Improved spatial modelling of crop productivity using geophysics-based soil mapping: a case study beyond the field scale

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Mitglied der Helmholtz-Gemeinschaft
Yield gap is a constant threat in agriculture

Reduces farmer’s income and can undermine the sustainability of agricultural practices.

- **Water scarcity in soil** is one key cause for reduced crop performance
- Other causes such as nutrients availability, pests, disease and weeds contribute to further yield gaps

An accurate soil description is key to simulate and predict the effects of water scarcity.
Accurate soil description

<table>
<thead>
<tr>
<th>Small-scale</th>
<th>Field-scale</th>
<th>Intermediate</th>
<th>Large-scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>(few m²)</td>
<td>(~1 to 5 ha)</td>
<td>(~1 km²)</td>
<td>(~10 km² or more)</td>
</tr>
</tbody>
</table>

- Soil sampling
- Lab analysis
- Geophysics
- EMI inversion
- Remote sensing
- Soil map

General-purpose maps are often not detailed enough

Can geophysics-based soil mapping fill this gap?

And what is the added value? For example in:

- Hydrological and agro-ecosystem modelling
- Precision agriculture (management zones)
- Yield simulation and prediction
Electromagnetic Induction EMI

Measures the apparent electrical conductivity (ECa) of the ground. ECa is related to texture, layering, water content, temperature, and other characteristics of the soil.

Increased distance between transmitter and receiver results in an increased depth of investigation

Different sensitivity of EMI instrument for six different coil distances

Modern multi-configuration instruments can measure multiple depths of investigation simultaneously.

**High Resolution:**
- In line resolution = ~30 cm
- Measurement lines every 2.5 m

**Fast Methodology:**
- Measure 1 ha in ~1 hour
1x1 km study area

Soil heterogeneity affects crop development during water scarcity.

Water stress in silage maize and sugar beet
Courtesy of F. Jonard

The thickness of loess top soil overlying coarse layers and the characteristics of these soils is key to understand and simulate the occurrence of water stress.

Most detailed available soil maps probably cannot reproduce these patterns.
From EMI measurements to an EMI-based soil map

1) EMI measurements resulted in six ECa maps with depth of investigation between 0.5-2.7 m. These maps were combined in a multiband image.

2) The resulting multiband image that was analyzed with a supervised image classification technique (cluster soils with similar signatures).

3) Direct soil sampling at 100 locations and laboratory analysis provided quantitative soil description up to 2 m depth (texture and horizonation).
Comparison with patterns in crop stress

Correctly classified cells:
- Upper Terrace = 76.6%
- Lower Terrace = 91.1%

How to valorize and exploit these quantitative information?
Agro-ecosystem modelling using EMI-based data

The agro-ecosystem model AgroC was used to simulate soil-crop interaction and crop growth on the 1km² study area.

One AgroC model was set-up in each unique soil-crop combination:

- 80 different model set-ups (each with one soil unit and one crop)

Meteorological information for 2016 were used:

- (e.g. rain, temperature, humidity, solar radiation).
Agro-ecosystem model AgroC

AgroC is a 1-D numerical model that couples three modules:

- **SOILCO2**: vertical water, heat, and CO2 fluxes
- **RothC**: turnover of organic carbon
- **SUCROS**: crop growth and organic matter accumulation rates

Pressure head influences crop stress (Feddes 1982) and reduces:

- Root water uptake
- Carbon assimilation and increase of biomass
Soil hydraulic parameters to feed AgroC model

Soil hydraulic parameters calculated using pedotransfer function (Rawls & Brakensiek 1985) for each horizon.

Horizonation and soil hydraulic parameters of each horizon are used in AgroC to simulate soil water content dynamics given an atmospheric input.
Agro-ecosystem stress simulation

Simulations of sugar beet in 2016 with different soil profiles

Clear difference in leaf area index (LAI) and weight of storage
Field-scale simulation of sugar beet

Patterns in sugar beet and soil classes

Four soil units present in the analyzed field

Simulated LAI (lines) vs satellite LAI\textsubscript{NDVI} (dots) and productivity on the four soils

Compared with LAI\textsubscript{NDVI} obtained from RapidEye satellite images for 2016 (Ali et al. 2014).

