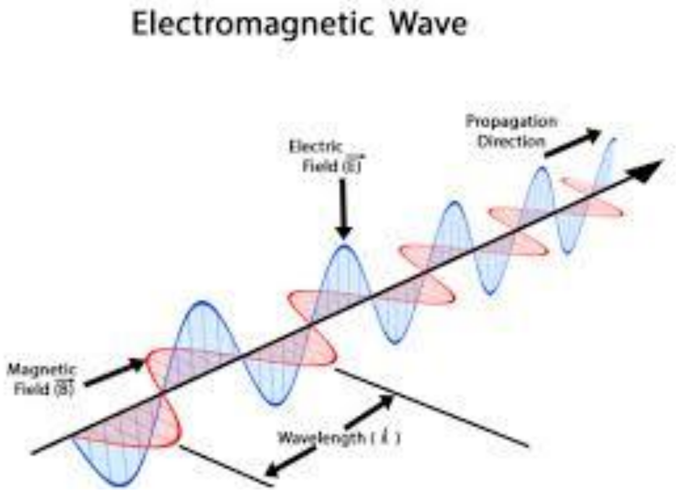
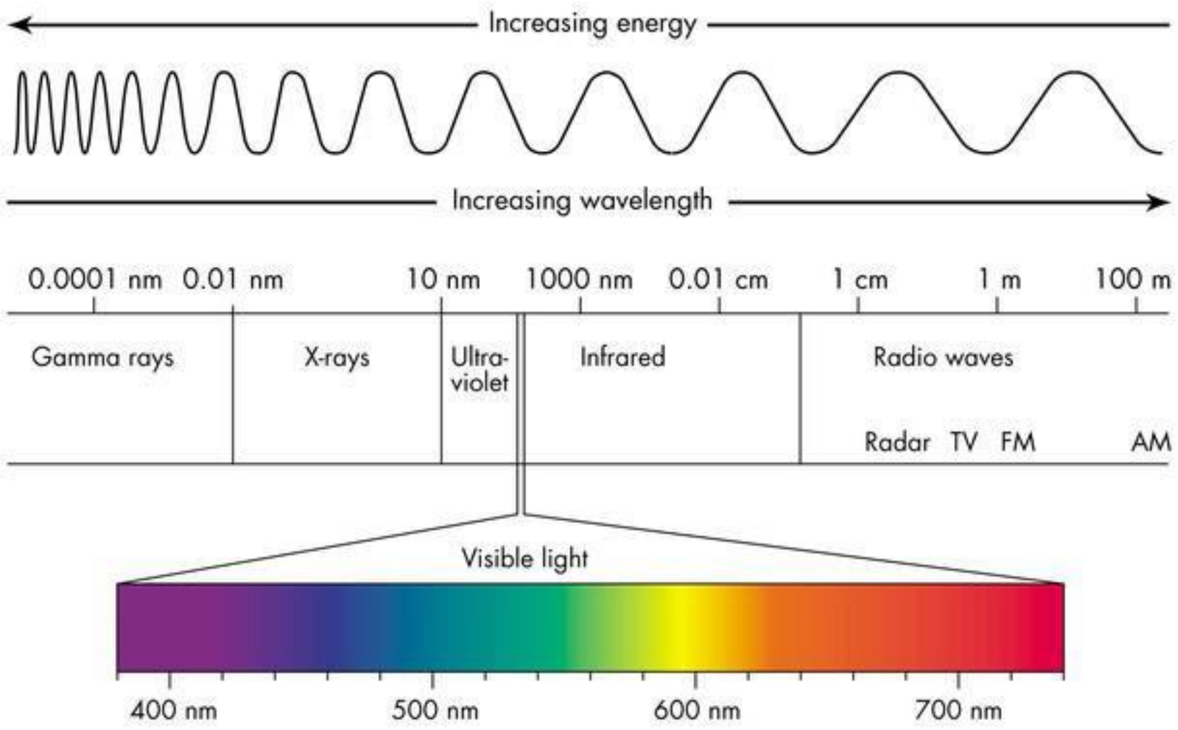
Introduction to optics for plant breeders

