VARIABLE RATE IRRIGATION AND NITROGEN FERTILIZATION IN POTATO; ENGAGE THE SPATIAL VARIATION (POTENTIAL)

Background document - with guidelines for variable rate application of water and nitrogen in potato

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Content

1 //
Introduction

With a total acreage of more than 5200 km² in all four countries, potato is an important agricultural crop in Belgium, Denmark, the Netherlands and Germany. In these countries percolation water contains nitrate (NO_3^-) concentrations higher than a safety limit of 25 mg/l, hence it is of common interest to reduce the leaching of nitrogen (N) from NO_3^- and to increase the water use efficiency from irrigation of potato fields. It is envisaged that irrigation in potato will be crucial in the future to maintain stable yields as scenarios predict an increased occurrence of climatic extremes. The objective of the project "Variable rate irrigation and nitrogen fertilization in potato; engage the spatial variation" (abbreviated POTENTIAL) is to increase N and water use efficiency in potato by the use of innovative precision farming solutions. Spatio-temporal variation in water and N deficit in potato fields is revealed using remotely sensed data from satellite, drone, electromagnetic induction (EMI) and tractor-mounted and hand-held sensors. The combination of these different types of information on above- and belowground crop and soil information opens up new opportunities for sound decision making. The project envisaged the translation of years of research on mapping the variability in crop vitality and soil condition to specific task maps for farmers in order to optimize their management. The consortium was composed of the Soil Service of Belgium (SSB), VITO, Université de Liège (ULg), Aarhus University (AU), Fasterholt Maskinfabrik (FM), Forschungszentrum Jülich (FZJ and Wageningen University & Research (WUR).

A range of sensors were applied to characterize spatio-temporal variations in soil and crop at field trials in potato farms in Belgium (SSB and WUR) and Denmark (AU) from 2017 to 2019. The sensors were satellite, drone, machine-mounted and handheld. Soil moisture and soil nitrate content is collected in situ, and compared with apparent electrical conductivity (ECa) maps obtained with multi-configuration EMI soil scanners (FZJ, ULg, AU) and a tractor mounted soil water content mapping system developed at AU using Time-Domain Reflectometry (TDR) sensors. Output from these sensor systems was related to in-field crop response maps to water and N stress as well as yield. Classical agronomic recommendation services for irrigation and nitrogen management in the four partnering countries were be listed and assessed. A way of practice indicating how spatial information can be integrated into the classical agronomic recommendations for irrigation and fertilization was outlined. Special attention was given to the investigation of spectral information to distinguish between nitrogen and water deficits and their relation to soil properties. For the implementation of the variable application of water and nitrogen the consortium had the assistance of Jacob Van den Borne in the Netherlands. Jacob Van Den Borne is a potato farmer and is equipped with machinery that allows variable N fertilization, as well as a Fasterholt irrigation gun. The Danish SME Fasterholt Maskinfabrik A/S is an experienced manufacturer of raingun machines primarily for the European market. Fasterholt is currently developing a variable rate raingun with GPS positioning, with the ability to adjust for wind-deflection and to direct the gun according to pre- programmed maps of desired surface application rates.

This background document is valuable to adapt the irrigation and fertilization strategy of potato varieties or for the improvement of the existing strategies. It can also be used as a starting point to focus the potato management on the recommended points. The outcomes of the project and presented in the guideline should be robust, because they are based on information from different pedo-climatic and technical conditions.

Irrigation in potato will be crucial in the future to maintain stable yields as most future climate scenarios predict an increased occurrence of climatic extremes.

2 //
Main goals of the project

The objective of the proposed POTENTIAL project is to increase N and water use efficiency in potato by co-scheduling of N and irrigation water. This implies the reduction of water percolation and N leaching out of the soil profile. Innovative sensing solutions and fertilizer and water application technologies are used to meet this objective. Four specific goals are set:

1. Assess spatio-temporal variation in water and N deficit in potato fields using various data sources (satellite, drone, EMI, tractor-mounted sensors) to collect information on crop and soil state variables.
2. Distinguish between water stress and nitrogen deficiencies and quantify these in potato crops through sensor technology.
3. Integrate information about the spatial variation in operational services for co-scheduling irrigation and N fertilization.
4. Develop, apply and assess variable rate irrigation and N fertilization based on this integrated service.

