# UAV Phenotyping and Proximal Sensing for Maize Assessments in Breeding Programs

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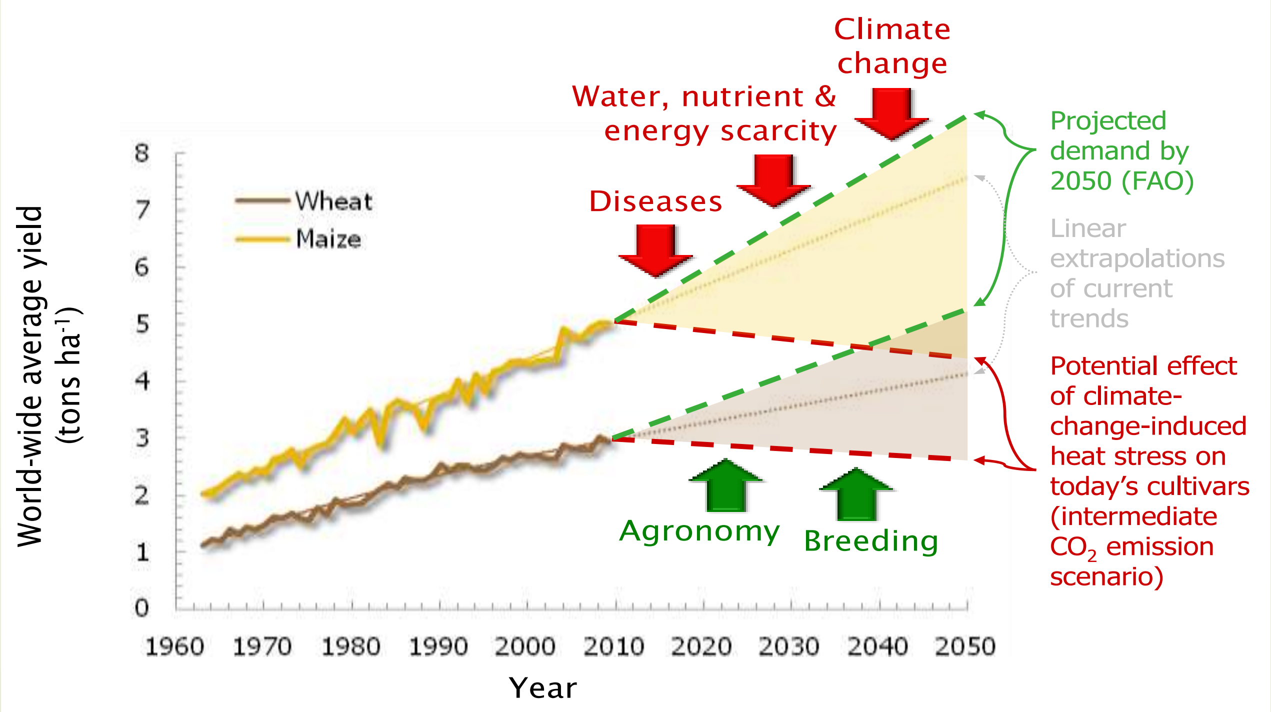
# Global Challenge of Phenotyping

## How to enhance annual yield gains of maize from 1.6% to 2.4% on essentially the same land area, and as climates change and the costs of fertilizer, water, and labor increase?



# RGB, Red, Green and Blue broad-band visible light reflectance

Meaningful data can be had from these normal digital images, especially considering 1. excellent color calibration during production covering photosynthetically active radiation (PAR) and 2. very high spatial resolution (mm).

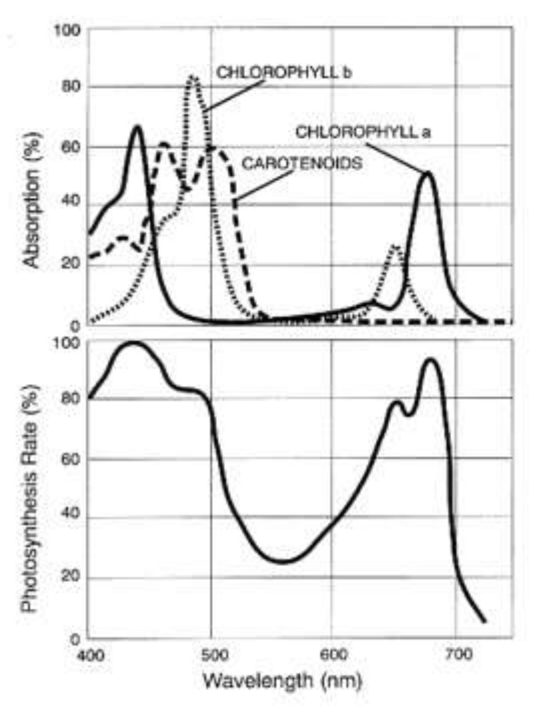
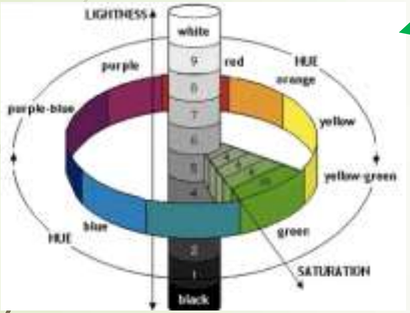


**Image processing** → **FIJI** → **CIMMYT Maize Scanner**

**Breedpix** (Casadesús et al., 2007)

**Canopy Macros**

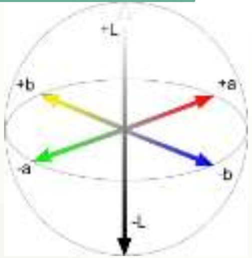
HIS color space




- Green Area (GA) (pixels with 60 ° < Hue < 180°)
- Greener Green Area (GGA) (pixels with 80° < Hue < 180°)
- Crop senenence index (CSI) $\frac{100 \times (GA - GGA)}{GA}$