Dr. Vuk Đorđević

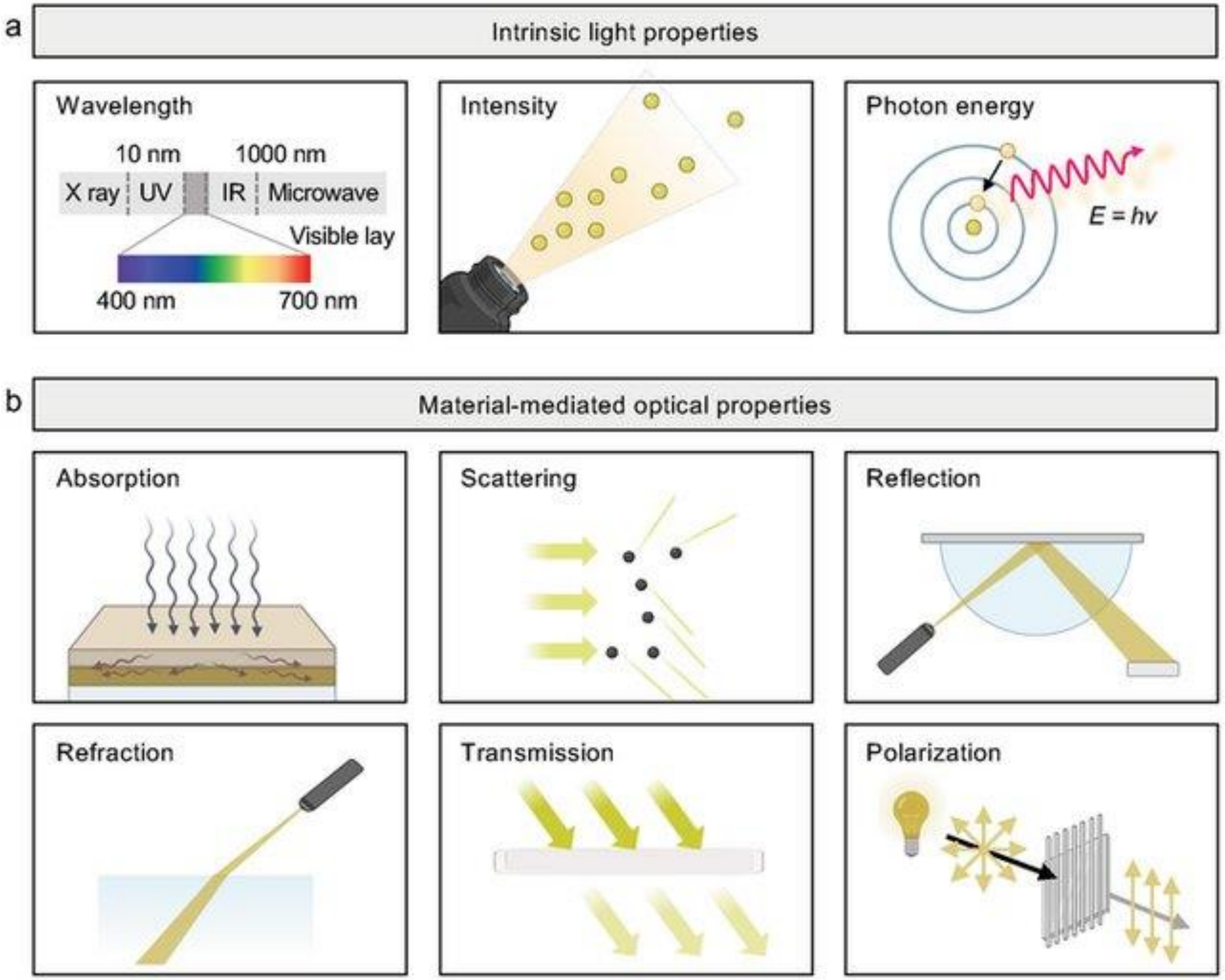
Legumes Department, IFVCNS

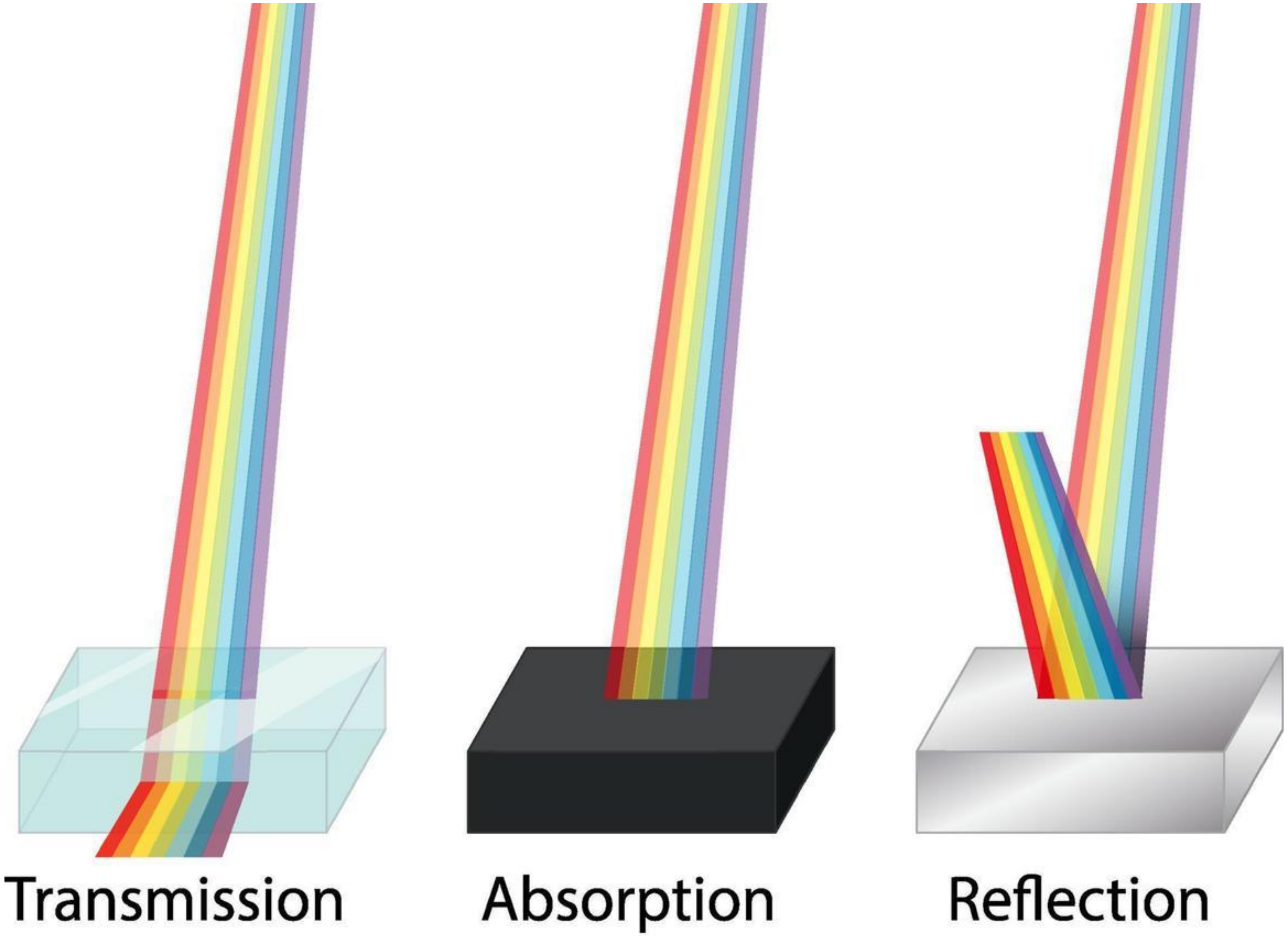
Nature of light



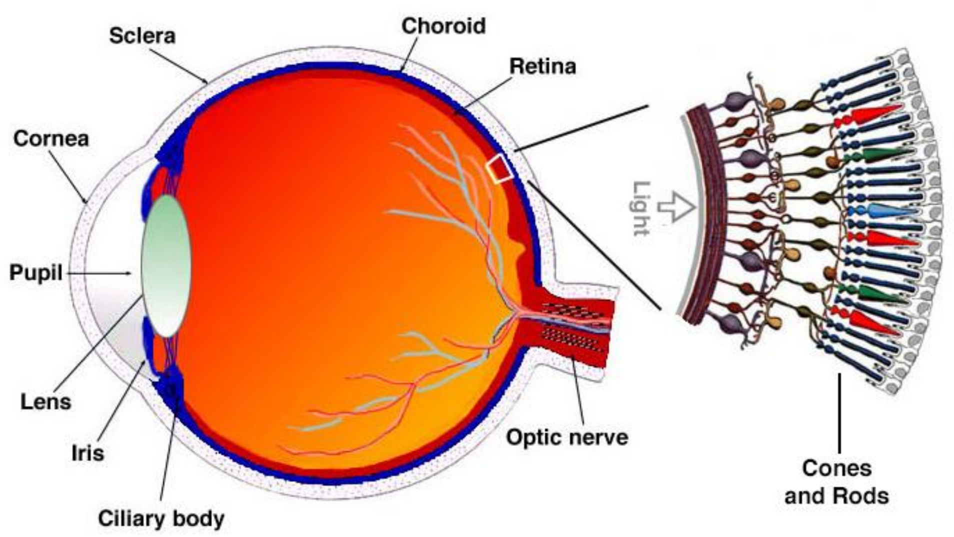


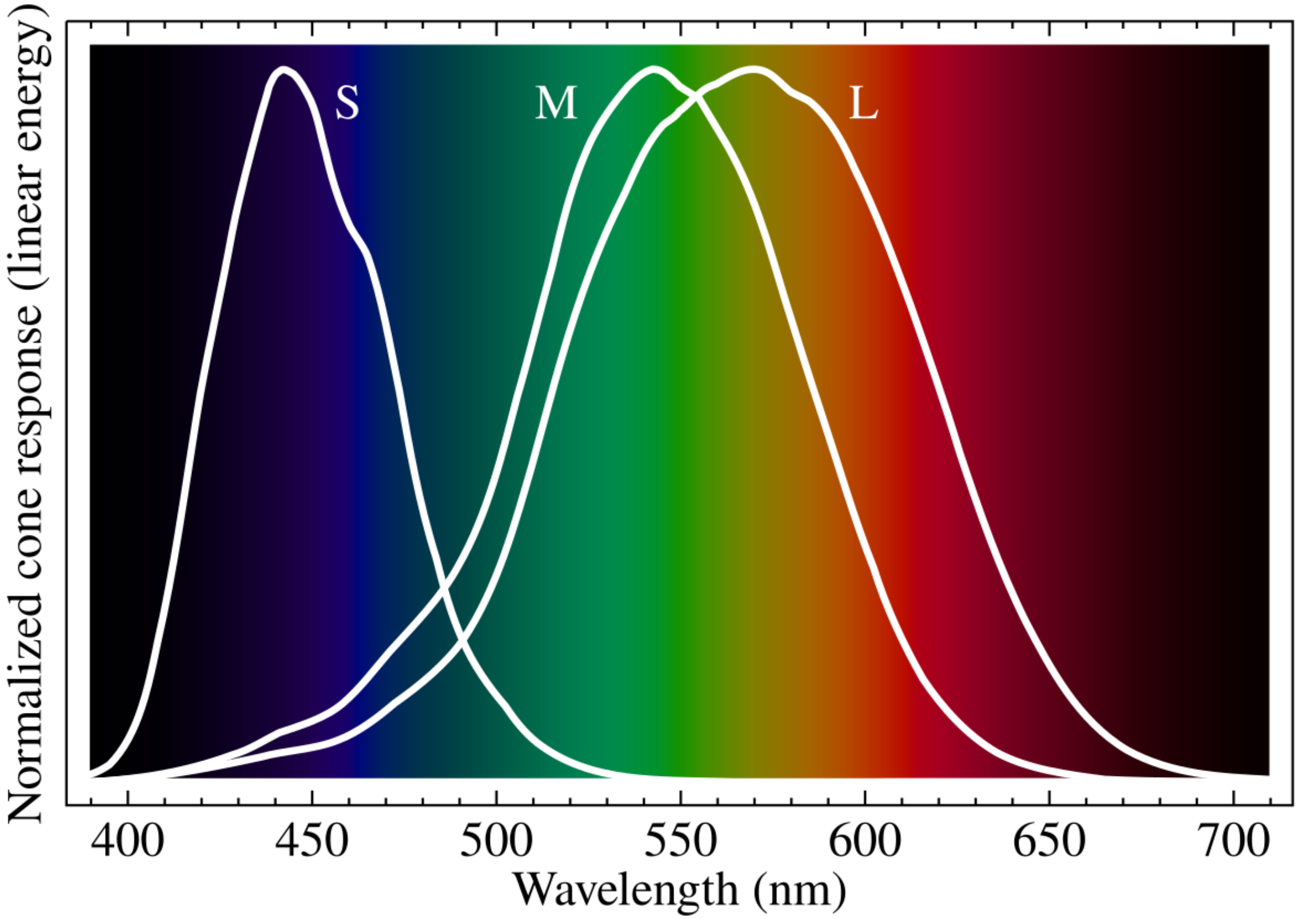
Light properties

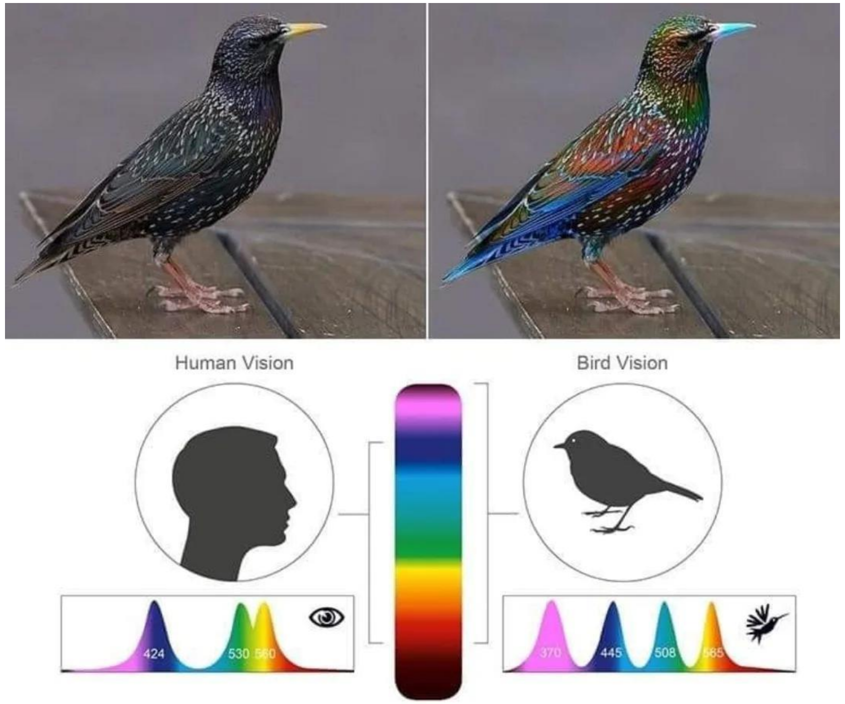




properties of light


Sclera
Choroid
Retina
Cornea
Pupil
Lens
Iris
Ciliary body
Optic nerve
Light
Cones
and Rods