3 //

Current practices for irrigation and N-fertilizer scheduling in potato

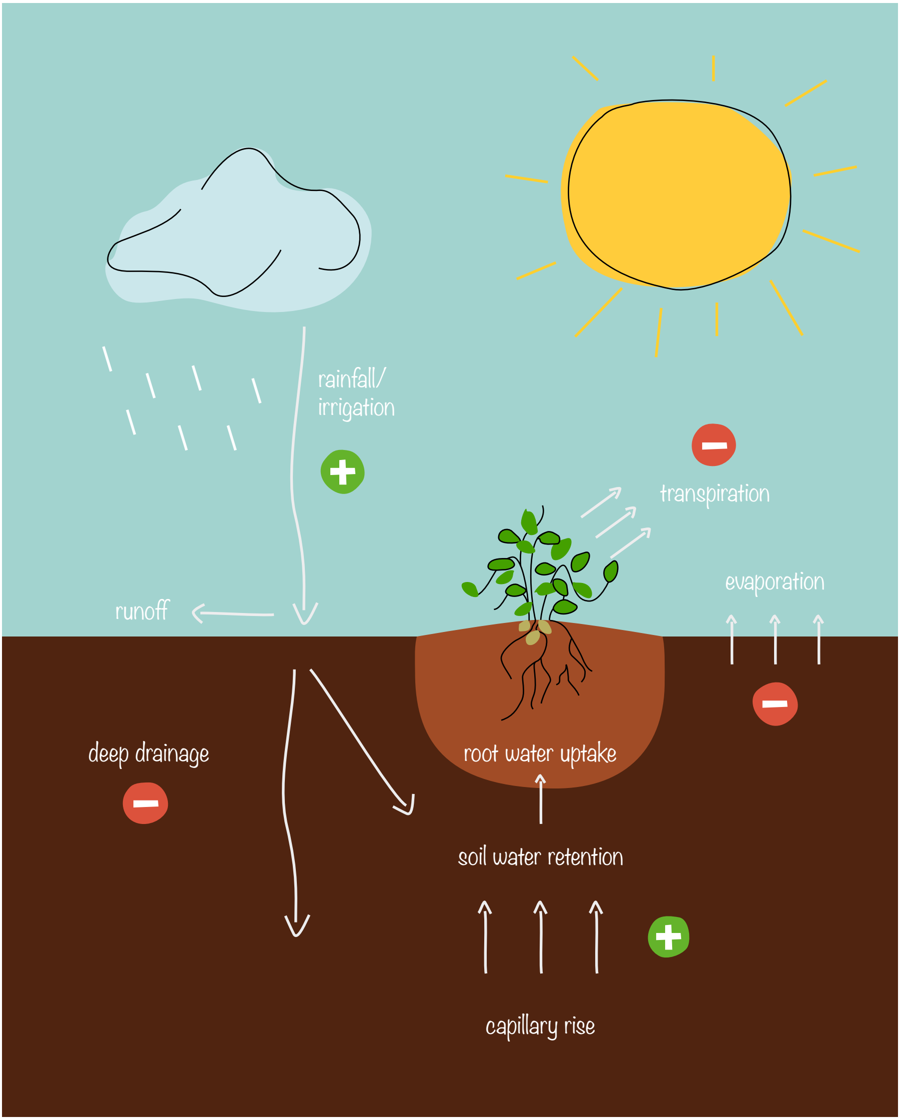
3.1 ESTIMATION OF THE IRRIGATION NEED

Irrigation can be scheduled using a soil water balance, soil sensors, plant sensors or combinations between them. Irrigation scheduling aims to optimize the crop yield with a minimal input of irrigation water. Excess irrigation results in a suboptimal economic result for the farmer, especially in the majority of potato farms in Northwestern Europe, where irrigation is applied with sprinklers, which consume a lot of energy. Furthermore over-irrigation increases the risk of nutrient leaching out of the root zone, to the environment. Popular soil water balances used to schedule irrigation, or to evaluate the irrigation need are BUDGET (Raes et al., 2006), AQUACROP (Raes et al., 2018) or Cropsyst (Stöckle et al., 2003).

To define the optimal time and dose of irrigation, a wide range of soil and plant sensors can be used. These sensors monitor water status at the level of the soil, or at the level of the plant. However, a forecast of irrigation need is rarely provided, since this approach lacks a forecast model. A classical soil water balance model as for example BUDGET (Raes et al., 2006) calculates the root zone depletion for the simulation period (Δt = 1 day) by considering the measured soil water content in the root zone at day i (D_i), the daily rainfall (R), irrigation (I), estimated capillary rise (CR), and the crop evapotranspiration which is calculated by multiplying reference evapotranspiration (ET_o) with the crop coefficient K_c (Allen et al., 1998). Deep percolation (DP) is considered when soil water content exceeds Field Capacity (Eq. 1, Figure 1).