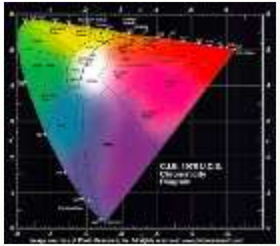
(Zaman-Allah et al., 2015)

Cie-Lab




- a*
- b*

Cie-Luv



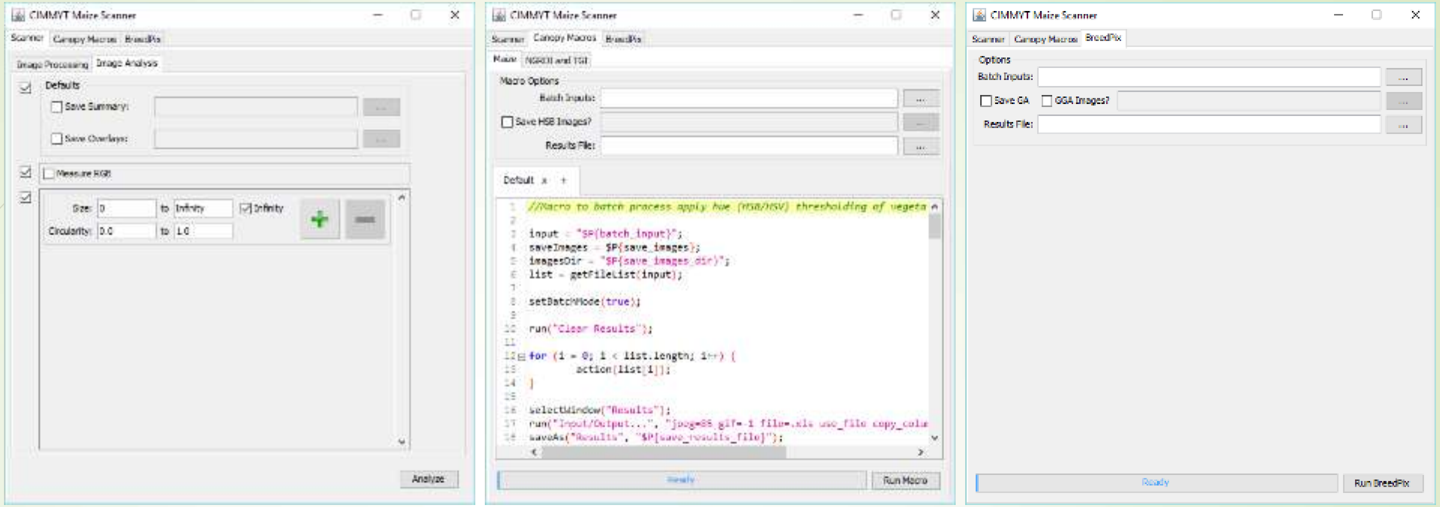
- u*
- v*

$Triangular\ Greennes\ Iindex\ (TGI) = -0.5\,[190(R670 - R550) - 120(R670 - R480)]$

(Hunt et al., 2012)

$Normalized\ Green - Red\ Difference\ Index\ (NGRDI) = \frac{(Green\ DN - Red\ DN)}{(Green\ DN + Red\ DN)}$

(Hunt et al., 2005)




# CIMMYT Maize Scanner

RGB field-based phenotyping (http://github.com/george-haddad/CIMMYT)

Calculates a number of RGB based indexes for estimating disease impacts, crop vigor, LAI, biomass at the leaf and canopy scale, including Breedpix (GA and GGA), Triangle Greeness Index (TGI), and Normalized Green Red Difference Index (NGRDI)

# University of Barcelona HTPP


Multispectral Tetracam MCA11+ILS

TEAX ThermalCapture
FLIR Tau 640 Camera


Lumix GX7 16 MP RGB

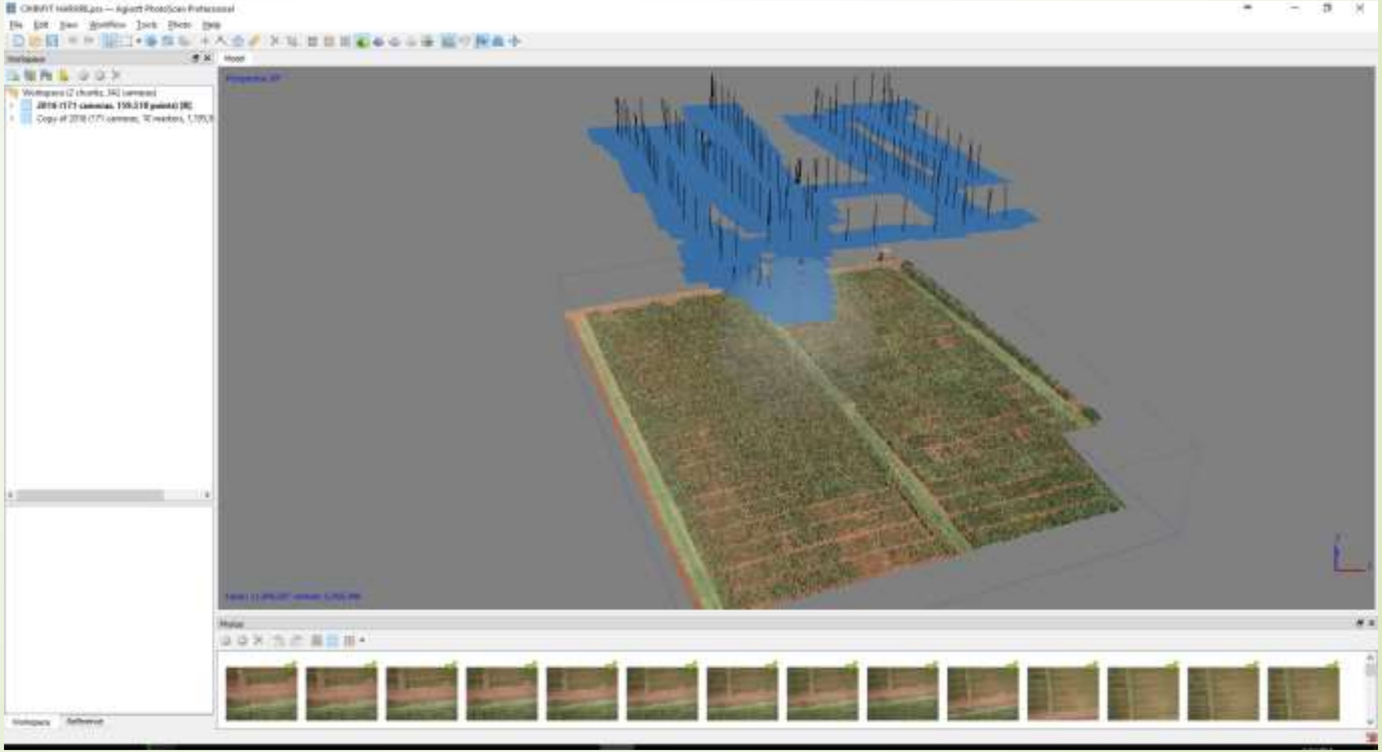
Also AIRINOV MultiSpec 4 NDVI/PRI, SonyQX1 and Tetracam MCA-6 custom