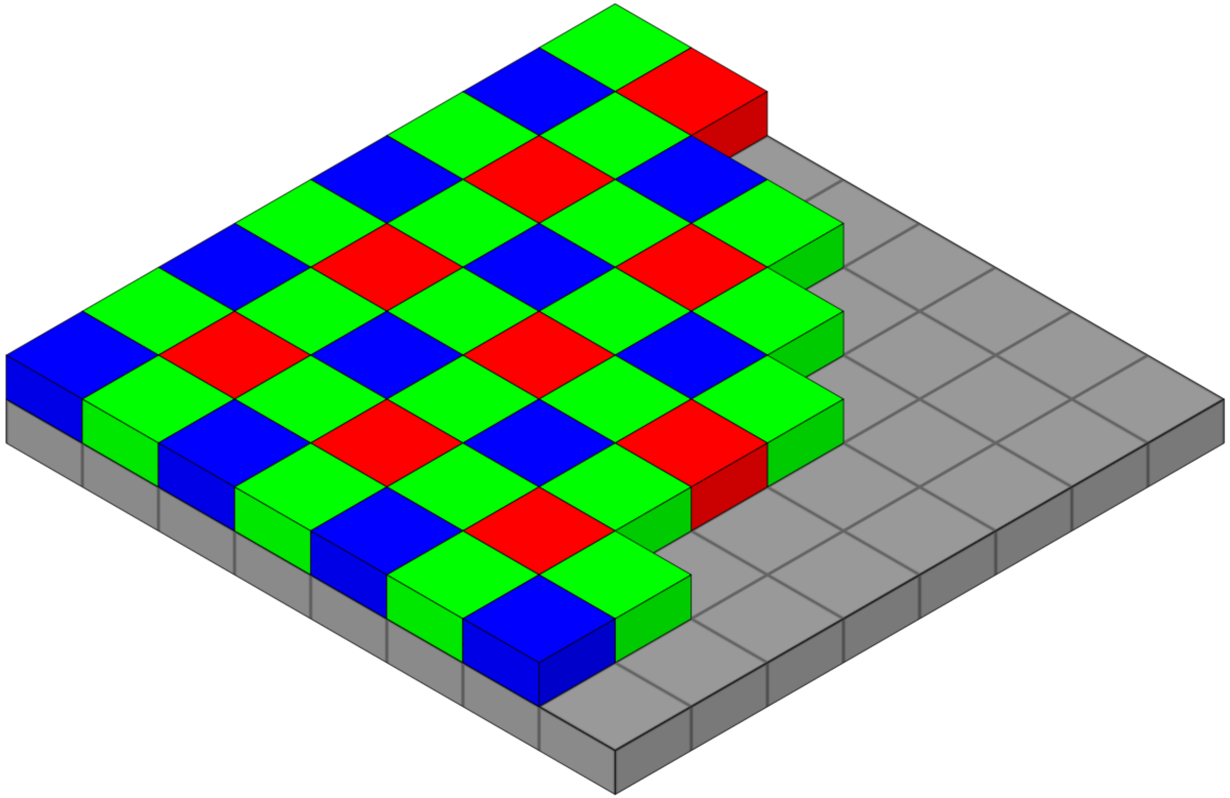

S
M
L
Normalized cone response (linear energy)
400
450
500
550
600
650
700
Wavelength (nm)