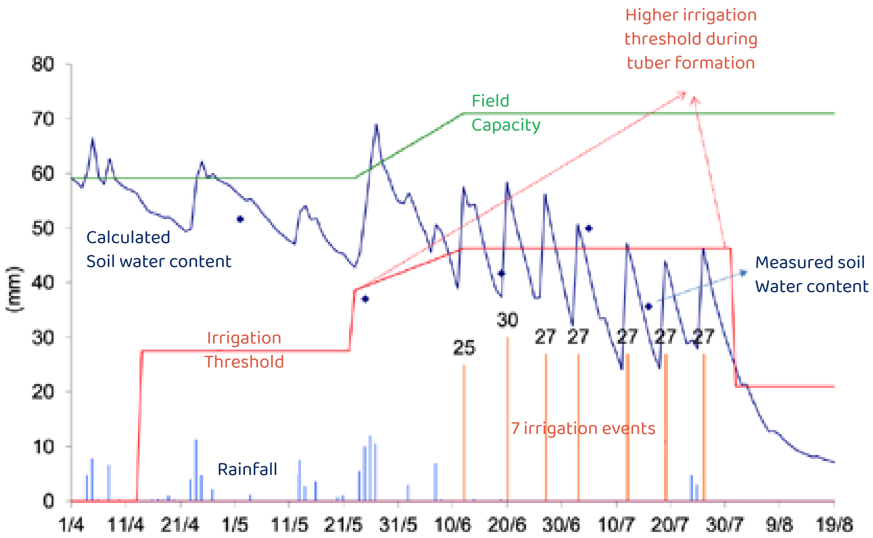
$$D_i \text{ [mm]} = D_{i-1} + R + CR - DP + I - K_c\, ET_o \tag{1}$$

Figure 1 **Schematic of a soil water balance model, which can be used to forecast irrigation need.**



In the POTENTIAL project, a soil water balance model was used to schedule irrigation. For example in experimental field nr 7 (Kasterlee, Belgium), 7 irrigation events were scheduled to maintain soil water status close to the irrigation threshold, which identifies possible water shortage (Figure 2).

Figure 2 Soil water balance used to schedule irrigation on an experimental field in Kasterlee, Belgium (experimental field nr 7).



Soil sensors can be used to estimate soil water potential (Ψ_{soil}) or soil water content (θ) who can be related to each other through the water retention curve. Sensors can measure in real time, and are easily accessible although they lack forecast. Often multiple sensors are needed to get a good view of the spatial variation in the soil, and site specific calibration is requested (Jackisch et al., 2019; Dane et al., 2002; Lukangu et al., 1999). Several sensor and datalogger combinations are on the market to help farmers in the organization of their irrigation (Table 1).

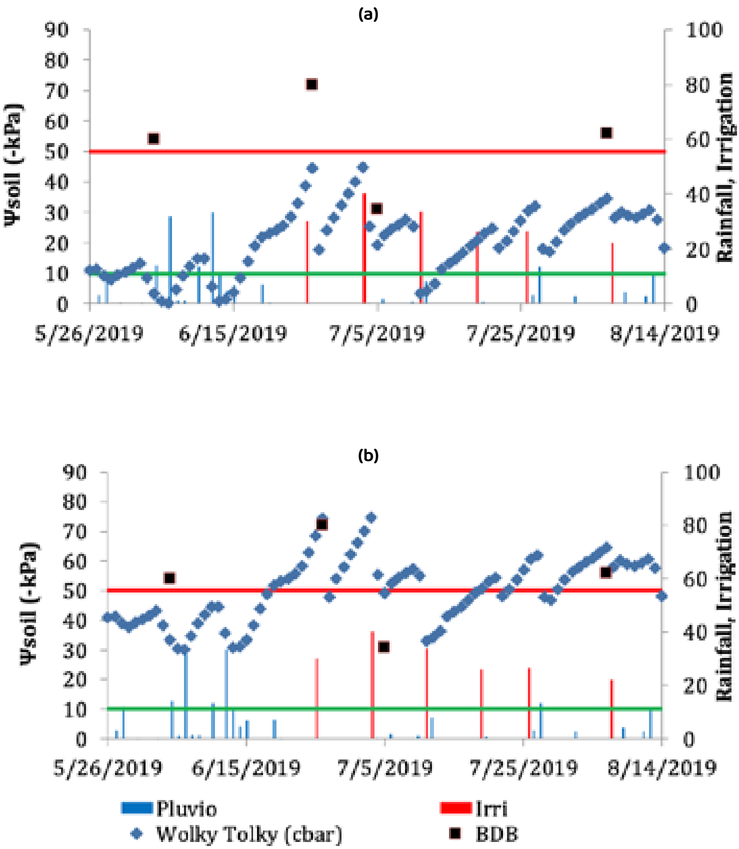
Table 1 Commercially available soil moisture sensors used in potato farms in Belgium and the Netherlands (non-exhaustive list, price level 2019)

