Interest and limits of UAV and UGV systems for field high-throughput phenotyping

UAV: Unmanned Airborne Vehicle; UGV Unmanned Ground Vehicle

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Importance of high throughput phenotyping in field conditions

Controlled conditions are not representative of field environment

- Soil (pots)
- Climate (green house)
- Competition between plants

Large number of µ-plots to characterize (1000-2000)
Monitoring the dynamics to access canopy functioning

New measurements methods need to be developed

1. High throughput (quick)
2. Non-destructive (monitoring)
3. Cost effective (per plot)
Experimental platform with microplots
What to measure (with high throughput)?

- **Climate**
- **Pathogen Pressure**
- **Soil**
  - Moisture/ Tension
  - Root Biomass and distribution

- **Structure**
  - Leaf area (GAI per layer)
  - Clumping
  - Inclination/orientation of organs
  - Density of plants/stems/ears
  - Height (per layers)
  - FIPAR
  - Leaf rolling ....

- **Biochemical content**
  - Chlorophyll, water, dry matter, Nitrogen...

- **State**
  - Fluorescence
  - Skin temperature
The (MGV*) experiment
Toulouse in 2011-2012

Experimental design
6 contrasted cultivars
3 nitrogen levels
2 densities

Destructive measurements
LAI
Biomass
Structure
Nitrogen content

Tractor borne remote sensing
Photo @0° & @57°
Reflectance spectra @0° & @57°

Continuous PAR balance
PASTIS sensors in 6 plots

*Manned Ground Vehicule
Semi-automatic prototype phenotyping system

Light characterization
- Irradiance probe
- BF2 (diffuse estimation in PAR)

Current throughput:
100 µplots/hour
Computation of green fractions

Green fraction @ 0° (GF(0°))  Green fraction @ 57° (GF(57°))

Automatic classification based on colorspace (SATVA)

Po=1-GF
Po=Gap fraction  GF=Green fraction
sensitivity to structure depending on direction

Plano (Hysun)  Erecto (Caphorn)

@ 57°
parallel

@ 0°

@ 57°
perpendicular

Difficulty to estimate LAI from green traction measurements @ 0°:
Relationships depend on canopy structure
# Vegetation indices

<table>
<thead>
<tr>
<th>Name</th>
<th>Formula</th>
<th>Variable Targeted</th>
<th>authors</th>
</tr>
</thead>
<tbody>
<tr>
<td>FV</td>
<td>Picture segmentation</td>
<td>LAI</td>
<td>Chen</td>
</tr>
<tr>
<td>MTCI</td>
<td>$\frac{\rho_{753} - \rho_{708}}{\rho_{708} - \rho_{681}}$</td>
<td>Chlorophyll</td>
<td>(Dash and Curran, 2004)</td>
</tr>
<tr>
<td>NDVI</td>
<td>$\frac{\rho_{800} - \rho_{670}}{\rho_{800} + \rho_{670}}$</td>
<td>Mainly LAI</td>
<td>(Rouse et al., 1974)</td>
</tr>
<tr>
<td>MCARI2</td>
<td>$1.5 \frac{2.5(\rho_{800} - \rho_{670}) - 1.3(\rho_{800} - \rho_{550})}{\sqrt{(2\rho_{800} + 1)^2 - (6\rho_{800} - 5\sqrt{\rho_{670}} - 0.5)}}$</td>
<td>LAI</td>
<td>(Haboudane et al., 2004)</td>
</tr>
<tr>
<td>REIP</td>
<td>$\frac{(\rho_{670} + \rho_{780})/2 - \rho_{700}}{700 + 40 \frac{\rho_{740} - \rho_{700}}{\rho_{740} - \rho_{700}}}$</td>
<td>(Leaf surface + chlorophyll)</td>
<td>Baret – (Mistele and Schmidhalter, 2010)</td>
</tr>
<tr>
<td>PRI</td>
<td>$\frac{\rho_{531} - \rho_{570}}{\rho_{531} + \rho_{570}}$</td>
<td>Xanthophyll and Chlorophyll/Carotenoids</td>
<td>(Gamon et al., 1992), (Garrity et al., 2011)</td>
</tr>
<tr>
<td>CRIgreen</td>
<td>$\left(\frac{1}{\rho_{510-552}} - \frac{1}{\rho_{560-570}}\right)\rho_{760-780}$</td>
<td>Carotenoids</td>
<td>(Gitelson et al., 2006)</td>
</tr>
</tbody>
</table>
Sensitivity to the green fraction

The relationship between MCARI2 and the green fraction is independent from cultivar and nitrogen modalities.
Validation with radiative transfer models

Green fraction is the Best estimated from Bulk reflectance Measurements

FAPAR (light interception efficiency) is not accurately retrieved without

LAI (Leaf Area Index) shows saturation problems for high LAI: lack of sensitivity
Not accurately retrieved without

Need for additional
- information on structure or
- other direction measurements
Differences between cultivars
Simple modeling of the dynamics

- **Date (degree day)**
  - Beginning of Senescence, $T_{bs}$
  - End of Senescence, $T_{es}$

- **Rate of change (slope):**
  - Vegetative phase, $S_v$
  - Senescence phase $S_s$

- **Value at beginning of senescence**, $F(T_{bs})$

- **Integrated values**
  - Totale, $I_{Tot}$
  - Vegetative phase, $I_{veg}$
  - Senescence phase, $I_{sen}$
Heritability of high throughput measurements (HTM)

P Value for a linear model of variance analysis:
HTM= Nitrogen + Cultivar + Density + (Nitrogen: Density) + \( \varepsilon \)