# Improved processing techniques:
# 3D models and image segmentation

- Computer intensive processes should be batched remotely.
- Semi-automatic process should be as efficient and consistent as possible.
- Agisoft Photoscan 3D and University of Barcelona MosaicTool built as a plug-in within FIJI (ImageJ)

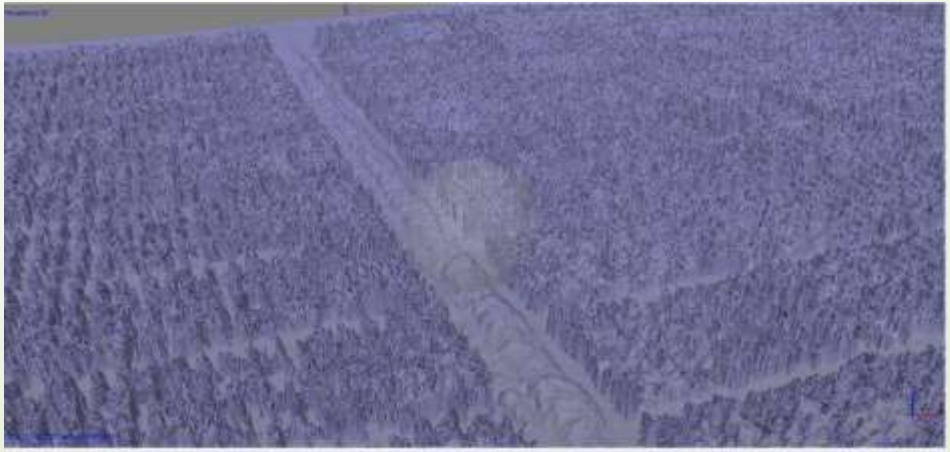
# 3D modelling example, low N trial, 2016 Maize phenotyping, Zimbabwe

Agisoft Photoscan Dense cloud + camera alignment



Dense cloud creation and dense cloud classification (DSM)

3D wireframe “mesh” and triangulated surface model



Benefits of 3D models for UAV plant phenotyping

- Orthorectifaction of UAV movement/terrain effects
- 3D related data products

Costs of 3D models for UAV plant phenotyping

- High computing requirements (CPU+GPU)
- Commercial software options (educational discounts can be great)
- Required high percentage of image overlap (continuous capture)

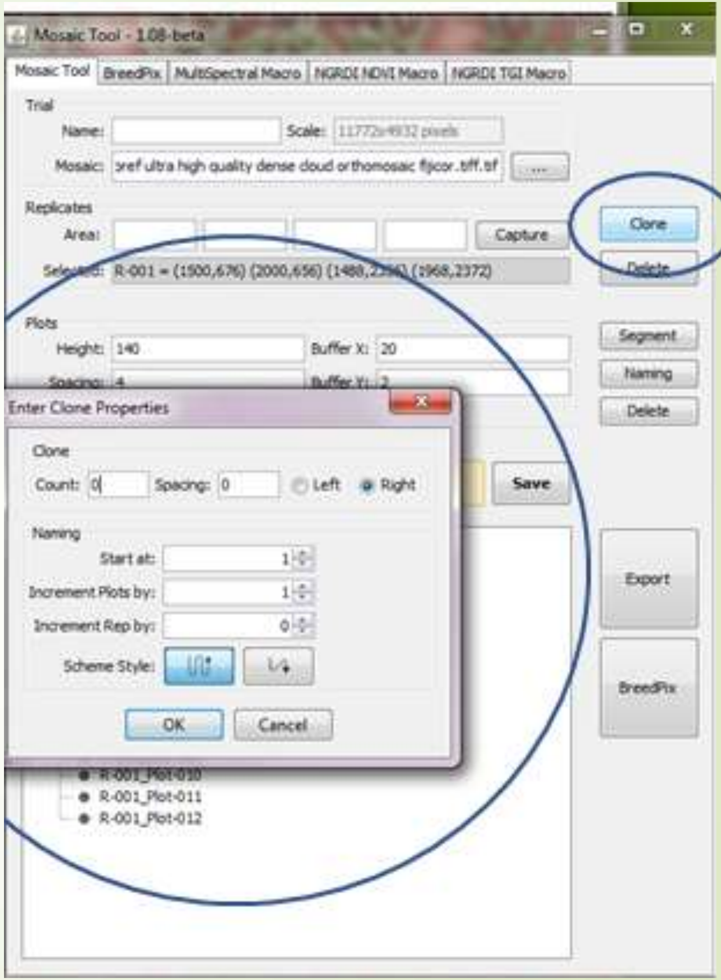
## Dense cloud model over 3D mesh with texture

200 million points per ha, 1.5 cm xy

# MosaicTool:
# University of Barcelona
# FIJI Plugin (ImageJ)

Allows for segmenting (and processing!) exact same ground spatial area for hundreds of plots in less than one student/hour. Supports RGB, Multispectral (4-12 bands) and TIR sensor indexes.