SENSOR	URL	TECHNIQUE	OUTPUT	COSTS
Dacom Sensetion	www.dacom.nl/en/products/sensetion		Soil moisture (mm)	€1.095+€250/j
Dacom Terrasen	www.dacom.nl/en/products/terrasen		Soil moisture (mm) Precipitation (mm) Soil temperature	€2.295+€250/j
WolkyTolky	www.wolkytolky.com/en	Watermark	Precipitation Soil moisture Temperature Soil temperature Wind (force and direction) Relative humidity Solar radiation UV index Barometric pressure Leaf wetness (disease treatment)	
SoilMate	www.smartfarm.nl/en/sensors/soilmate		Volumetric soil moisture (%)	€189+€7,50/m
Sensoterra	www.sensoterra.com/en/product		Volumetric soil moisture (%)	
GeoBas	www.vantage-agrometius.nl/product/geobas-bodemvochtsensor	Watermark	Volumetric soil moisture (%) Water suction pressure (kPa) Precipitation	€500 (LoRa)+€75/j
RMA	www.rmacompany.nl/bodemvocht-en-neerslag-via-lora		Volumetric soil moisture (%) Precipitation	€800+€250/j

Weather station and different soil sensors as installed on the field of Jacob Van Den Borne in the Netherlands in 2019 (Field nr 12)

Experiences with the soil sensors on experimental field nr 12, in the Netherlands, showed that calibration is needed to ensure correct observations of soil water status (Figure 3). Also sensors connected to DACOM, RMA or Geobas dataloggers needed to be calibrated to deliver correct absolute soil moisture values.

Figure 3 Evolution of Ψsoil observed with Watermark sensor connected to Wolky Tolky datalogger in the experimental field in the Netherlands in 2019. Readings are compared to Ψsoil observations of Soil Service of Belgium derived from gravimetric sampling and calculated to Ψsoil trough the water retention curve before (a) and after (b) calibration of the sensor Ψsoil data, using the gravimetric soil moisture measurements.



3.2 ESTIMATION OF THE N- FERTILIZER NEED

A crop decision support system of N fertilization in potato should take in to account N uptake of the crop in relation to N supply to the crop due to soil mineralization. This estimation should lead to a N fertilization advise, which can be split into multiple fractions to ensure efficient N uptake (Goffart et al., 2008). In the experimental country's (Belgium, The Netherlands, Denmark) organic manure is mostly applied before potato planting in combination with mineral fertilizer. About 100 kg N/ha is given by manure, the rest (100-150 kg N/ha) is applied by N-fertilizers with e.g. KAS. Mostly the farmer adds an application during late June/July as a topdress.

There are however N-scheduling tools available to apply the amount of N-fertilizer in a more efficient way and minimize the amount of N-fertilizer. These scheduling tools are called N-sidedress systems. Instead of applying most N-fertilizer at planting, only about 2/3 is applied. The rest is applied as a side dress during June/July based on an estimation of what the crop still needs. This estimation is based on the N-availability in the soil and/or estimation of the N-uptake of the crop. Besides soil sampling several methods have been described to outline optimal side dress N rate (Muñoz-Huerta et al., 2013). Plant tissue can be sampled followed with a Kjeldahl digestion or Dumas combustion, however these analyses are destructive. Optimal sensors can estimate chlorophyll concentration such as the SPAD sensor or fluorescence using a Dualex or Multiplex sensor. Optimal sensors can also observe spectral crop reflectance on an active or passive basis and can be installed on various platforms varying from hand held over drone to satellite.

3.2.1 Belgium

On all field trials in Belgium and the Netherlands available N for crop growth is estimated based on nitrate-N and ammonium-N content in the soil, pH, %C and crop characteristics. All of these parameters are considered by Soil Service of Belgium in the N-INDEX expert system (Vandendriessche et al., 1996). For potato soil analysis was conducted to a depth of -60 cm. Soil analysis was conducted in early spring, after which fertilization treatments, as outlined in paragraph 5, were installed. During the growing season additional soil N analysis was conducted to evaluate the various fertilization treatments.

3.2.2 Denmark

On all field trials in Denmark the soil N availability is determined by soil sample analysis for N, P, K and Mg contents in spring before planting. Composite samples from the plough layer (0-25 cm) are collected and analyzed in the lab. Thereafter, the recommended amount of fertilizer (legal quota) applied to the crop is "corrected" by the amount obtained from the soil N analysis (estimated amount of N from mineralization). The recommended amount of fertilizer is based on N response curves obtained from numerous trials on national level, which are cultivar- and soil type specific and the data are compiled and updated annually by advisory services organized by the Danish Ministry of Food and Environment.

3.2.3 The Netherlands

In the trial fields at Van Den Borne the N-uptake of the crop is estimated with biomass maps from a drone camera or nearby Fritzmeijer sensor (Fritzmeier Umwelttechnik, Isaria, Germany). With a growth model the potential N-uptake of the crop is predicted. This potential N-uptake is based on the expected yield and the historic temperature from planting to the date of N-side dress. The difference between the current N-uptake and the potential N-uptake is the amount of N-fertilizer which was applied.

4 //
Available platforms to facilitate the use of satellite images for farmers

4.1 BELGIUM

WatchITgrow is a Belgian platform launched to support farmers to monitor the status and evolution of arable crops and vegetables, in view of increasing yields, both qualitatively and quantitatively. It centralizes various types of data such as satellite, weather and soil data and field data provided by the farmer. The platform is freely accessible after registration at: www.watchitgrow.be.