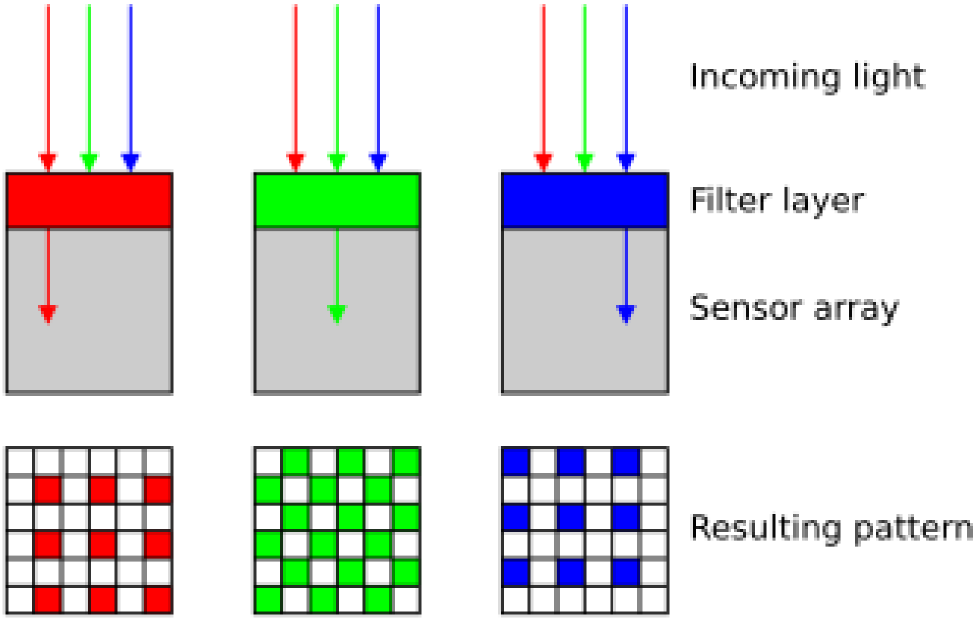

Human Vision
Bird Vision
424
530
560
370
445
508
565

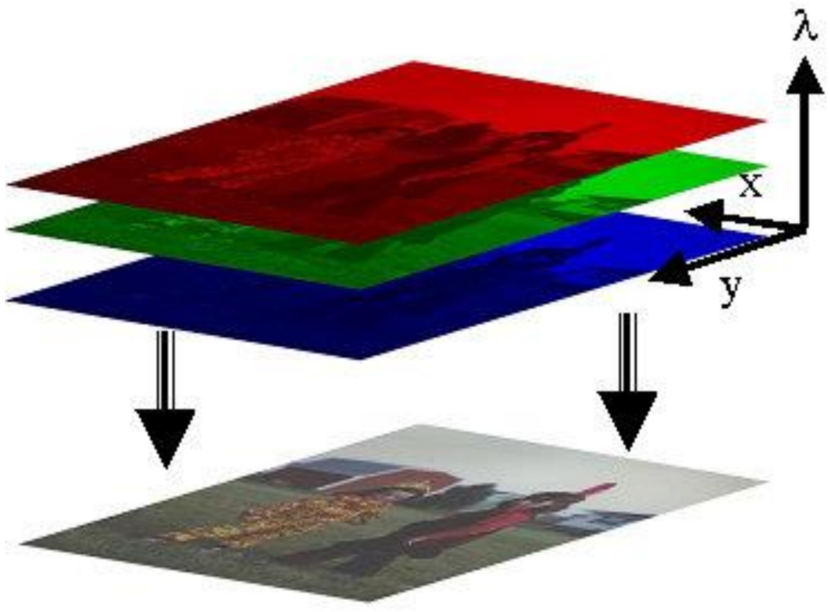

HUMAN VISION
COW VISION

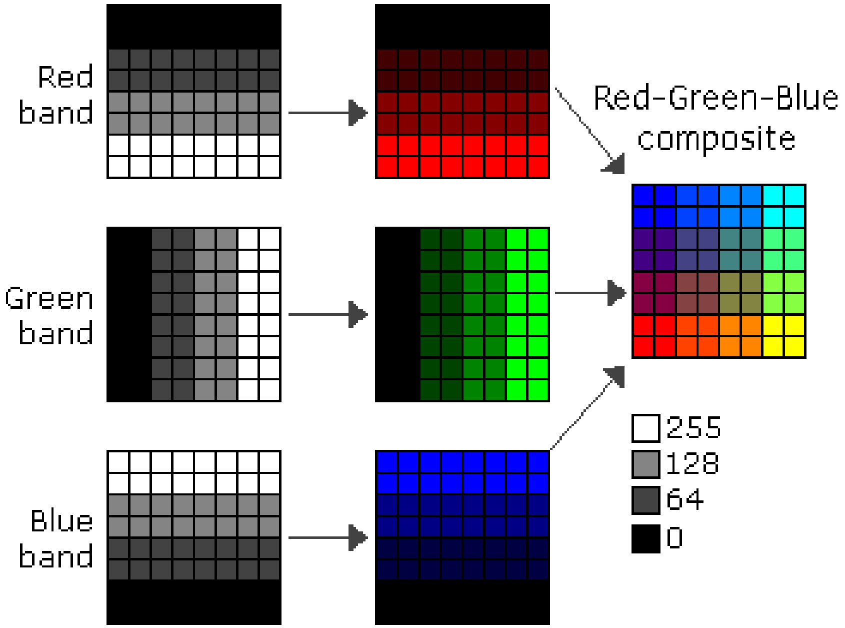

Human View
Dog View


people
cats




Incoming light
Filter layer
Sensor array
Resulting pattern


λ
x
y


Red band
Green band
Blue band
Red-Green-Blue composite
255
128
64
0

HTPP in Field Trials

Dr. Predrag Ranđelović

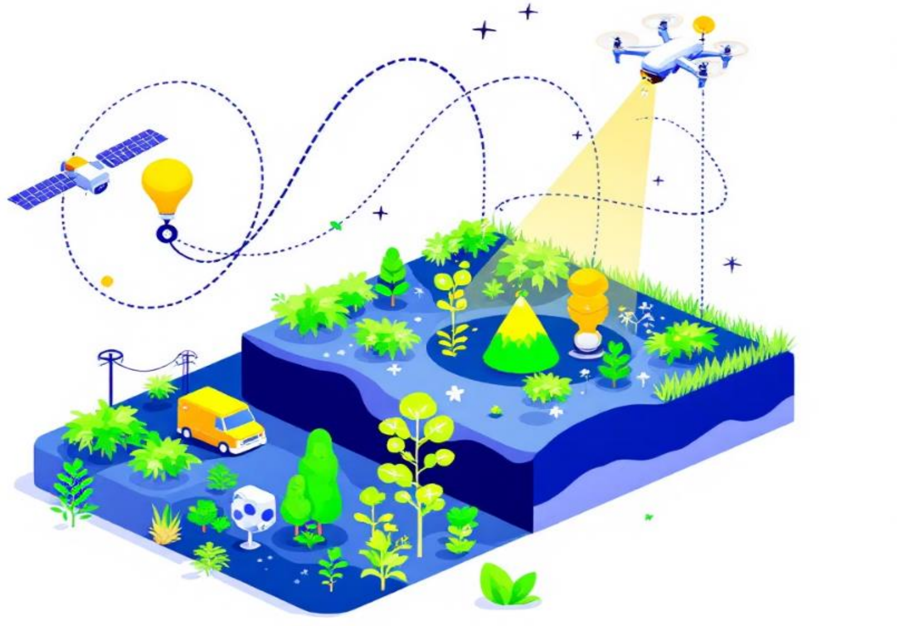
Legumes Department, IFVCNS

The Science of Phenotyping

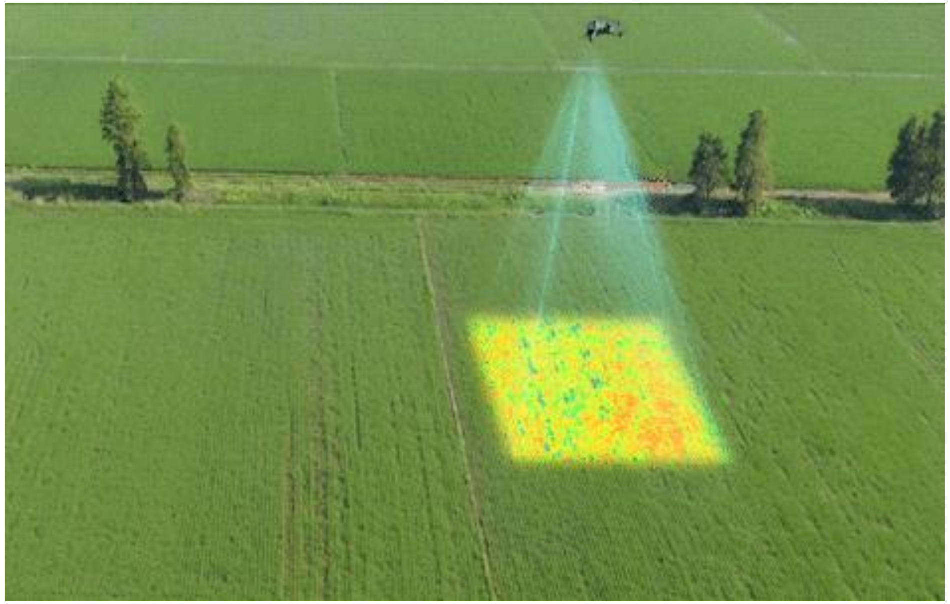
Phenotyping is the discipline of observing, measuring, and analyzing the phenotype resulting from genotype-environment interactions.

The Challenge: Traditional phenotyping relies on manual measurements that limit our ability to analyze large plant populations efficiently.

What is HTPP?



- **High-throughput phenotyping (HTPP)** combines different platforms, digital imaging sensors, and advanced analytics
- Enables fast assess of various plant characteristics across large agricultural areas
- HTPP transforms agricultural monitoring from labor-intensive processes to automated, data-driven insights
- Can be integrated within breeding programs



Traditional vs. HTPP

Traditional Phenotyping

Advantages:

- Simplicity in implementation
- Minimal equipment requirements
- Lower initial investment costs

Disadvantages:

- Time-intensive processes
- High labor costs
- Greater potential for human error
- Limited data collection capacity

High-Throughput Phenotyping

Advantages:

- High efficiency and throughput
- Enhanced precision and accuracy
- Rapid response times
- Non-invasive measurement approaches
- Long-term cost effectiveness

Disadvantages:

- High initial equipment costs
- Requires specialized personnel
- Complex data processing requirements

The Foundation: Remote Sensing & Photogrammetry

01

Remote Detection Principle

Monitor changes in analyzed objects across space and time efficiently without direct contact

02

Light Reflection Analysis

Remote sensing collects data based on light reflection patterns from plant surfaces

03

Photogrammetric Measurements

Photogrammetry enables precise measurements of observed objects from photographs

04

Three Platform Types

Satellites, ground-based equipment, and unmanned aerial vehicles (UAVs)

Satellite Systems

Pros: Continuous coverage of large areas

Cons: Low resolution (0.3-20 m/pixel)

Best for: Large-scale monitoring

Ground-Based Equipment

Pros: High image resolution, hyperspectral imaging

Cons: Limited area coverage, high operational costs

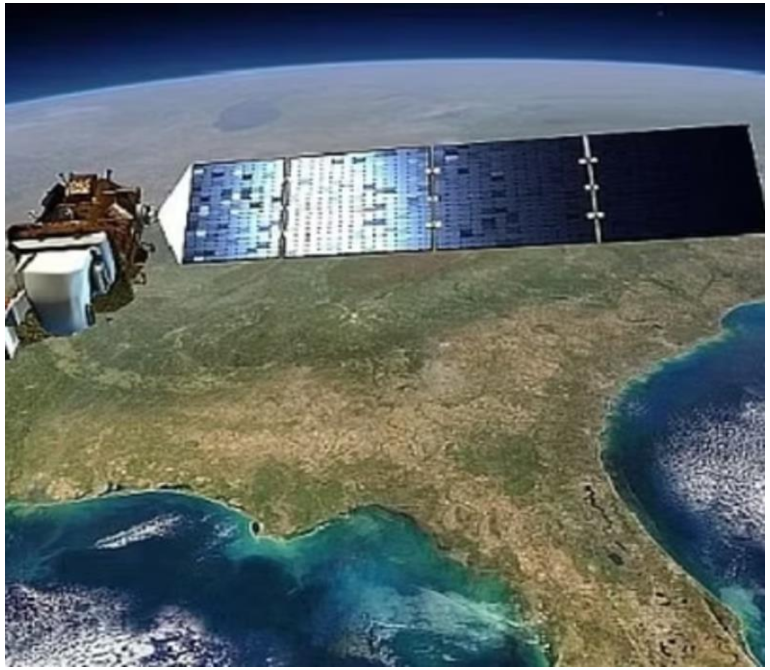
Best for: Detailed plot analysis

Unmanned Aerial Vehicles

Pros: Optimal balance of coverage and detail

Cons: Limited flight autonomy

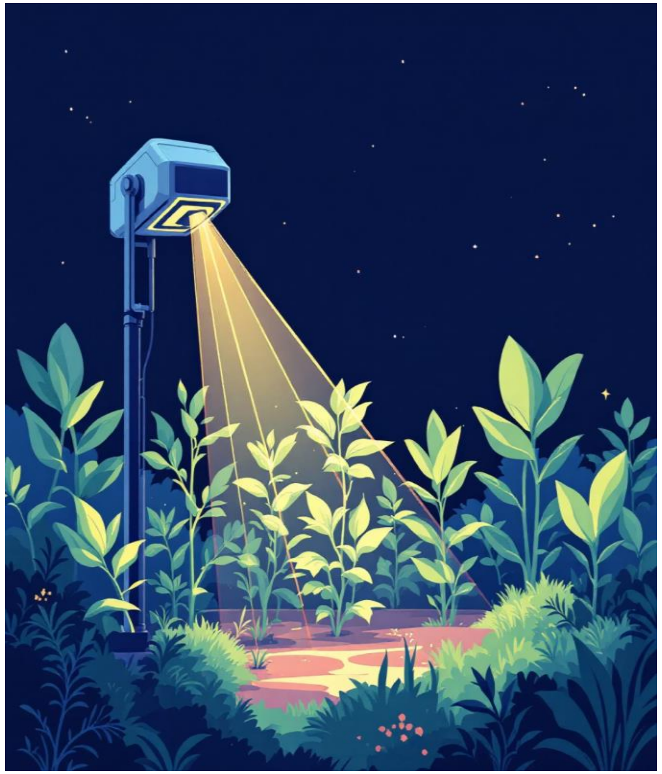
Best for: Field trial phenotyping



Active Sensors: LiDAR Technology

Operating Principle

Active sensors such as LiDAR (Light Detection and Ranging system), emit radiation and record values based on return signals.



Primary Applications

- Plant height determination with high precision
- Canopy structure analysis through vegetation penetration
- Biomass estimation and growth monitoring
- Crop density and distribution mapping

Current Limitations

High equipment costs, complex data acquisition processes, and specialized knowledge requirements for data processing remain significant barriers to widespread adoption.

Passive Sensor Technologies

<u>Passive sensors detect reflected radiation from imaged objects and can function as standalone devices or integrated systems</u>.

RGB Cameras (400-700nm)

Single optical sensor providing data from red, green, and blue spectral regions. Essential for visual assessment and basic morphological measurements.

Multispectral Cameras (400-1000nm)

Multiple monochromatic sensors covering R, G, B, Red Edge, and NIR channels. Ideal for vegetation indices health assessment, trait estimation.