<u>Field season post-processing down from 9 months to 6 weeks!!!</u>




Kefauver et al. In preparation

# RGB comparisons from UAV and ground for low N phenotyping Zimbabwe

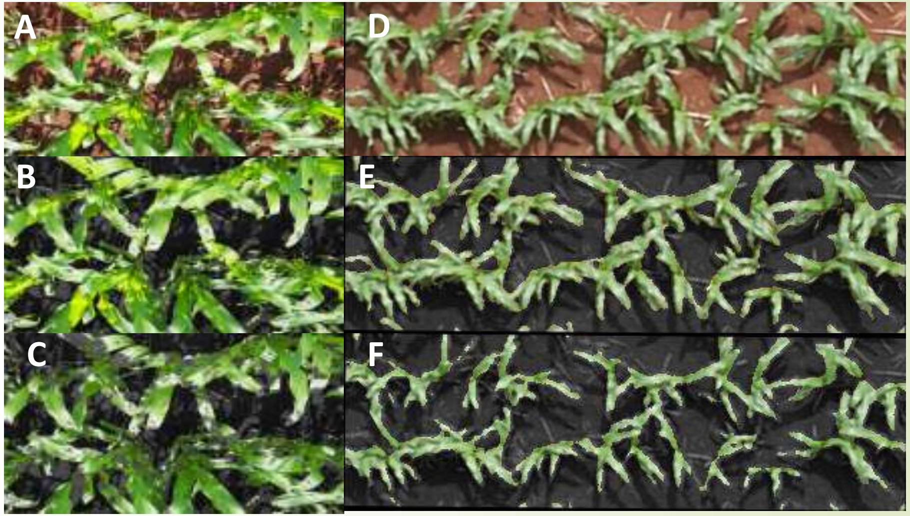
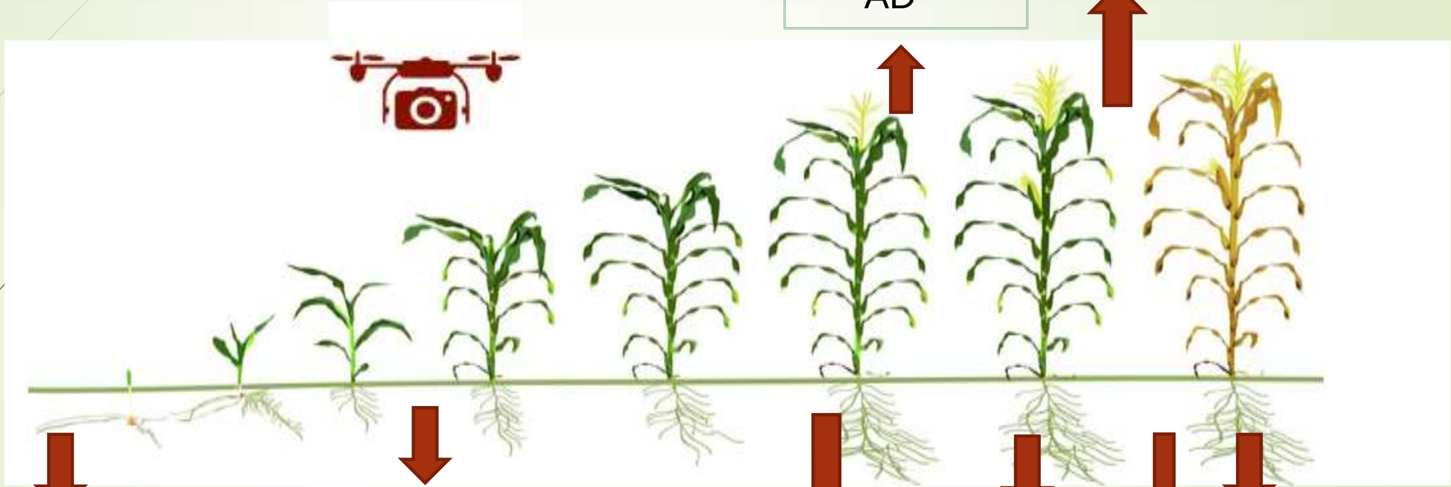



Figure 3. Examples of the differences in resolution between the images of maize taken at ground level and aerial level. A) maize plants at ground level. B) maize image at ground level with GA (Green Area). C) maize image at ground showing GGA (Greener Green Area). D) maize image at aerially. E) maize aerial image with GA (Green Area). F) maize aerial image with GGA (Greener Green Area).

Buchaillot et al., in preparation

## Plot Sampling



16/12/15
- Sown

28/01/16
- RGB-ground
- RGB- aerial
- NDVI-ground

18/02/16
- SPAD[1]

20/02/16-08/03/16
- ASI
- AD

29/02/16
- Plant Height

01/03/16
- SPAD[2]