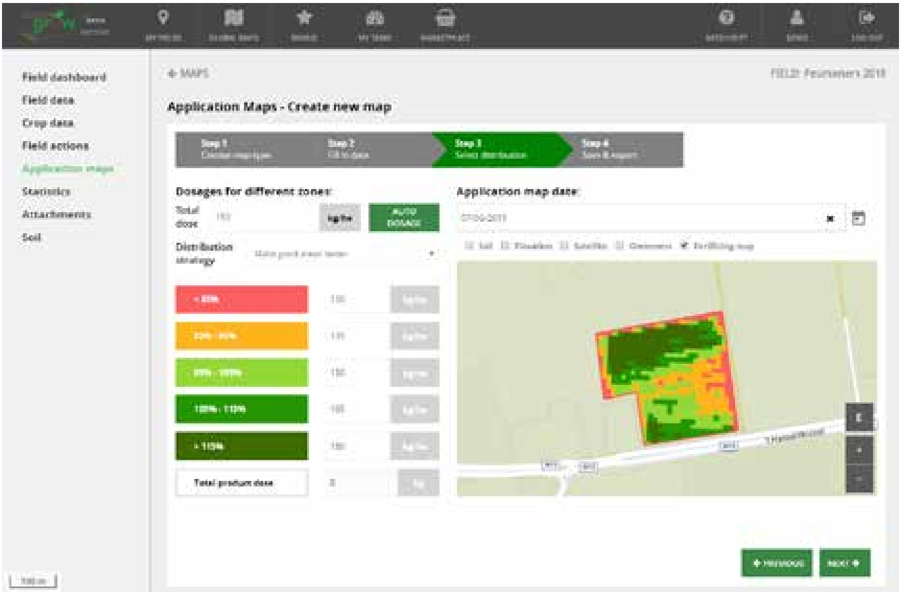
WatchITgrow provides information on crop growth and development as observed from Sentinel-2 satellite images. Light reflectances measured by the satellite sensor are converted into fAPAR (fraction of absorbed Photosynthetically Active Radiation). In WatchITgrow fAPAR is referred to as *greenness*. fAPAR is a measure of the crop's productivity and health and is often used as an indicator of the state and evolution of crop cover. Low greenness values indicate that there is no crop growing on the field (bare soil, fAPAR=0). When the crop emerges the greenness will increase until the crop has reached maturity (fAPAR=0.95-1.00). Then the index will decrease again until harvest. WatchITgrow produces new greenness maps every time the satellite passes. Archive images are available since July 2015. In addition to the maps, greenness graphs can be retrieved showing the fAPAR evolution throughout the season at field level. From this *growth curve* information on phenology and crop development can be derived.

The Sentinel satellites have a revisit frequency of 5 days, in some regions even every 2 to 3 days. The images have pixel sizes of 10x10m. Under cloud free conditions, the availability of such frequent high resolution satellite images allows a close follow up of the fields and an early detection of possible anomalies. The satellite shows a picture 'from above' and this may reveal variability in crop growth within the field which is not always visible when visiting the field from the road. The reasons for this variability can be diverse, however, and can include (natural) soil heterogeneity, climate induced problems such as drought or water logging and local damages due to pests or diseases, emergence problems, among others.

Satellite based information on variability within the field allows farmers to manage the fields more effectively. By accounting for the various zones detected within the field, more representative soil or crop samples can be taken. In WatchITgrow application maps can be generated for variable rate fertilization, irrigation and haulm killing, based on the satellite greenness. The farmer enters the product dose (fertilizer, water, herbicide, …) that he or she would normally apply on the field. The dose is then redistributed according to the differences in greenness detected from the satellite image (Figure 4). For N-fertilization, the farmer can choose between two strategies, either applying a higher dose of a fertilizer to zones with a higher greenness index or applying a lower dose to these zones. For farmers, variable rate applications are crucial in order to make cost savings in inputs, increase yields, and use their fields in a more sustainable way. Similarly, application maps can be created for variable rate planting, by accounting for the shadow zones within the field.

The current approach whereby variable rate application maps are based only on satellite greenness has some limitations. Satellite images may reveal variability within the field but to make sound decisions on how to respond to this variability it is important to find out what is causing the variability. Therefore it is recommended to combine satellite data with other sources of information such as soil maps or soil scans, elevation maps, weather data or field observations. Thanks to the knowledge gained in the POTENTIAL project we will be able to further improve this WatchITgrow component in the future.

Figure 4 Creating variable rate fertilization maps in WatchITgrow



As the satellite images cover large areas, they are ideal to *remotely* monitor fields which are located further away from the farm. They can also be used to compare and rank different fields with a region, from low to high greenness or vice versa. This information can then be used to organize field visits in a more efficient way, for instance by prioritizing fields that are showing greenness anomalies. During the harvest period information on the greenness of the fields can be useful for harvest planning and logistics.

