High-Throughput Crop Phenotyping Monitoring: An Accelerator for Breeding and Precision Agriculture Development (Postprint)

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Abstract

Phenotype serves as a crucial bridge for investigating the "genotype-phenotype-environment" interaction mechanism. The development of crop phenotyping monitoring platforms with independent intellectual property rights holds significant importance for accelerating breeding processes and supporting precision agriculture monitoring. The Crop3D phenotyping monitoring system focuses on major staple crops such as rice and maize, achieving multi-scale, multi-temporal dynamic monitoring of crop growth throughout the entire growth period, thereby providing essential data support for breeding. This article first reviews research progress on phenotyping platforms both domestically and internationally, then introduces the main research advances of the Crop3D system platform, and finally offers an outlook on future directions for phenotyping research.

Full Text

Special Topic: Designer Breeding by Molecular Modules

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Phenotyping serves as a critical bridge for studying the interaction mechanism of "genotype-phenotype-environment." Developing crop phenotyping platforms with independent intellectual property rights is of great significance for accelerating the breeding process and assisting precision agriculture monitoring. The Crop 3D phenotyping monitoring system, focusing on major food crops such

as rice and maize, has achieved multi-scale and multi-temporal dynamic monitoring of crop growth throughout the entire growth cycle, providing important data support for breeding. This article first reviews research progress on phenotyping platforms both domestically and internationally, then introduces the main research advances of the Crop 3D system platform, and finally provides prospects for future phenotyping research directions.

Keywords: breeding, high-throughput, phenotype, LiDAR, unmanned aerial vehicle
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Significance of High-throughput Phenotyping and Current Research Status

Boosting Production Through Technology to Ensure Food Security

As a major agricultural country, China must continuously advance agricultural science and technology and develop new agricultural modernization with Chinese characteristics. The “Innovative System for Molecular Module Design Breeding” initiative, which analyzes and couples molecular modules to optimize multi-module assembly at the whole-genome level, provides a cutting-edge solution for simultaneously improving both yield and quality in current breeding programs [1,2]. Ensuring food security is crucial for China’s national economy and people’s livelihood, representing a major strategic demand for socio-economic development. Although China’s grain production continues to grow steadily, due to ongoing reduction in arable land and population growth, the country still faces a grain deficit of approximately 200 billion jin (100 million tons) by 2020. The 13th Five-Year Plan proposes “storing grain in technology” to increase grain production capacity through green yield-enhancing technologies, accelerating the development of new agricultural varieties and technologies.

“Phenotype is king, gene is queen” is a common saying among scholars in phenotyping-related fields. For breeding and agricultural management, phenotypic analysis is a key link in understanding gene function and environmental effects. Throughout the breeding process, phenotyping monitoring not only guides indoor germplasm screening in the early stages but also evaluates field performance of varieties during later promotion and cultivation. Therefore, high-throughput phenotyping monitoring can accelerate the entire breeding process and provide important data support for resource regulation and management strategy formulation in precision agriculture monitoring [3].

Current Status of Crop Phenotyping Platform Development

Phenotyping platforms equipped with different types of sensors can acquire multi-source remote sensing data in a short time, making high-throughput phenotypic measurement possible [4,5]. Based on their working environment, phenotyping platforms can be divided into indoor fixed platforms and outdoor mobile platforms. Indoor fixed platforms offer advantages of high precision, strong repeatability, and immunity to external interference. Currently, indoor fixed platforms can be categorized according to the movement status of target crops and sensors during operation into "plant-to-sensor" (crop-moving) and "sensor-to-plant" (sensor-moving) modes.