Hyperspectral Cameras (400-1000nm)

Collect data across numerous wavelengths at nanometer intervals. Provide detailed spectral signatures for crop analysis.

Thermal Cameras

Determine temperature of imaged objects, primarily used for water stress detection and plant physiological monitoring.

HTPP - Image Processing Workflow

Software Platform

Stitching software (Agisoft, Pix4D...) are used for comprehensive photograph processing and analysis

Spatial Alignment

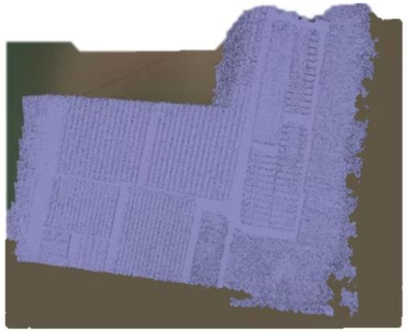
Photographs aligned using common reference points for accurate positioning

Dense Point Cloud (DPC)

Structure-from-Motion creates 3D models from multiple viewing angles

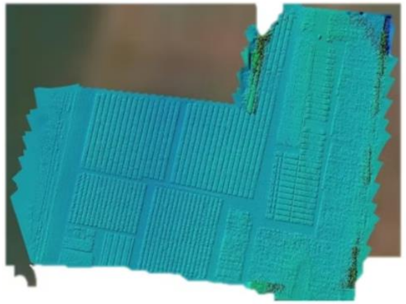
Final Products

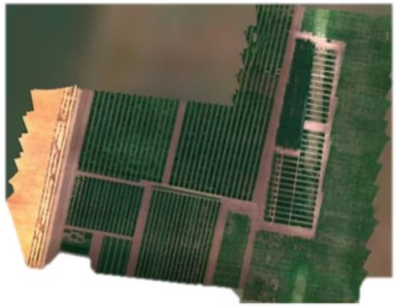
Digital Elevation Model (DEM) and orthomosaic generation for analysis



DPC

DEM





ORTHOMOSAIC

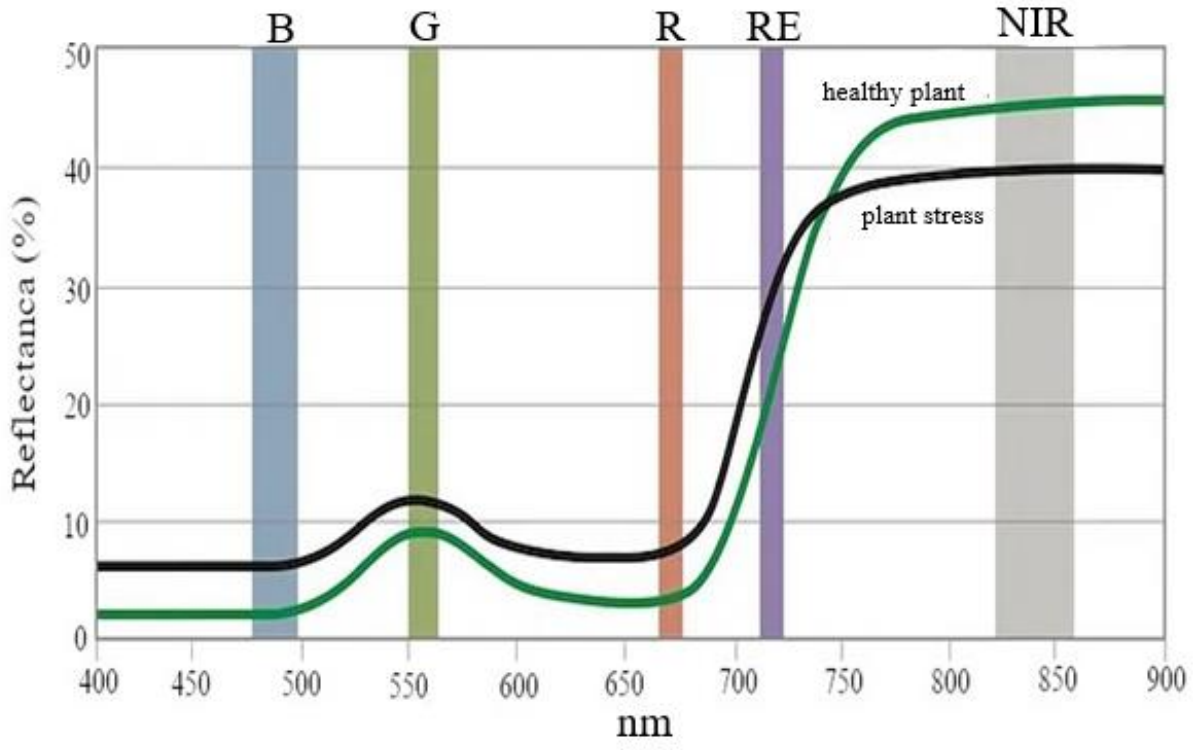
Spectral Reflectance Fundamentals

Healthy Plant Response

- Absorbs visible light efficiently
- Reflects NIR radiation strongly
- Optimal photosynthetic activity

Stressed Plant Response

- Increased RGB reflection
- Reduced NIR reflection
- Compromised chlorophyll function



Solar radiation reflection patterns depend on leaf chemical composition and physiological characteristics - enabling vegetation index calculations through mathematical transformations

Vegetation Indices Overview

RGB Indices

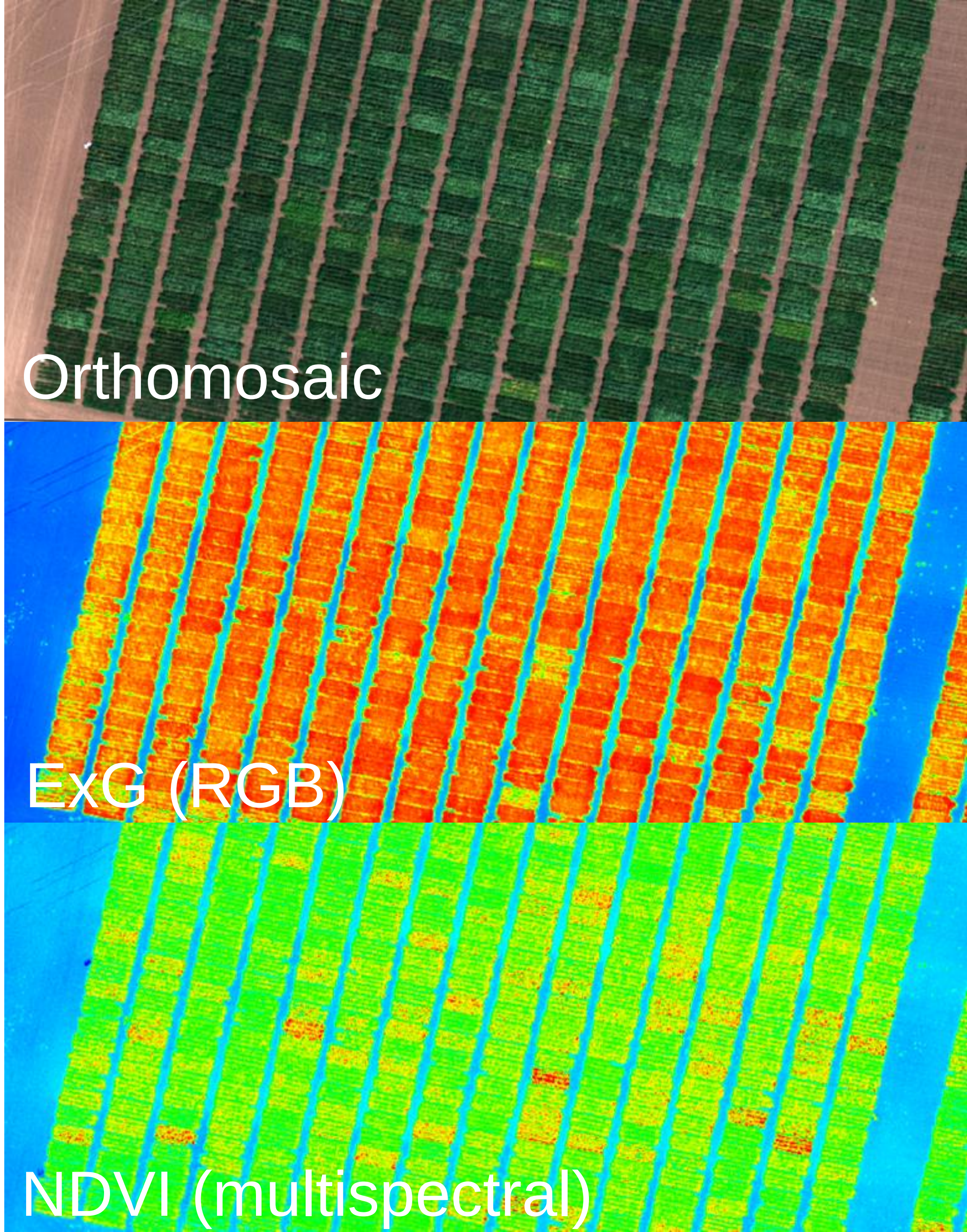
Combine visible spectrum data for segmentation, plant pixel detection, biomass assessment, and yield estimation