Crop production is largely influenced by the weather. By monitoring temperature and rainfall, production risk or quality losses can be assessed. WatchITgrow offers maps showing temperature and rainfall deviations from the long term average. In addition, graphs can be retrieved showing the evolution of these meteorological variables at field level.

The WatchITgrow platform also provides access to basic information layers such as soil type, erosion risk and elevation maps. These may be helpful when trying to find the cause of variability in crop growth within a field. Further, information on the field history is provided, showing the main crops that have been grown on the fields since 2013.

WatchITgrow also includes a field registration tool. The platform can be used to store and exchange field data in a digital way. This may include basic information such as the variety, planting date, date of haulm killing, harvest date or more specific information on application of fertilizers, pesticides, irrigation, or on damage assessed at the field. Yield data collected via WatchITgrow are used to train yield forecasting models. Important to note is that the farmer remains the owner of the data at all times. He or she decides whether to share these data or not with advisors, contractors, buyers.

The final objective of WatchITgrow is to combine the various data sources (satellite, weather, soil, field data, ...) using new technologies such as big data analytics and machine learning to provide farmers with personalized advice to increase their yields.

The WatchITgrow platform was developed in the frame of a research project, *iPot*, a collaboration between researchers from Flanders and Wallonia (VITO, CRA-W and ULg) together with the Belgian potato trade and processing industry association *Belgapom*. After the research phase, the platform became operational in 2017 and was rebranded as *WatchITgrow*. WatchITgrow is an independent platform, hosted by VITO, guaranteeing data-privacy, data-security and data access. It is freely accessible after registration at www.watchitgrow.be. Since 2018 VITO receives funding from Belgapom and the Flemish farmers' organization *Boerenbond* to further improve the application and integrate new features. Both organizations are actively promoting the platform among the farmers in the context of the "digitalization of agriculture" in Belgium. VITO is also involved in several Flemish projects such as POTENTIAL, PPIDD, WikiLeeks, Irrigatie 2.0, as well as in European projects, ensuring the further development of the platform. In collaboration with various partners such as the Soil Service of Belgium, AVR, Inagro, ILVO, … new data layers, improved products and tools have been added, integrating the results of common research projects and using the latest Big Data and cloud processing technologies. Although the platform was initially oriented towards potato monitoring, WatchITgrow can now be used for monitoring a broad range of arable crops, vegetables and grasslands. Since 2017 more than 800 users registered on WatchITgrow, including farmers, traders, processing companies, suppliers, contractors, advisors, researchers, … In 2019, about 1700 Belgian fields, approximately 8000 hectares, were monitored with WatchITgrow. The platform is currently being extended to enable monitoring of fields across the border with the neighboring countries (France, the Netherlands and Germany).

4.2 THE NETHERLANDS

Akkerweb (www.akkerweb.eu) is an online platform from Wageningen University and Research. Scientific results are translated to applications useful for variable rate applications. Akkerweb provides access to external data sources as weather, parcel boundaries, satellite and farm management data. It stores georeferenced data like soil maps and drone images. Applications translate these data to recommendations and prescription maps for field work, like spraying machines or spreaders (Van Evert et al. 2018). Most applications work on absolute recommendation models, whereas other platforms rely on relative prescription maps, where the farmer can only distribute his inputs more effectively. Apps useful for the cultivation of potato are Haulm Killing App (variable rate of haulm killing herbicides, based on satellite or drone images), N-fertilizer app (variable rate of N-fertilizer based on satellite, drone images, a growth model and weather) and Late Blight App (based on weather data better scheduling of crop protection for late blight) (Kempenaar et al. 2018).

Figure 5 Screenshot of the N-sidedress App on Akkerweb which shows a N-Fertilizer recommendation based on satellite data for the Van den Borne field of 2018.

5 //
Experiments

During the POTENTIAL project, between 2017 and 2019, 11 experimental fields were set up in Belgium, 3 in the Netherlands and 3 in Denmark. In the experiments two different setups were used. On a part of the experimental fields a variation in water and N status was induced by applying varying doses of irrigation and fertilization. In another experiment the variation in the field was studied, without adding extra degrees of variation in water or nutrient input.

Hose reel irrigator installed in potato field.