The "plant-to-sensor" approach refers to sensors remaining fixed while target crops enter the working area via conveyor belts or other transport platforms, allowing sensors to collect data from different batches of crops. Currently, such platforms developed abroad are relatively mature, primarily in France, Germany, Belgium, the Netherlands, and Australia. Among them, CropDesign in Belgium designed the world's first phenotyping platform—TraitMill; LemnaTec's indoor platform in Germany can automatically, high-throughput, and throughout the entire growth period acquire structural parameters, physiological parameters, and conduct environmental stress analysis; the French National Institute for Agricultural Research established the Phenoscope and PHENOPSIS platforms suitable for small plants; similar integrated platforms for genetic and phenotypic traits include KeyGene's PhenoFab platform in the Netherlands and Australia's PlantScan platform. In contrast, domestic phenotyping platforms started late and lagged in development. Research teams represented by Huazhong Agricultural University have developed tomography scanners and digital seed testers to obtain structural information such as plant height and tillering of individual rice plants, as well as seed traits after harvest [6]. In summary, "plant-to-sensor" platforms are generally mature, mainly benefiting from small sample sizes per operation, uniform environment, and lower difficulty. However, the "plant-to-sensor" approach has low overall efficiency and can affect mature and easily lodging crops, causing monitoring errors and crop damage. More importantly, many important agronomic traits only manifest when crops are grown in real-environment populations. Therefore, obtaining data under fixed field planting patterns is particularly necessary.

The "sensor-to-plant" indoor platform moves sensors to target crop areas for image acquisition and information collection. This scanning approach maintains fixed crop positions, minimizes interference with actual crop growth, offers greater flexibility in sensor movement, and provides high work efficiency, becoming the main direction for current phenotyping platform development. However, real-time collection of population data during sensor movement and achieving high-throughput phenotypic parameter extraction pose enormous challenges for both hardware integration and software development.

Crop 3D: An Independently Developed Crop Phenotyping Monitoring System

Indoor Fixed Monitoring Platform

Crop 3D, China's first high-throughput crop three-dimensional phenotyping monitoring system, was developed by the Institute of Botany, Chinese Academy of Sciences in 2014. The system includes indoor fixed platforms, outdoor mobile monitoring platforms, UAV monitoring platforms, and large-scale fixed field monitoring platforms under construction [7]. The indoor platform integrates four types of sensors—LiDAR, high-resolution cameras, multispectral and thermal imagers—adopting the "sensor-to-plant" approach to complete scanning of 20 m^2 crop area within 240 seconds (Figure 1a [Figure 1: see original paper]). Among them, point cloud data obtained by LiDAR can provide millimeter-precision phenotypic structural information, offering unparalleled advantages in extracting three-dimensional structural parameters such as leaf inclination angle, leaf area density, leaf area index, and crop three-dimensional volume; high-resolution imagery provides complete canopy coverage information at the population level, offering rich texture information for crop three-dimensional reconstruction; hyperspectral images, after processing such as stitching, correction, and color balancing, provide high spatial resolution vegetation indices applicable for crop growth status and physiological state assessment; thermal imagers provide all-weather monitoring of crop canopy temperature, reflecting crop physiological status under growth stress in real time. To enable data collection in different greenhouse environments, a small indoor mobile platform transplants sensor modules from the fixed platform, allowing cross-greenhouse operations with greater flexibility and portability (Figure 1b [Figure 1: see original paper]).

To facilitate multi-source data analysis, the Crop 3D software module integrates individual plant segmentation and branch-leaf separation algorithms based on LiDAR point cloud data, achieving automated, high-throughput extraction of phenotypic structural parameters from population to individual plant and from individual plant to leaf levels (such as canopy coverage, canopy height model, plant height, leaf inclination angle, etc.) (Figure 2 [Figure 2: see original paper]). Additionally, the software module includes functions such as point cloud and image data fusion, vegetation index extraction, and temperature analysis, providing comprehensive support for plant phenotyping and physiological ecology research.

Outdoor Phenotyping Monitoring Platforms

2.2.1 Vehicle and Backpack Mobile Monitoring Platforms

High-throughput phenotyping monitoring of crops is easily achieved under controlled conditions but faces challenges in the field due to environmental factor interactions and high-density planting. Given the scale and precision requirements of field monitoring, vehicle platforms become the preferred choice. In the Crop 3D platform system, an unmanned ground vehicle (UGV) equipped with LiDAR achieves rapid and efficient collection of crop canopy three-dimensional data (Figure 1b [Figure 1: see original paper]). This remote-controlled mobile platform aims for "multiple uses for one machine, multiple capabilities for one specialization," with the capacity to carry various sensor modules that can be selected according to actual needs. Simultaneously, the system is equipped with a lifting module to automatically adjust the sensor platform height according to crop growth, ultimately achieving long-distance, large-scale plot data collection.