Satellite derived LAI and simulated LAI at two different dates

Simulated LAI well matches observed LAI\textsubscript{NDVI} from satellite.
Simulation of LAI (km² scale)

AgroC simulation of six crop types:

- Sugar beet
- Potato
- Winter raps
- Corn
- Winter barley
- Winter wheat

Simulated LAI well match observed LAI_{NDVI}.

Satellite derived LAI and simulated LAI throughout the 2016 growing season.
Maps of simulated yield

- 100% = not limited by water
- Sugar beet and winter barley match well actual harvest data
- Corn and winter wheat correspond to literature values

What is the added value of geophysics-based compare to commonly-available maps?
Added value compared to conventional soil maps

A geophysics-based soil map provides:
- Quantitative information allows large-scale simulation
- Identify and simulate small-scale patterns

Further AgroC simulations were set-up using information from two commonly available soil maps and compared to the EMI-based.
### Added value in simulation of LAI\textsubscript{NDVI}

<table>
<thead>
<tr>
<th>Date</th>
<th>Geophysics-based</th>
<th>1:5000 Soil map</th>
<th>Soil taxation map</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>RMSE</td>
<td>$R^2$</td>
<td>RMSE</td>
</tr>
<tr>
<td>March</td>
<td>0.62</td>
<td>0.84</td>
<td>0.63</td>
</tr>
<tr>
<td>April</td>
<td>1.07</td>
<td>0.72</td>
<td>1.09</td>
</tr>
<tr>
<td>May</td>
<td>0.64</td>
<td>0.93</td>
<td>0.67</td>
</tr>
<tr>
<td>June</td>
<td>0.64</td>
<td>0.89</td>
<td>0.69</td>
</tr>
<tr>
<td>August</td>
<td>0.64</td>
<td>0.47</td>
<td>0.89</td>
</tr>
<tr>
<td>September</td>
<td>0.56</td>
<td>0.78</td>
<td>0.78</td>
</tr>
</tbody>
</table>

**Winter crops**
- Slight improvements for winter crops at the km\(^2\) scale.
- Strong improvements in summer and over soil heterogeneities.

**Summer crops**
- RMSE and $R^2$ of the 1km\(^2\) simulations of LAI

<table>
<thead>
<tr>
<th>Fields</th>
<th>Geophysics-based</th>
<th>1:5000 map</th>
<th>Taxation map</th>
</tr>
</thead>
<tbody>
<tr>
<td>F-12</td>
<td>0.72</td>
<td>0.73</td>
<td>0.73</td>
</tr>
<tr>
<td>F-47</td>
<td>0.51</td>
<td>0.45</td>
<td>0.43</td>
</tr>
<tr>
<td>F-01</td>
<td>0.45</td>
<td>0.53</td>
<td>0.88</td>
</tr>
<tr>
<td>F-13</td>
<td>0.56</td>
<td>0.73</td>
<td>0.73</td>
</tr>
<tr>
<td>F-48</td>
<td>0.62</td>
<td>0.78</td>
<td>0.90</td>
</tr>
</tbody>
</table>

**Relatively homogeneous soils**
- With Geophysics-based soil map, average reduction of RMSE of 25% and 31% in heterogeneous areas and for summer crops.
Added value of geophysics-based soil mapping

Image classification of EMI produces high resolution and large-scale soil maps provided with quantitative layering and texture.

Simulate time series of:
- Productivity at harvest
- Stress (caused by water scarcity)
- LAI that matches satellite LAI_{NDVI}

Agricultural applications:
- Optimize irrigation
- Maximize productivity
- Evaluate management practices
- Costs/benefits estimation

Environmental applications:
- Estimate carbon sequestration

Simulated water-limited productivity of four crops in 2016 within the study area
Optimize irrigation with perfect 7-day forecast

By adding irrigation water, we can decrease water stress and increase crop productivity.

- Economical and environmental irrigation cost (€ & CO₂ emissions)

Add weekly irrigation to keep water stress below a certain level considering seven days of forecasted precipitation.

~2200 m³/ha

= +23.3 t/ha wet beets

Plus ~27.5%
ATLAS: real-time optimized irrigation

Experimental apple orchards plots in Agia (Greece) + Digital Soil Mapping (EMI & ground truth)

Network of: - SoilNet sensors - Cosmic Ray Neutron Probes

Combination of:
+ Near real-time monitoring of soil moisture and matrix potential
+ Weather forecast
+ Hydrological modelling
+ Crop modelling
= Optimized irrigation scheduling

Make our farmers happy!