05/04/16
- SEN

12/05/16
- Harvest

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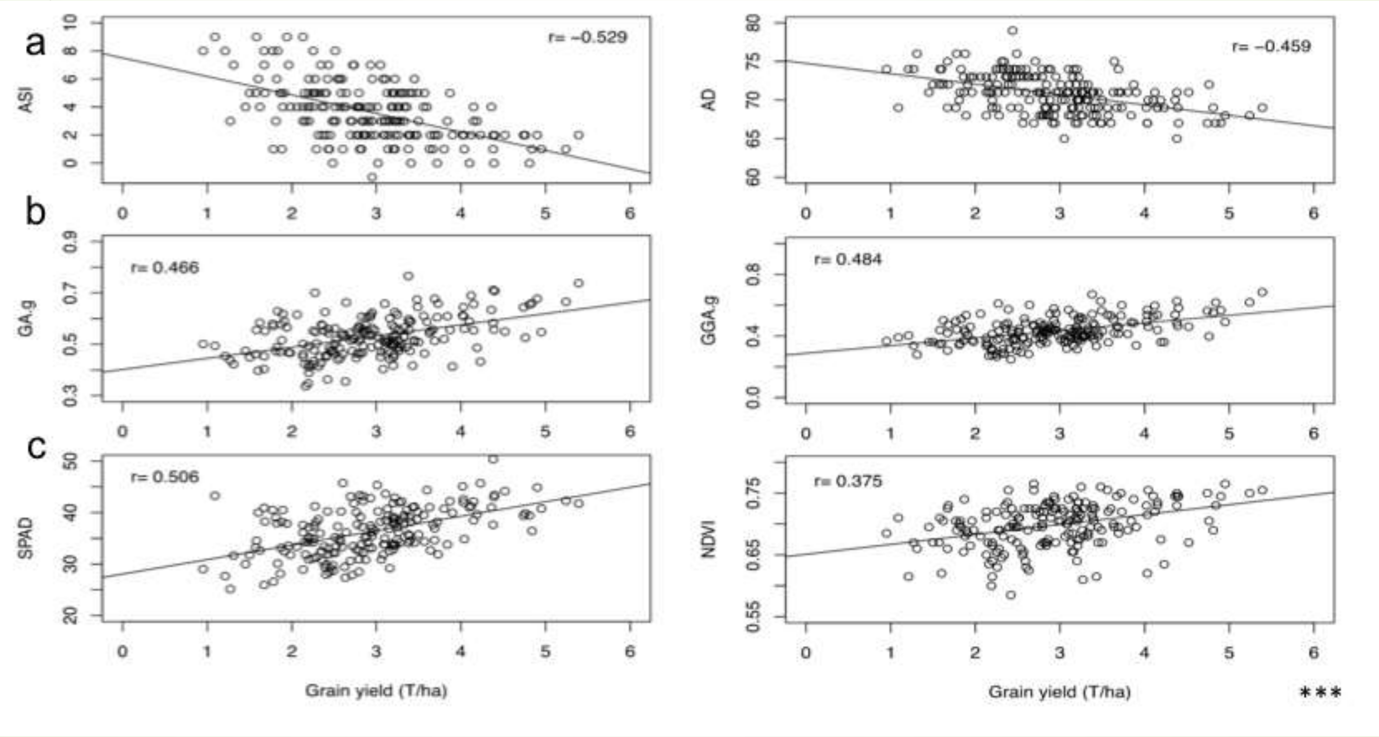
# RGB comparisons from UAV and ground for low N phenotyping Zimbabwe




Buchaillot et al., in preparation

# Multivariate models assessments

Estimations of Grain Yield (GY) with different categories of remote sensing traits including: RGB ground and aerial level and agronomic data, such as ASI (Anthesis Silking Interval), AD (Anthesis Data), MOI (Moisture), SEN (Canopy Senescence) and PH (Plant Height).

| | $R^2$ | P |
|---|---|---|
| RGB ground | 0.249 | *** |
| RGB ground+ Field sensors | 0.403 | *** |
| RGB aerial | 0.239 | *** |
| RGB aerial + Field sensors | 0.384 | *** |
| | | |
| Agronomic + RGB ground | 0.559 | *** |
| Agronomic + RGB aerial | 0.560 | *** |

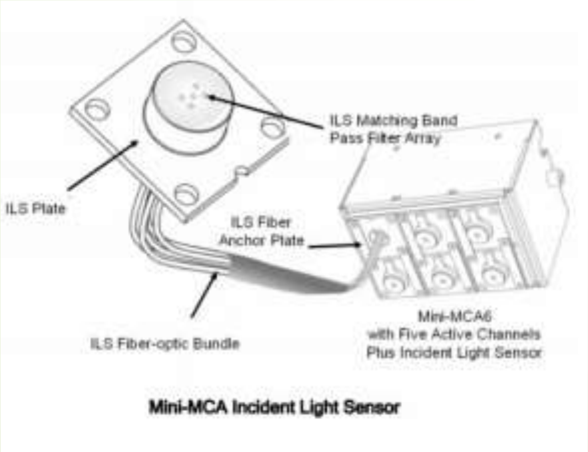
***, *P*<0.001

Buchaillot et al., MS thesis

# Multispectral sensors for UAVs

Working with multiple sensors each with a specific bandpass filter. Tetracam sensors with real-time calibration to reflectance with a matching micro filter array in the  incident light sensor.

Mosaic ortho-rectification of 11 bands using Agisoft PhotoScan, which permits 11 band multispectral 3D point clouds.




# Multispectral Indexes

| | | |
|---|---|---|
| Normalized Difference Vegetation Index (NDVI) | (R840-R670)/(R840+R670) | (Rouse et al., 1973) |
| Soil Adjusted Vegetation Index (SAVI) | (R840-R670)/(R840+R670+L)*(1+0.5) | (A. R. Huete, 1988) |
| Optimized soil-adjusted vegetation index (OSAVI) | ((1+0.16)*(R780-R670))/((R780+R670+0.16)) | (Rondeaux et al., 1996) |
| Renormalized Difference Vegetation Index (RDVI) | (R840 - R670) / ((R840 + R670)^1/2) | (Roujean and Breon, 1995) |
| Enhanced Vegetation Index (EVI) | 2.5*(R840-R670)/(R840+(6*R670)-(7.5*R450)+1) | (Huete et al., 2002) |
| Photochemical Reflectance Index (PRI) | (R550-R570)/(R550+R570) | (Gamon et al., 1997) |
| Modified Chlorophyll Absorption Ratio Index (MCARI) | [(R700-R670)-0.2*(R700-R550)]*R700/R670 | (Daughtry, 2000) |
| Transformed Chlorophyll Absorption in Reflectance Index (TCARI) | 3*(R700-R670)-0.2*(R700-R550)*(R700/R670) | (Haboudane et al., 2002) |
| Anthocyanin Reflectance Index 2 (ARI2) | R840*(1/R550-1/R700) | (Gitelson et al., 2001) |
| Carotenoid Reflectance Index 2 (CRI2) | 1/R550-1/R700 | (Gitelson et al., 2002) |
| Water Band Index (WBI) | R950/R900 | (Peñuelas et al., 1993) |