Due to heterogeneous soil distribution and other field characteristics, vehicle systems inevitably experience bumps and vibrations during movement. In this vehicle system, the mobile LiDAR system consists of four components: a laser ranging unit, an inertial measurement unit (IMU), a global positioning system (GPS), a synchronization control unit, and a data storage unit, which together record the sensor's trajectory and attitude information in real time during data collection for post-processing settlement. The accuracy of crop three-dimensional canopy point cloud data is related to the sensor's own precision, while point cloud density is related to the vehicle platform's traveling speed. The Crop 3D vehicle system's traveling speed can be customized according to needs, ranging from 0.1 to 2 m/s. Overall, the vehicle platform features high integration with integrated mechanical, electrical, and electronic systems. The data collection module and carrier platform can be connected through standard hardware interfaces, offering strong migratability and high flexibility. In addition to being mounted on field mobile platforms, it can also be mounted on UAVs and airships.

The backpack mobile monitoring platform is a new type of carrier platform that has emerged in recent years. By integrating sensors into a simple backpack system, it can flexibly and conveniently complete data collection in target areas. Currently, the more mature system is the backpack integrated indoor-outdoor LiDAR scanning system, which combines LiDAR and simultaneous localization and mapping (SLAM) technology to obtain high-precision three-dimensional point cloud data of the surrounding environment in real time. This has been successfully applied in indoor-outdoor integrated measurement, forestry resource surveys, and underground spatial information acquisition (Figure 3a [Figure 3: see original paper]). Drawing on this concept, integrating sensors required for agricultural monitoring, such as cameras and plant canopy analyzers, is expected to enable rapid acquisition of field crop canopy data.

2.2.2 Fixed Field Monitoring Platforms

For long-term fixed observation plots, fixed “gantry” platforms are a good option. By installing corresponding sensors on fixed brackets built in the field or on existing observation towers, continuous observation of crops within a fixed effective measurement area can be achieved. Planting patterns determine that field phenotypic data acquisition can only adopt the “sensor-to-plant” approach. Therefore, currently constructed fixed-frame platforms typically use a square frame, with sensor modules completing scanning within the coverage area through stepwise cyclic movement, generally similar to the operation mode of indoor fixed platforms (Figure 1a [Figure 1: see original paper]). This platform mode is suitable for long-term plot monitoring to complete field screening of superior varieties or quantitative trait locus identification related to stress phenotypes. However, compared with indoor platforms, fixed-frame platforms are exposed to natural environments and require continuous attention and maintenance of platform integrity, thus incurring certain costs (Figure 3c [Figure 3: see original paper]).

2.2.3 UAV Monitoring Platforms

Due to limitations in collection speed and area, vehicle systems exhibit a certain degree of temporal asynchrony for large-scale farmland canopy data collection, which to some extent leads to errors in some canopy parameters. Over the past two decades, UAV platforms have been widely applied in large-scale agricultural yield estimation and disaster assessment. Compared with traditional airborne platforms, UAV platforms often face limitations such as limited payload and short endurance. The independently developed 8-rotor UAV platform has an effective payload of 5 kg, an effective cruising radius of 2 km, and a maximum endurance of 30 minutes (with 4 kg payload). Taking UAV LiDAR as an example (Figure 3d [Figure 3: see original paper]), its ranging accuracy is 10 mm, covering a range of 3–920 m, using near-infrared laser, with a maximum effective measurement rate of 500,000 points/s. Using this platform can quickly obtain large-area crop three-dimensional point clouds, enabling calculation of phenotypic parameters related to crop photosynthesis and yield (leaf area index, coverage, crop height, etc.), as well as acquisition of centimeter-level fine terrain, thereby providing data support for clarifying phenotypic differences caused by terrain factors.

