at harvest.

Different statistical and machine learning (Crossa et al., 2024; Farooq et al., 2024) approaches will be compared in terms of predictive ability, stability, and practical usefulness. Model performance will be evaluated through cross-validation and through prediction scenarios that reflect real breeding situations, including prediction across genotypes, environments, and years. Particular attention will be paid to avoiding overestimation of predictive accuracy caused by spatial or temporal autocorrelation in field data.

Training population structure will also be evaluated. Models will be developed using inbred line data, testcross data, and combined datasets. Because testcross performance is directly relevant for hybrid breeding, phenotypic data from testcrosses will serve as a key reference for model training and validation, while inbred line performance will provide complementary information.

An additional practical goal is optimization of data acquisition. Since a large number of UAV flights can increase data volume and processing requirements, the project will identify the most informative time points and image-derived variables. This will help determine whether reliable predictions can be obtained from a reduced number of strategically selected flights. Early prediction of agronomic performance would be especially useful for breeding programs, as it could support earlier selection decisions and more efficient allocation of field and seed resources (Figure 3).



Testing the PHENO_MaizE model prediction performance in different scenarios. E1 - Environment 1, E2 - Environment 2, P1 - Population 1, P2 - Population 2. **Scenario 1**: Train P1 using HTFP and TC flowering time (FT), grain yield (GY) and grain moisture at harvest (GMH) from E1- test P1 using HTFP from E1. **Scenario 2**: Train P1 using HTFP and TC FT, GY and GMH from E1- test P1 using HTFP from E2. **Scenario 3:** Train P1 using HTFP and TC FT, GY and GMH from E1- test P2 using HTFP from E1. **Scenario 4:** Train P1 using HTFP and TC FT, GY and GMH from E1- test P2 using HTFP from E2.

Figure 3. Testing PHENO_MaizE model prediction performance in different scenarios
Figura 3. Testiranje prediktivnih performansi PHENO_MaizE modela u različitim scenarijima

Practical relevance, challenges, and future perspectives

UAV-based high-throughput field phenotyping has considerable potential to improve maize breeding by enabling rapid, objective, and non-destructive collection of phenotypic data under field conditions. In breeding programs, such data can support evaluation of a larger number of genotypes, repeated monitoring of crop development, and earlier identification of promising material. The practical value of this approach is particularly important for traits that are difficult, slow, or expensive to measure manually across many plots and developmental stages.

At the same time, implementation of HTFP in routine breeding practice faces several challenges. Image acquisition is influenced by weather conditions, light intensity, crop developmental stage, and field uniformity. In addition, processing of large image datasets requires adequate computational resources, standardized analytical procedures, and careful quality control. Predictive models developed in one environment or season must also be tested across broader conditions before they can be reliably used in selection decisions.

The PHENO_MaizE project addresses these challenges by focusing on a realistic breeding context and on a workflow that can be applied with available UAV equipment and open-source software. The expected results should provide practical recommendations regarding flight timing, useful image-derived traits, and modeling strategies suitable for temperate maize breeding. In the longer term, integration of UAV-based phenotyping (Xie and Yang, 2020; Tanaka et al., 2024) with genomic, environmental, and agronomic data may further improve selection accuracy and support development of high-yielding and climate-resilient maize hybrids.

Conclusion

The PHENO_MaizE project represents an important step toward the integration of high-throughput field phenotyping into temperate maize breeding. By combining UAV-based RGB imaging (Feng et al., 2021), automated extraction of image-derived traits, and predictive modeling, the project aims to develop a practical framework for improving phenotypic evaluation and selection efficiency. Its particular value lies in adapting digital phenotyping approaches to the needs and capacities of medium-sized breeding programs.

The project is expected to identify the most informative growth stages and UAV-derived traits for prediction of grain yield, flowering time, and grain moisture at harvest. The results may contribute to more efficient use of field data, reduction of labor-intensive manual measurements (Chen et al., 2026), and earlier selection decisions. More broadly, PHENO_MaizE may support the transition from traditional field evaluation toward digitally assisted and data-driven maize breeding under changing environmental conditions.

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Author contributions

Conceptualization, S.P. i S.B.; Methodology, S.B.; Software, V.G.; Data curation, J.P.; Formal analysis, N.G.; Investigation, A.K.; Resources, J.V.; Project administration, M.M.; Supervision, S.B.; Visualization, S.P.; Validation, S.B., N.G. i V.G.; Funding acquisition, A.K.; Writing — original draft, S.P.; Writing — review & editing, S.B.

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PHENO_MAIZE: UAV-ZASNOVANA VISOKOPROPUSNA FENOTIPIZACIJA U POLJSKIM USLOVIMA U OPLEMENJIVANJU KUKURUZA U UMERENOM KLIMATSKOM POJASU

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Sažetak

Visokopropusna fenotipizacija u poljskim uslovima (High-Throughput Field Phenotyping – HTFP) predstavlja značajan pristup unapređenju efikasnosti i objektivnosti procene fenotipskih osobina u savremenim programima oplemenjivanja biljaka. U okviru projekta PHENO_MaizE istražuje se mogućnost praktične primene fenotipizacije zasnovane na RGB snimcima prikupljenim bespilotnim letelicama (UAV) u oplemenjivanju kukuruza u uslovima umerenog klimata. Projekat obuhvata integraciju višekratnog snimanja useva tokom vegetacije, ekstrakciju osobina izvedenih iz snimaka i primenu prediktivnih modela radi procene potencijala digitalne fenotipizacije za identifikaciju i selekciju superiornih genotipova kukuruza. Eksperimentalni materijal čine samooplodne linije kukuruza i njihova test-ukrštanja, koji se ispituju u više agroekoloških uslova na teritoriji Srbije. UAV snimanja tokom vegetacionog perioda omogućiće praćenje dinamike razvoja useva kroz vreme i izdvajanje fenotipskih osobina kao što su visina biljaka, pokrivenost zemljišta vegetacijom, vegetacioni indeksi i parametri dinamike rasta. Istraživanja u okviru projekta obuhvatiće i procenu mogućnosti primene fenomskih predikcionih modela za predviđanje važnih agronomskih svojstava, uključujući prinos zrna, vreme cvetanja i sadržaj vlage u zrnu pri žetvi. Poseban akcenat biće stavljen na razvoj praktičnog, ekonomičnog i merljivog sistema visokopropusne fenotipizacije prilagođenog potrebama oplemenjivačkih programa srednjeg obima. Očekuje se da rezultati projekta doprinesu široj primeni digitalne fenotipizacije i selekcije zasnovane na tim podacima, čime bi se unapredila efikasnost oplemenjivanja kukuruza i ubrzalo stvaranje novih, visokoprinosnih i adaptabilnih genotipova.

Ključne reči: visokopropusna fenotipizacija, bespilotne letilice, oplemenjivanje kukuruza, RGB snimci, fenomski predikcioni modeli, digitalna phenotipizacija

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