# RGB and multispectral measurements from the UAV and ground compared against yield in low and optimum Phosphorous treatments

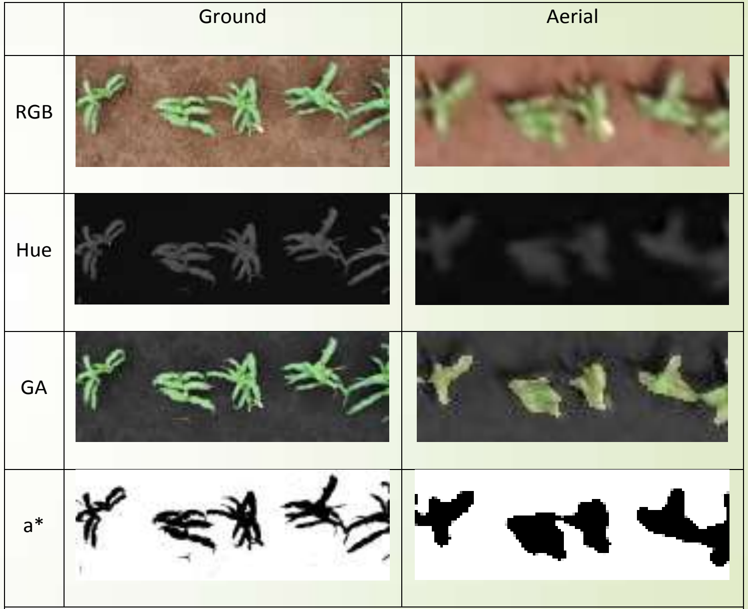
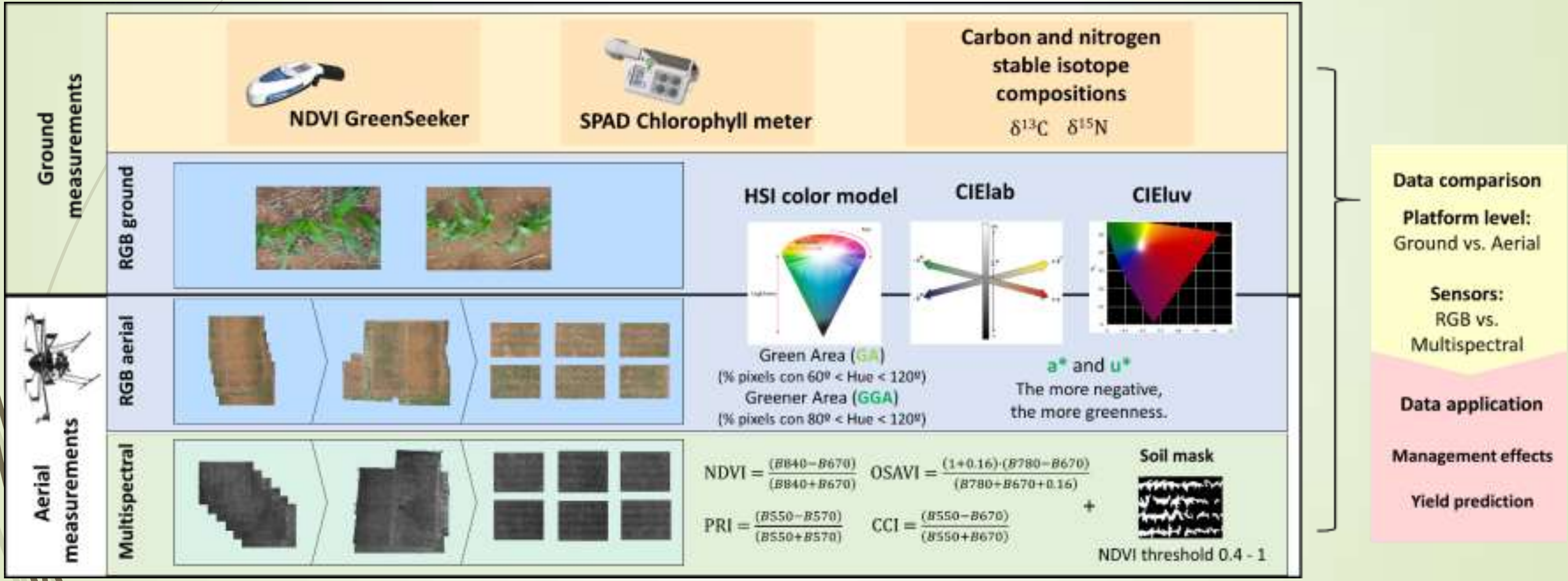



**Figure 2**. Examples of the differences in resolution between the images taken at ground level and at aerially.

Gracia-Romero et al., 2017 Frontiers in Plant Science https://doi.org/10.3389/fpls.2017.02004