FIELDNR	YEAR	LOCATION	FARMER	POTATO VARIETY	GROWING PERIOD
1	2017	Belgium	Van Eyck	Zorba	09/04/2017-17/08/2017

AIM	Achieve maximal variation in water and N status in the crop trough the field
Treatments	Four treatments were set up with a variation on irrigation and N-fertilizer dose, with as aim to achieve a variation in water and N-status trough the field: • **No mineral N-fertilizer**, only organic fertilizer (11 ton pig slurry (0.53%N)) and **deficit irrigated** (35 mm irrigation spread over two irrigation events)) • **No mineral N-fertilizer**, only organic fertilizer (11 ton pig slurry (0.53%N)) and **full irrigated** (102 mm irrigation spread over four irrigation events) • **Optimal N-fertilization**, organic fertilizer (11 ton pig slurry (0.53%N)) combined with 250 kg CAN (Calcium ammonium nitrate (27% (w/w) total nitrogen of which 13.5% (w/w) NO_3-N and 13.5% (w/w) NH4-N)) and **deficit irrigated** • **Optimal N-fertilization**, organic fertilizer (11 ton pig slurry (0.0053%N)) combined with 250 kg CAN and **full irrigated** Treatments were set up in a split plot design, with four observation plots in each treatment.
Observations	**In situ soil observations** per observation plot: Soil water retention characteristics, %C content, pH, soil moisture (7 time steps), NO_3-N content in soil (7 time steps) **In situ plant observations** per observation plot: Stomatal conductance (4 time steps) **Potato yield** per observation plot. N exported by the crop, by measuring N content in the foliage and the tubers. **Drone flights** were organized at 5 moments during the season whereby images were taken with a RGB and multispectral camera. At 2 moments hyperspectral and thermal images were acquired as well. The following indices were derived: fCover, NDVI, NDRE, OSAVI, CIgreen and CIrededge, and a digital surface model (DSM) was generated. **Sentinel-2 satellite images** were obtained every 2-3 days during the season via the Terrascope platform. The following indices were derived: fCover, NDVI, NDRE, CIgreen, CIrededge, fAPAR, LAI, CCC, CWC, MSI, NDII, RVI. **EMI Soil scan:** The field was scanned with EMI systems that measure simultaneously apparent electrical conductivity (ECa) [mS/m], i.e., weighted average over 9 depth ranges between 0-0.25 m and 0-2.7 m. **Yara N plant scan** executed 14/06/2017
Lay out of the field	 Figure 6 Map with indication of 16 observation plots, 4 plots per treatment lay out in a split plot design as indicated above

FIELDNR	YEAR	LOCATION	FARMER	POTATO VARIETY	GROWING PERIOD
2	2017	Belgium	Peurteners	Felsina	14/04/2017-01/09/2017

AIM	Study spatial variation in the field
Treatments	No specific treatments, fertilization (20 ton cattle slurry, 120 kg N trough mineral fertilizer) and irrigation (110 mm irrigation spread over 4 irrigation events) according to farmers practices.
Observations	**In situ soil observations** per observation plot: Soil water retention characteristics, %C content, pH, soil moisture (5 time steps), NO_3-N content in soil (5 time steps) **Potato yield** per plot. N exported by the crop, by measuring N content in the foliage and the tubers. **Drone flights** were organized at 3 moments during the season whereby images were taken with a RGB and multispectral camera. The following indices were derived: fCover, NDVI, NDRE, OSAVI, CIgreen and CIrededge, and a DSM was generated. **Sentinel-2 satellite images** were obtained every 2-3 days during the season via the Terrascope platform. The following indices were derived: fCover, NDVI, NDRE, CIgreen, CIrededge, fAPAR, LAI, CCC, CWC, MSI, NDII, RVI. **EMI Soil scan:** The field was scanned using EMI (CMD-MiniExplorer and CMD-MiniExplorer Special Edition GF-Instruments, Czech republic). The combination of these two devices in measures the apparent electrical conductivity (ECa) simultaneously over nine depth ranges between 0-0.25 m and 0-2.7 m.
Lay out of the field	 Figure 7 **Map with indication of 8 observation plots scattered over the field**

<table>
<tr><th>FIELDNR</th><th>YEAR</th><th>LOCATION</th><th>FARMER</th><th>POTATO VARIETY</th><th>GROWING PERIOD</th></tr>
<tr><td>3</td><td>2017</td><td>Belgium</td><td>Van Oeckel</td><td>Fontane
(partly replanted with Markies)</td><td>14/04/2017-01/09/2017</td></tr>
</table>