Multispectral Indices

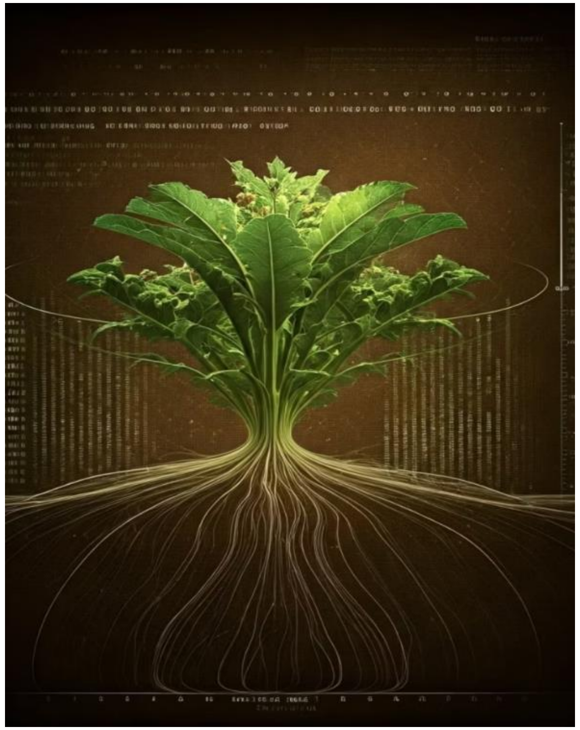
Incorporate visible, red-edge, and NIR data for enhanced remote sensing applications

NDVI

Most recognized vegetation index combining NIR and red channels for crop health analysis, yield prediction, and nitrogen use efficiency



Machine Learning (ML) Integration



ML Algorithms

SVR, KNN, ANN, CNN, PLSR, RF enable pattern recognition in large datasets

HTPP and ML

Reliable prediction models

Cross Validation

Data splitting (training/test) reduces model overfitting risks

Random Forest (RF)

- Groups data using binary trees
- Effective for classification and regression
- Handles complex agricultural datasets

Partial Least Squares Regression (PLSR)

- Determines relationships through principal components
- Links dependent and independent variables
- Reduces dimensionality effectively

HTPP application

01

Quantitative Trait Assessment

Evaluation of multiple traits critical for new genotype selection

02

Growth Monitoring

Dynamic tracking of plant development throughout growing season

03

Stress Quantification

Measurement of abiotic and biotic stress factors affecting performance

04

Enhanced Breeding Efficiency

Improved germplasm characterization through precise phenotypic analysis

HTPP applications - plant height

01

DSM captures crop canopy surface

Digital Surface Model records top elevation of vegetation and terrain

02

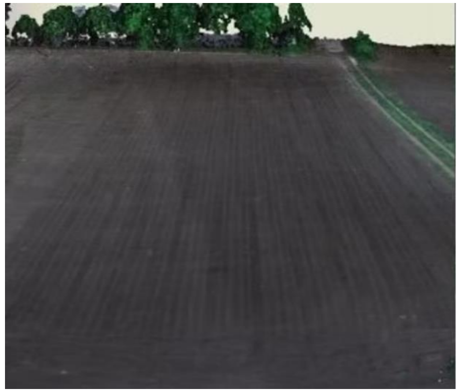
DTM represents bare soil baseline

Digital Terrain Model provides ground reference elevation

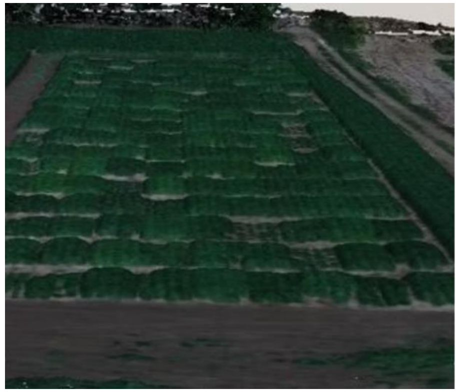
03

Plant Height = DSM – DTM

Precise phenotypic measurements for breeding programs

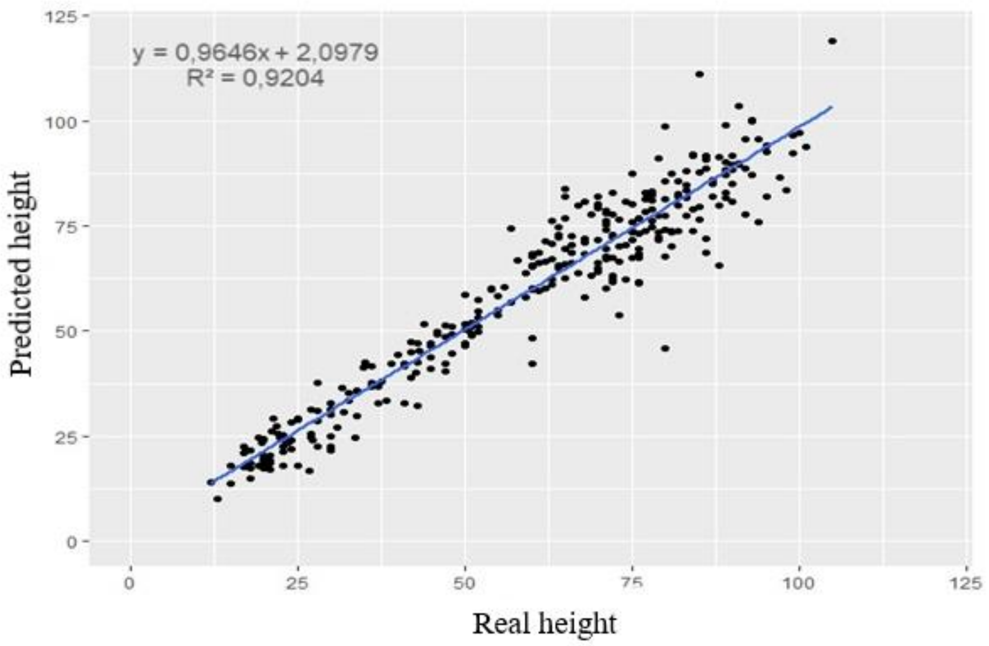


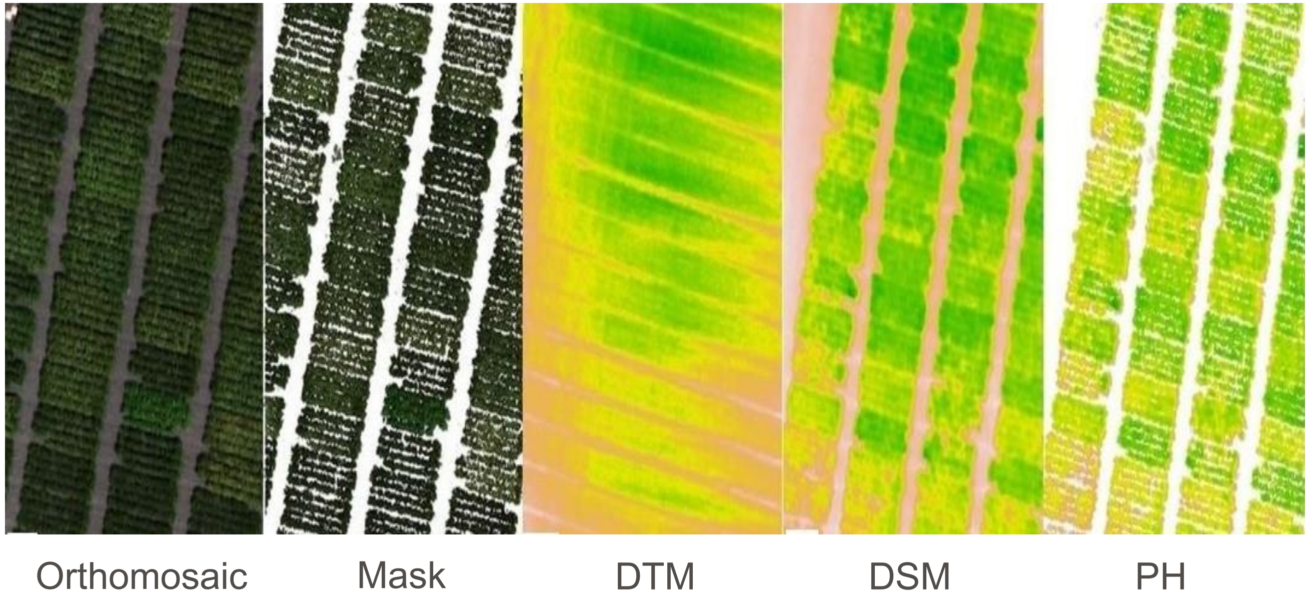
DTM - Digital Terrain Model



DSM - Digital Surface Model

HTPP applications - plant height





1. Orthomosaic
   High-resolution aerial imagery
2. Plot Mask
   ROI boundary definition
3. DTM Generation
   Terrain elevation baseline
4. DSM Creation
   Surface height mapping
5. PH Calculation
   Final height measurement

Strong correlation between ground-measured and HTPP-derived plant heights validates remote sensing accuracy

HTPP applications - canopy cover (CC)