# Comparisons of Sensors for Ground and Aerial (UAV) Phenotyping



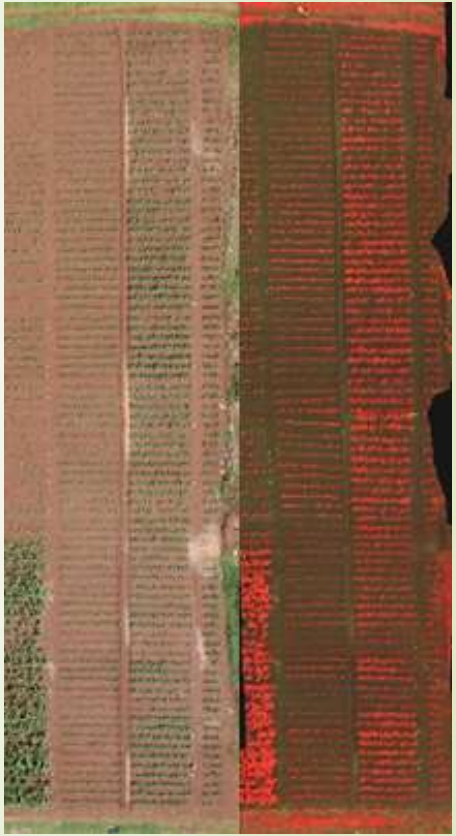
# RGB and multispectral measurements from the UAV and ground compared against yield in low and optimum Phosphorous treatments

| | Grain yield | | | P content | | |
|---|---|---|---|---|---|---|
| | NPF | OP | Comb. | NPF | OP | Comb. |
| **RGB INDICES/GROUND** | | | | | | |
| *Intensity* | 0.194 | −0.217 | −0.084 | −0.014 | −0.067 | −0.041 |
| *Hue* | 0.777*** | 0.732*** | 0.827*** | 0.336 | −0.370 | 0.594* |
| *Saturation* | 0.468* | −0.027 | −0.179 | 0.065 | 0.247 | −0.429* |
| *Lightness* | 0.459* | −0.014 | 0.205 | 0.086 | −0.152 | 0.126 |
| *a** | −0.601** | −0.725*** | −0.818*** | −0.334 | 0.405* | −0.643** |
| *b** | 0.572** | 0.226 | 0.171 | 0.110 | −0.020 | −0.157 |
| *u** | −0.300 | −0.729*** | −0.786*** | −0.267 | 0.425* | −0.667** |
| *v** | 0.642*** | 0.362 | 0.434** | 0.151 | −0.152 | 0.094 |
| *GA* | 0.816*** | 0.817*** | 0.878*** | 0.111 | −0.369 | 0.707** |
| *GGA* | 0.822*** | 0.816*** | 0.877*** | 0.122 | −0.367 | 0.711** |
| **RGB INDICES/AERIAL** | | | | | | |
| *Intensity* | −0.223 | −0.715*** | −0.620*** | 0.166 | 0.021 | −0.359 |
| *Hue* | 0.731*** | 0.798*** | 0.868*** | −0.062 | −0.361 | 0.624** |
| *Saturation* | 0.149 | 0.266 | −0.235 | −0.539* | −0.112 | −0.581* |
| *Lightness* | −0.102 | −0.653*** | −0.526*** | 0.109 | −0.047 | −0.316 |
| *a** | −0.856*** | −0.784*** | −0.883*** | −0.284 | 0.339 | −0.750** |
| *b** | 0.192 | 0.002 | −0.292* | −0.466* | −0.221 | −0.575* |
| *u** | −0.830*** | −0.777*** | −0.873*** | −0.424* | 0.284 | −0.777** |
| *v** | 0.318 | 0.084 | 0.016 | −0.333 | −0.337 | −0.283 |
| *GA* | 0.837*** | 0.814*** | 0.891*** | 0.139 | −0.343 | 0.693** |
| *GGA* | 0.790*** | 0.752*** | 0.837*** | 0.206 | −0.309 | 0.697** |

*Correlations were studied across plots within the non-phosphorus fertilization (NPF) and the optimal phosphorus (OP) trials, as well as both in combination (Comb.). Levels of signification: *$P < 0.05$; **$P < 0.01$; ***$P < 0.001$.*

| | Grain Yield | | | P Content | | |
|---|---|---|---|---|---|---|
| | NPF | OP | Comb. | NPF | OP | Comb. |
| **MULTISPECTRAL INDICES** | | | | | | |
| *NDVI.ground* | 0.734*** | 0.711*** | 0.883*** | 0.058 | −0.423* | 0.669*** |
| *NDVI* | 0.629*** | 0.643*** | 0.823*** | 0.324 | −0.347 | 0.800*** |
| *SAVI* | 0.652*** | 0.644*** | 0.823*** | 0.159 | −0.269 | 0.790*** |
| OSAVI | 0.657** | 0.655** | 0.829*** | 0.216 | −0.303 | 0.797*** |
| *RDVI* | 0.658*** | 0.650*** | 0.829*** | 0.198 | −0.286 | 0.795*** |
| *EVI* | 0.613*** | 0.529** | 0.798*** | 0.119 | −0.220 | 0.782*** |
| *PRI* | 0.039 | 0.312 | 0.406** | 0.428* | 0.032 | 0.466* |
| *MCARI* | 0.358 | −0.019 | 0.452** | −0.035 | −0.033 | 0.463* |
| TCARI | 0.172 | −0.200 | 0.238 | −0.147 | 0.055 | 0.314 |
| TCARI/OSAVI | −0.401* | −0.618** | −0.748*** | −0.368 | 0.283 | −0.700*** |
| *ARI2* | −0.012 | 0.286 | −0.133 | −0.286 | −0.002 | −0.383 |
| *CRI2* | 0.016 | 0.359 | −0.091 | −0.162 | −0.064 | −0.364 |
| *WBI* | 0.241 | 0.595** | 0.598*** | −0.014 | −0.064 | 0.414* |
| **MULTISPECTRAL BANDS** | | | | | | |
| B450 | −0.348 | −0.688*** | −0.638*** | −0.459 | 0.318 | −0.383 |
| B550 | 0.261 | −0.505** | −0.102 | −0.206 | 0.371 | 0.036 |
| B570 | 0.032 | −0.529** | −0.419** | −0.498* | 0.212 | −0.354 |
| B670 | −0.302 | −0.586** | −0.739*** | −0.540* | 0.398 | −0.731*** |
| B700 | −0.116 | −0.525** | −0.602*** | −0.463* | 0.324 | −0.567** |
| B720 | 0.269 | −0.045 | 0.153 | −0.319 | 0.125 | 0.047 |
| B780 | 0.465* | 0.477* | 0.741*** | −0.020 | −0.122 | 0.688*** |
| B840 | 0.496* | 0.550** | 0.779*** | 0.010 | −0.137 | 0.744*** |
| B860 | 0.442* | 0.492* | 0.753*** | −0.061 | −0.129 | 0.736*** |
| B900 | 0.425* | 0.537** | 0.761*** | −0.063 | −0.083 | 0.739*** |
| B950 | 0.390* | 0.411* | 0.724*** | −0.024 | −0.091 | 0.741*** |