Current Development Bottlenecks and Future Directions

Addressing National Strategic Needs

As a populous country, China faces not only a huge food gap but also threats to food security such as reduction in available arable land, low utilization efficiency of agricultural irrigation water, and susceptibility to pests and diseases. The Ministry of Science and Technology has clearly identified grain production increase with quality and efficiency improvement, and agricultural non-point source pollution prevention and control as key research and development tasks supporting and leading modern agricultural development in the 13th Five-Year Plan for science and technology innovation. Agriculture needs to shift from the extensive “heavy water and heavy fertilizer” model to a new normal relying on scientific and technological innovation. Although China has achieved certain results in breeding and yield estimation, in the long term, the excavation and utilization of high-quality crop germplasm resources remain relatively low. One of the main reasons is the lack of systematic identification and in-depth research on germplasm resources, especially the excavation of superior phenotypic traits and associated genetic information from germplasm resources. As the result of genotype and environmental variable interactions, phenotyping monitoring is significant for researchers to dissect quantitative genetics traits related to yield and stress tolerance, and to monitor field variables in real time for resource allocation under the background of precision agriculture.

To better identify high-feedback, fast-growing, and high-yield varieties, precisely and rapidly recognizing complex structural traits related to crop growth and development, physiological ecology, stress tolerance, and yield remains one of the urgent challenges in current phenotyping technology development. Over the past two decades, phenotyping technology has developed rapidly and is gradually meeting the demands for high precision and high throughput. Under the background of global climate change, stress-related quantitative traits manifest throughout the entire growth period. High-throughput phenotyping data, genotyping data, and environmental monitoring data from multiple time series and multiple sources will inevitably create "big data," making data storage and management the next urgent problem to be solved. Faced with massive data sources, researchers need to establish effective management systems, improve data management and usage standards, and implement scientific collection and management of phenotyping data from large to small scales. The establishment of this system depends on establishing deeper and more effective cooperation between breeders and crop scientists, giving full play to interdisciplinary advantages, and truly leveraging big data to accelerate the development of breeding and agricultural precision and informatization.

Platform Integration and Algorithm Development

Currently, both domestic and international communities have gradually recognized the significance of phenotyping monitoring platforms for breeding and agricultural development, and several relatively mature phenotyping monitoring systems have emerged internationally. However, current usage of phenotyping platforms faces some problems, such as phenotypic data not being well matched with genotypic data and data redundancy caused by high-throughput phenotyping monitoring. These are inevitable in the development process from emergence to application to maturity.

We believe that future crop phenotyping research will continue to receive attention, with main development directions or challenges including the following five aspects:

(1) **High-dimensional parameter extraction.** Acquisition of precise three-dimensional crop structures relies on high-dimensional data from sensors such as LiDAR and RGB cameras. How to calculate structural features from high-dimensional data, especially feature extraction, target detection, and classification segmentation of high-dimensional data, requires further exploration.

(2) **Multi-scale analysis.** Current algorithms mostly focus on extracting phenotypic parameters at a single scale. Methods for extracting target crop information from different scales, such as extracting individual plant information from populations and extracting specific organ traits (such as roots and panicles) from individual plants, are seriously lacking.

(3) **Multi-source data fusion.** Multi-source data fusion involves two aspects: On one hand, researchers need to fuse data acquired by the same

sensor at different periods to achieve dynamic monitoring and analysis of traits throughout the entire growth period. On the other hand, for information acquired by multi-source sensors, how to fuse data of different dimensions and scales, especially indoor-acquired multi-source data lacking coordinate information, is a challenge for comprehensive research from morphology to physiology to mechanisms.

(4) **Interdisciplinary collaboration.** How to truly combine engineering disciplines with theoretical disciplines? Phenotyping research is not only a technological innovation but must also serve breeders and plant scientists. Conducting in-depth interdisciplinary cooperation helps to effectively transform technology into productivity, thereby accelerating "gene-phenotype-environment" research from a technical perspective.

(5) **Multi-database sharing platforms and standards.** To study the interaction of "gene-phenotype-environment" and better serve breeding work, high-throughput genotypic data, phenotypic data, and real-time changing environmental information from different data providers need to be organically integrated [8]. Therefore, establishing a set of data standards and sharing platforms is essential for crop phenotyping research in the big data era (Figure 4 [Figure 4: see original paper]).

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Note: Figure translations are in progress. See original paper for figures.