<table>
<thead>
<tr>
<th></th>
<th>Nitrogen</th>
<th>Cultivar</th>
<th>Density</th>
<th>Nitrogen:Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{I}_{\text{Tot}(\text{MCARI2})} )</td>
<td>0.00000</td>
<td>0.00000</td>
<td>0.00023</td>
<td>0.01132</td>
</tr>
<tr>
<td>( \text{T}_{\text{Tot}(\text{MTCI})} )</td>
<td>0.00000</td>
<td>0.00026</td>
<td>0.75646</td>
<td>0.23974</td>
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<tr>
<td>( \text{I}_{\text{Tot}(\text{CRIgreen})} )</td>
<td>0.00000</td>
<td>0.00000</td>
<td>0.00075</td>
<td>0.00017</td>
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<tr>
<td>( \text{Sv (MCARI2)} )</td>
<td>0.00000</td>
<td>0.00000</td>
<td>0.60242</td>
<td>0.00103</td>
</tr>
<tr>
<td>( \text{Sv (PRI)} )</td>
<td>0.02616</td>
<td>0.00029</td>
<td>0.95522</td>
<td>0.31448</td>
</tr>
<tr>
<td>( \text{Sv (CRIgreen)} )</td>
<td>0.00000</td>
<td>0.00000</td>
<td>0.24363</td>
<td>0.41487</td>
</tr>
<tr>
<td>( \text{T}_{\text{es}(\text{MCARI2})} )</td>
<td>0.00000</td>
<td>0.27150</td>
<td>0.55732</td>
<td>0.97792</td>
</tr>
<tr>
<td>( \text{T}_{\text{bs}(\text{MTCI})} )</td>
<td>0.00027</td>
<td>0.18393</td>
<td>0.12883</td>
<td>0.12802</td>
</tr>
<tr>
<td>( \text{T}_{\text{es}(\text{MTCI})} )</td>
<td>0.00000</td>
<td>0.61992</td>
<td>0.55072</td>
<td>0.79508</td>
</tr>
</tbody>
</table>

P value: probability that there is an effect
FIPAR estimates from 0° and 57° views

FIPAR = f(GF(0°), GF(57°))

Photos(0°, 57°) → GF(0°, 57°) → FIPAR
MCARI2(0°, 57°) → GF(0°, 57°) → FIPAR

IPAR Arche préflo = f(IPAR_flo_PASTIS)

y = 0.986x
R² = 0.9806

Effet ‘épis’
Use of FIPAR for phenotyping

Cumulated IPAR = \( \int_{t=t_1}^{t_2} FIPAR \cdot PAR_i \, dt \)

\[
LUE = \frac{\Delta t_2 \cdot \text{Biomass}}{\int_{t_1}^{t_2} FIPAR \cdot PAR_i \, dt}
\]
Comparison with UAV
The Sensor

Multispectral camera
4 Mo board cameras
Spatial resolution: 5-20 cm
Mass ≈200g
Calibration over gray carpet
Continuous incoming light measurements

$$BRF_{target}^i = \frac{DN_{target}^i}{t_{target}^i I_{target}} \frac{t_{ref}^i I_{ref}}{DN_{ref}^i} BRF_{ref}^i$$

BRDF of gray carpet for nadir view
Viewing configuration

Multiple views of a single μ-plot
Limited directional effects
Estimates of GAI
Using Look Up Tables technique

Distribution of input variables → RT model → Simulated reflectances → Cost function

Geometry of observation → Prior values on variables

Best match

Solution: Estimated GAI

Regularization:
mean value of estimates from the several directions available:

\[ J = \sum \frac{(R_{obs} - R_{sim})^2}{\sigma^2_{obs}} + \alpha \sum \frac{(R_{prior} - R_{sim})^2}{\sigma^2_{sim}} \]
First results on few plots

Green Area Index: GAI

01/02

23/03

Wheat
Rapeseed
Verification of stability of retrievals

Comparison between flights in the morning (AM) and in the afternoon (PM)

For 2 days

n = 360; RMSE = 0.12; R = 0.99
slope = 0.98; offset = -0.02
Retrieval performances (180 plots x 4 flights)

\[ n=432; \text{RMSE}=0.63; \text{R}=0.81 \]
\[ \text{slope}=1.01; \text{offset}=-0.07 \]
Access to canopy height/macro structure
CONCLUSION (1)

• Importance of the dynamics
• Difficulty to extract cultivar independent structural/biochemical variables from m² resolution
  – Need mm² resolution observations
  – Or need a priori knowledge of canopy structure
Conclusion 2
pros and cons of UAVs and UGVs

• **UGV (phenomobile):** Access to mm\(^2\) observations: 200 µ-plots/hour
  - Few hours between first and last µ-plots sampled
    • Need active measurements
  - Access to the detailed structure (3D)
  - Access to the organ level biochemical constituents (Chlorophyll ...)

• **UAV (multicoptere):** access to m\(^2\) observations: 10 000 µ-plots/hour
  - Few minutes between first and last plots sampled
  - Easy way to monitor the dynamics
  - Access to canopy macro-structure
  - Difficulty to access the detailed structure and organ level biochemical content
  - Possible confounding effects: retrievals may be cultivar specific
  - Access to instantaneous stress status: thermal IR, fluorescence
Conclusion 3

Complementarity between UAV and UGV

- **UAVs as a basic system for monitoring the dynamics:**
  - low cost, easy to setup
  - Need UGVs information to disentangle structure effects

- **UGVs: detailed measurements for organ level structure/optical properties**
  - Expensive, but

- **Still a lot of work to transform measurements into structural/functional traits**
  - 3D modeling of canopy structure
  - Assimilation in Functional Structural Plant Models
The team
UAVs & UGVs

RGB camera, lidar, spectro...
Active mode
(10 dates in 2013)

Multispectral camera
Passive mode
(10 flights in 2013)