*Correlations were studied across plots within the non-phosphorus fertilization (NPF) and the optimal phosphorus (OP) trials, as well as both in combination (Comb.). Levels of signification: *$P < 0.05$; **$P < 0.01$; ***$P < 0.001$.*



Gracia-Romero et al., 2017 Frontiers in Plant Science https://doi.org/10.3389/fpls.2017.02004

# RGB and multispectral measurements from the UAV and ground compared against grain yield in low and optimum phosphorous treatments

| | | Non-phosphorus application | | Optimum phosphorus | |
|---|---|---|---|---|---|
| | | | | | |
| Grain yield | RGB ground indices | GY = -1.26 - 1.38* + 0.72·u* - 440.53·GA + 469.95·GGA | | GY = 4.80 + 13.26·GGA | |
| | | **$R^2$= 0.762*** ** | RSE= 0.535 | $R^2$= 0.665*** | RSE= 0.593 |
| | RGB aerial indices | GY = 12.90 - 0.77·a* | | GY = 12.30 - 0.12·Lightness + 9.97·GA | |
| | | **$R^2$= 0.732*** ** | RSE= 0.531 | $R^2$= 0.704*** | RSE= 0.569 |
| | Multispectral bands | GY = 7.07 + 0.69·B840 - 0.69·B900 | | GY = 12.40 - 0.89·B450 + 0.37·B670 + 0.14·B900 | |
| | | $R^2$= 0.360** | RSE= 0.838 | $R^2$= 0.668*** | RSE= 0.616 |
| | Multispectral indices | GY = -0.52 +11.95·SAVI | | GY = -19.27 - 1476.63·NDVI+ 1011.59·SAVI + 16.54·WBI - 14.96·OSAVI | |
| | | $R^2$= 0.396** | RSE= 0.798 | $R^2$= 0.558* | RSE= 0.728 |

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# Conclusions Low N and P Maize Phenotyping with UAVs

- Maize breeding shows promise for improving GY in low N environments, variability in performance suggests potential for further improvements.
- RGB sensors are functional technology from the ground or UAV, similar to SPAD or NDVI, but complimentary to some agronomic measurements.
- Growth stage timing is critical in order to optimize HTPP benefits to plant breeding. Gains with new technologies in larger breeding platforms.
- We need to take advantage of known effects of low N on physiological processes to focus our efforts to bring HTPP to low N breeding.

# In collaboration with:

UNIVERSITAT DE BARCELONA

CIMMYT

KALRO
Kenya Agricultural & Livestock Research Organization

CGIAR

GOBIERNO DE ESPAÑA

MINISTERIO DE ECONOMÍA Y COMPETITIVIDAD

# Thank you for your attention

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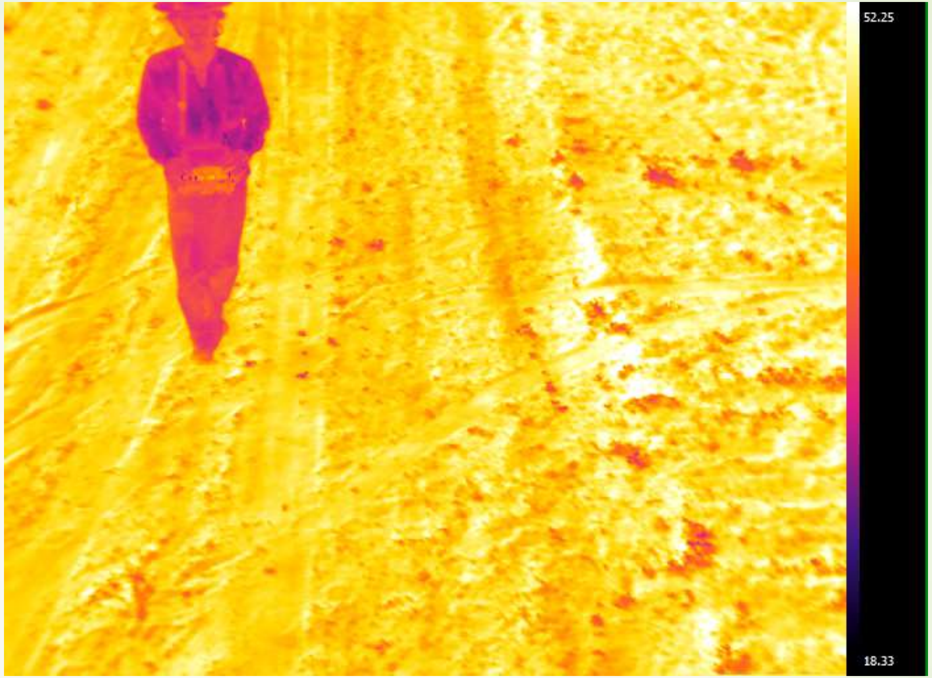


# Integrative Crop Ecophysiology Group


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