01

Plot Identification

ROI creation for each experimental plot with precise boundaries

02

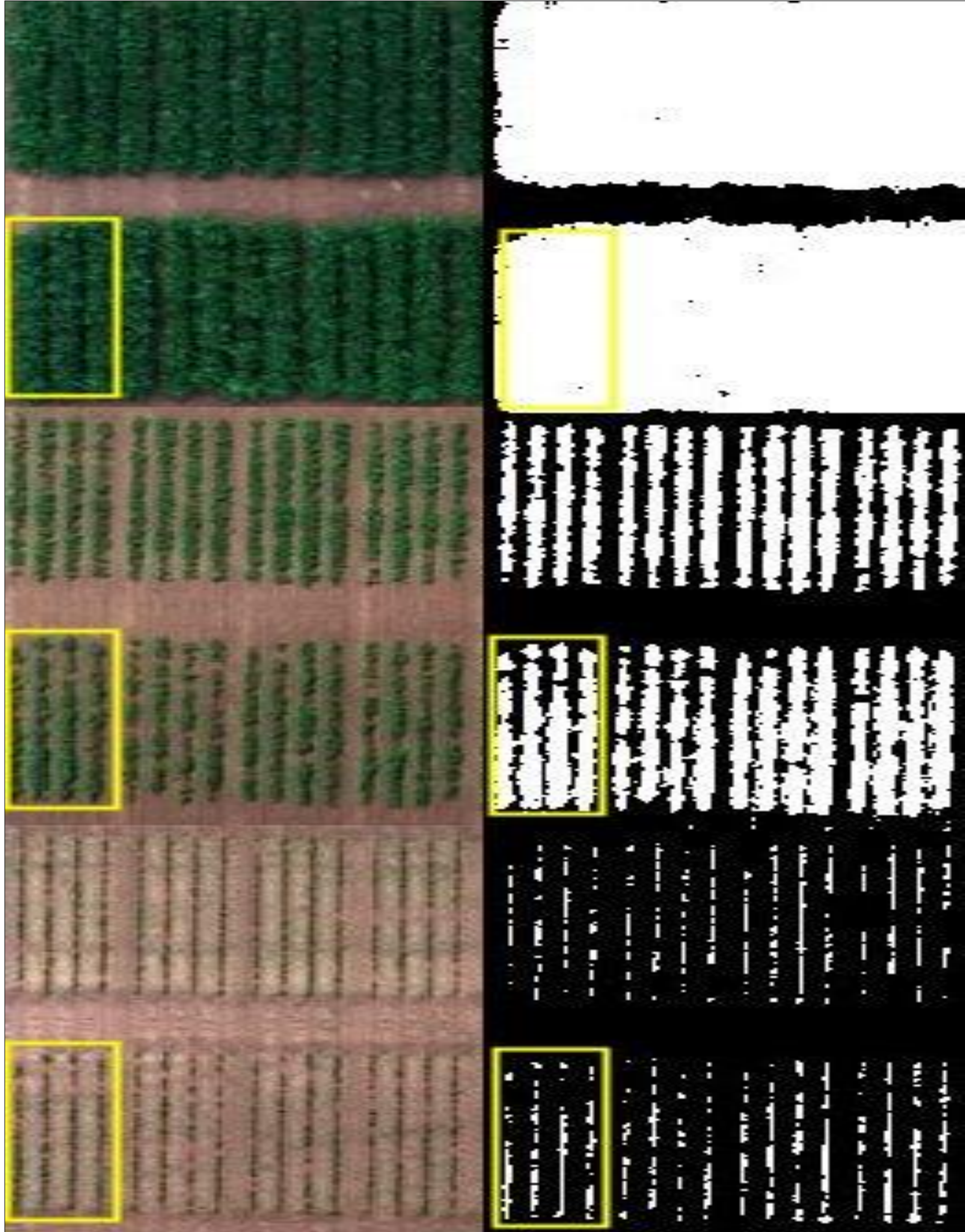
Spectral Analysis

NDVI and other vegetation indices for plant/soil segmentation

03

CC estimation

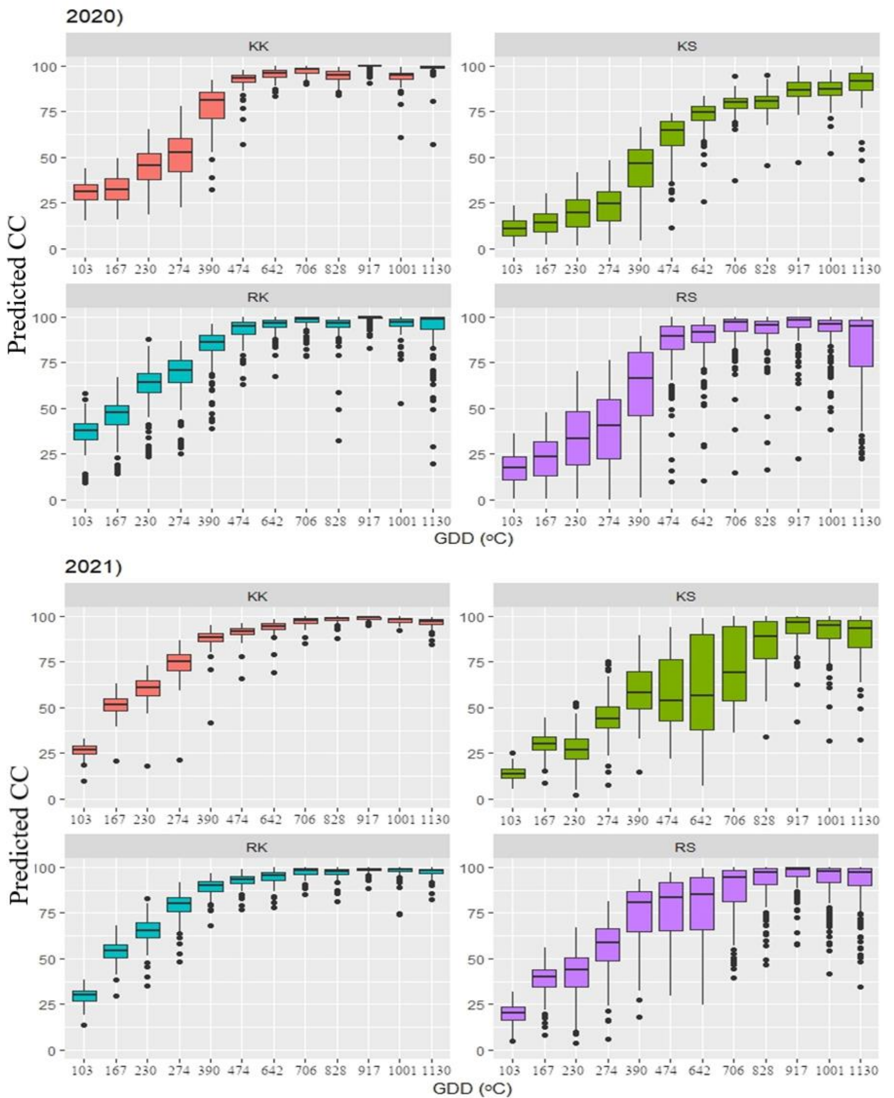
Binary image analysis determines percentage of plant pixels within each ROI



Canopy Cover Dynamics

- **Seasonal dynamics:** Track canopy cover development throughout the growing season
- **CCmax analysis:** Quantify days with >90% canopy coverage for genotype comparison
- **Selection criteria:** Identify genotypes with rapid canopy closure for improved resource utilization

This temporal analysis enables breeders to select for early vigor and efficient light interception traits.



HTPP applications - plant density

1

Channel Separation

RGB channels extracted from orthomosaic images for individual spectral analysis

2

Vegetation Index Calculation

Multiple vegetation indices computed for each experimental plot

3

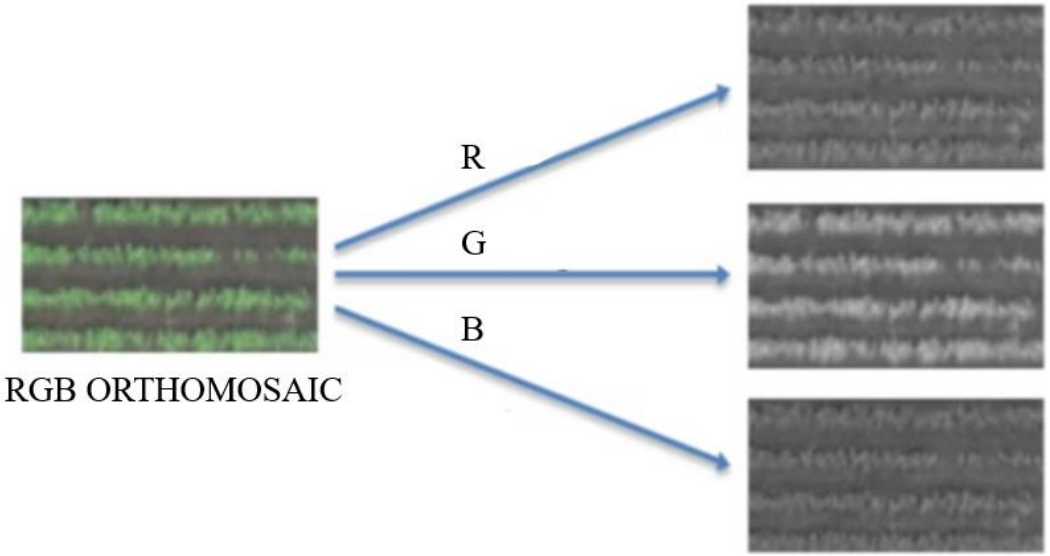
Random Forest Modeling

Algorithm uses vegetation indices as predictors for density estimation

4

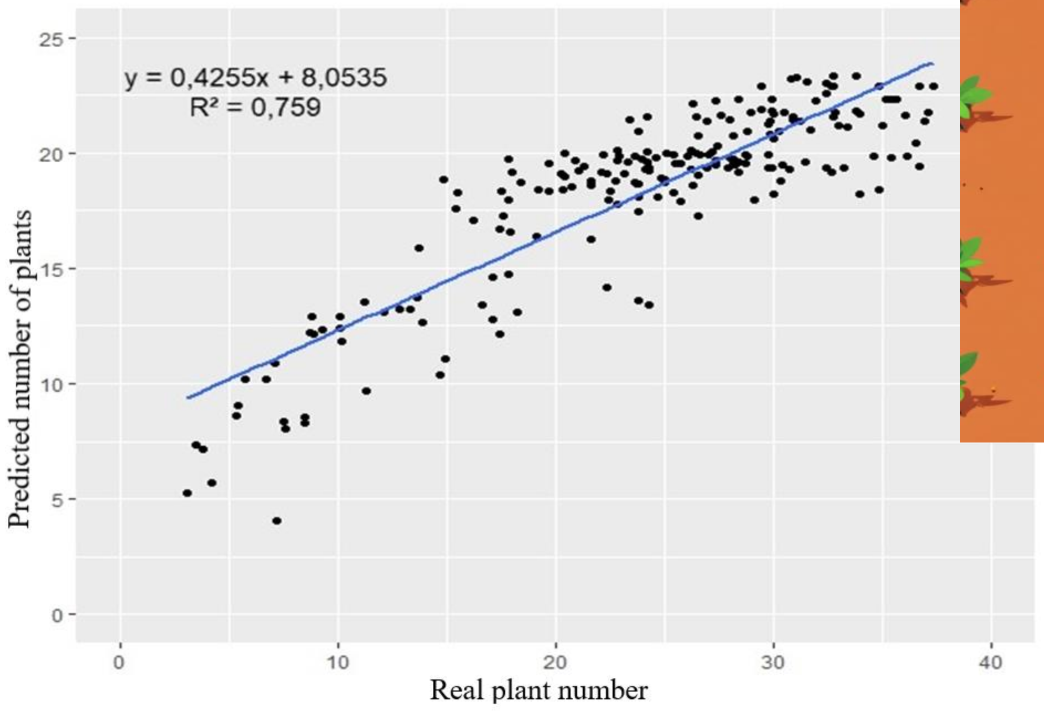
Model Validation

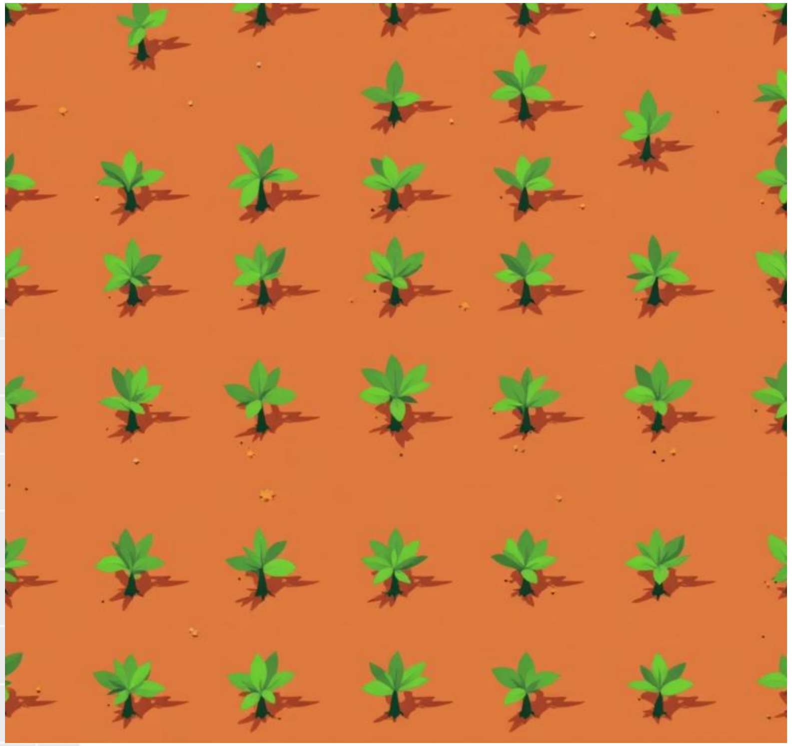
Performance assessed using correlation, R^2, RMSE, and MAE metrics



Vegetation index	Name	Formula
TGI	Triangular greenness index	G-0.39R-0.61B*
GLI	Green leaf index	(2G-R-B)/(2G+R+B)
NG	Normalized green	G/(R+G+B)*
ExGR	Excess green red	(3G – 2.4R-B)/(R+G+B)*
RGD	Red green difference	R-G
NGRD	Normalized green red difference	(G-R)/(G+R)
MNGRD	Modified normalized green red difference	$(G^2-R^2) / (G^2+R^2)$
MExG	Modified excess green	1.262G – 0.884R – 0.311B

HTPP applications - plant density

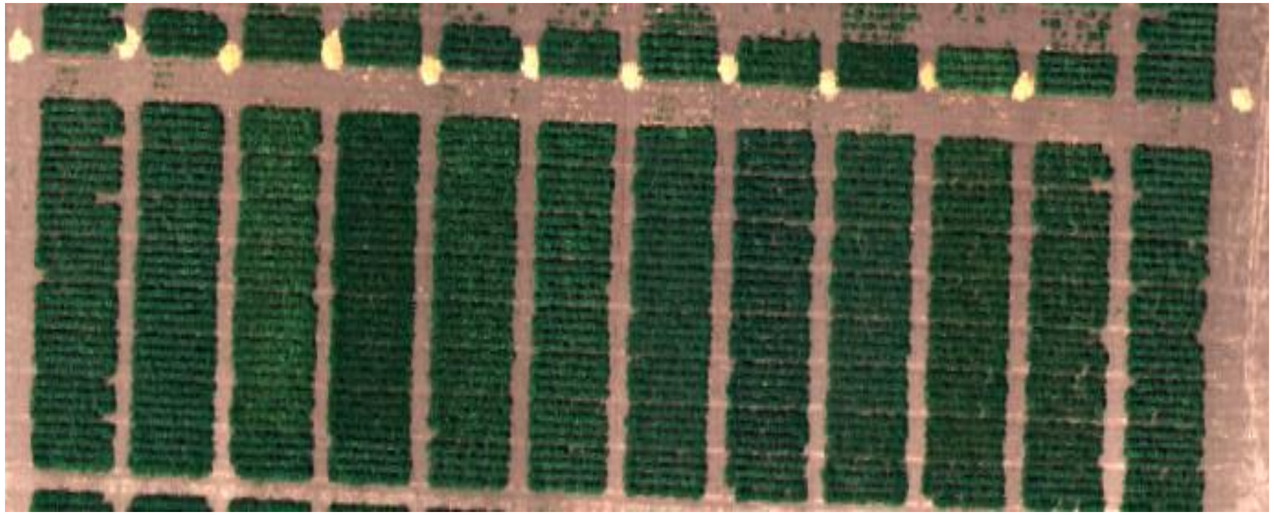




- **Emergence monitoring:** Early-season assessment of germination rate and row establishment
- **In-season monitoring:** Detection of plant loss due to environmental stress or disease
- **Final plant count:** Accurate harvest population for yield component analysis

These applications provide comprehensive plant population data throughout the growing season, enabling precise agronomic management and breeding decisions.

HTPP applications - biomas estimation



Data Collection

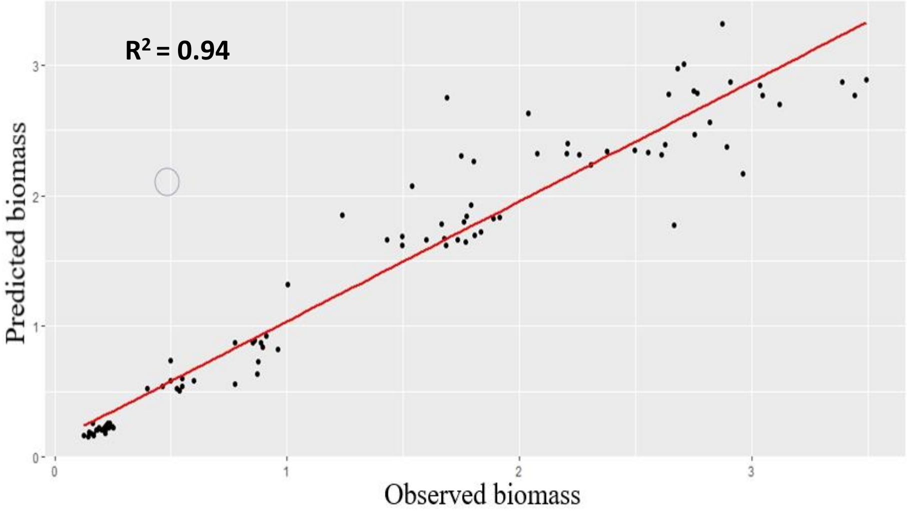
1

Extraction of vegetation indices, structural metrics (height, volume), and texture analysis from high-resolution UAV imagery

Predictive Modeling

2

Machine learning algorithms process spectral, structural, and textural features to create robust biomass prediction models



Key Finding

3

Plant height emerges as most critical variable for biomass prediction accuracy

HTPP applications - biomas estimation

Resource Utilization Assessment

Rating plant potential to use available resources efficiently

Growth Monitoring

Biomass as crop development indicator throughout season

Organic Matter Dynamics

Accumulation patterns for yield prediction modeling

HTPP Implementation Challenges

Plant Architecture Complexity

Plant architecture and dense planting lead to early plant overlap, complicating individual plant detection

Growth Stage Selection

Proper timing of image acquisition is critical for creating accurate predictive models and measurements

Weed Interference

Weeds increase plant pixel count and negatively impact model performance and phenotyping accuracy

Data Interpretation

Biological interpretation of HTPP data remains the primary challenge for practical application

Key Takeaway

Transforming Plant Breeding with HTPP & AI

Rapid Data Assessment

HTPP enables **fast, non-invasive assessment** of plant traits across large populations

AI-Powered Insights

Artificial Intelligence and Machine Learning unlock the full potential of HTPP data

Breeding Innovation

Faster, more accurate decisions in selection of superior varieties.

Thank you for your attention!

Any questions?