<table>
<tr><th>AIM</th><th>Study spatial variation in the field, similar as field 2</th></tr>
<tr><td>Treatments</td><td>No specific treatments, fertilization and irrigation (25 mm, 1 irrigation event) according to farmers practices.</td></tr>
<tr><td>Observations</td><td>**In situ soil observations** per observation plot: Soil water retention characteristics, %C content, pH, soil moisture (5 time steps), NO_3-N content in soil (5 time steps)
Potato yield per plot. N exported by the crop, by measuring N content in the foliage and the tubers.
Drone flights were organized at 3 moments during the season whereby images were taken with a RGB and multispectral camera. The following indices were derived: fCover, NDVI, NDRE, OSAVI, CIgreen and CIrededge, and a DSM was generated.
Sentinel-2 satellite images were obtained every 2-3 days during the season via the Terrascope platform. The following indices were derived: fCover, NDVI, NDRE, CIgreen, CIrededge, fAPAR, LAI, CCC, CWC, MSI, NDII, RVI.
EMI Soil scan: The field was scanned using EMI (CMD-MiniExplorer and CMD-MiniExplorer Special Edition GF-Instruments, Czech republic). The combination of these two devices in measures the apparent electrical conductivity (ECa) simultaneously over nine depth ranges between 0-0.25 m and 0-2.7 m. Preliminary ERT measurements on 1 transect to assess feasibility and experimental design necessary.
Yara N plant scan executed 14/06/2017</td></tr>
<tr><td>Lay out of the field</td><td>
Figure 8 Map with indication of 9 observation plots scattered over the field</td></tr>
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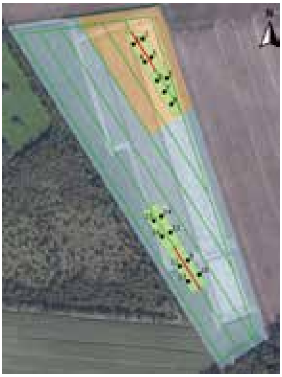
FIELDNR	YEAR	LOCATION	FARMER	POTATO VARIETY	GROWING PERIOD
4	2017	The Netherlands	Van Den Borne	Fontane	16/04/2017-02/10/2017

AIM	Achieve maximal variation in water and N status in the crop trough the field
Treatments	Four treatments were set up with a variation on irrigation and N-fertilizer dose, with as aim to achieve a variation in water and N-status trough the field: • **No mineral N-fertilizer**, only organic fertilizer (40 ton cattle slurry) and **deficit irrigated** (No irrigation) • **No mineral N-fertilizer**, only organic fertilizer (40 ton cattle slurry) and **full irrigated** (150 mm irrigation spread over six irrigation events) • **Optimal N-fertilization**, organic fertilizer (40 ton cattle slurry) combined with 59 kg N/ha mineral fertilizer and **deficit irrigated** (No irrigation) • **Optimal N-fertilization**, organic fertilizer (40 ton cattle slurry) combined with 59 kg N/ha mineral fertilizer and **full irrigated** Treatments were set up in a split plot design, with four observation plots in each treatment.
Observations	**In situ soil observations** per observation plot: Soil water retention characteristics, %C content, pH, soil moisture (6 time steps), NO_3-N content in soil (6 time steps) **In situ plant observations** per observation plot: Stomatal conductance (2 time steps) **Potato yield** per observation plot. N exported by the crop, by measuring N content in the foliage and the tubers. In addition potato yield was automatically registered on the harvesting machine. **Drone flights** were organized with a Micasense, instead of a eBee as used by VITO by the experiments on field 1, 2 and 3. **Sentinel-2 satellite images** were obtained every 2-3 days during the season via the Terrascope platform. The following indices were derived: fCover, NDVI, NDRE, CIgreen, CIrededge, fAPAR, LAI, CCC, CWC, MSI, NDII, RVI. **EMI Soil scan:** The field was scanned using EMI (CMD-MiniExplorer and CMD-MiniExplorer Special Edition GF-Instruments, Czech republic). The combination of these two devices in measures the apparent electrical conductivity (ECa) simultaneously over nine depth ranges between 0-0.25 m and 0-2.7 m. Preliminary ERT measurements on 1 transect to assess feasibility and experimental design necessary
Lay out of the field	 Figure 9 **Map with indication of 16 observation plots, 4 plots per treatment lay out in a split plot design as indicated above.**

FIELDNR	YEAR	LOCATION	FARMER	POTATO VARIETY	GROWING PERIOD
5	2017	Denmark	AU-Foulum	Oleva	11/05/2017-31/11/2017

AIM	Study and disentangle N and water stress and design variable rate irrigation and fertilization scheme for potato crop on coarse sandy soil

Treatments

Five treatments were set up with a variation on irrigation and N-fertilizer dose in a randomised factorial design (Irrigation x Fertilization, I x F), plot size 30 m x 30 m, four replicates:

- **I0 = full irrigation** (65 mm), when 90% of available soil moisture (pF2.0 – pF3.0) has been depleted (irrigated when soil water content is ca. 25 mm below field capacity)
- **I1 = low irrigation** (10 mm), when available soil moisture pF2.0 – pF2.4 has been depleted
- **I2 = variable rate** (50 mm), as I0 but site-specific, accounting for differences in available soil water content between subplots.
- **N1 = full fertilization**, 260 kg N ha^{-1} (24 kg N ha^{-1} expected soil min + 86 kg N ha^{-1} from chicken manure and pig slurry as starter + additional 150 kg N ha^{-1} as calcium ammonium nitrate to fill max legal quota)
- **N2 = variable rate**, 166-186 kg N ha^{-1} (24 kg N ha^{-1} expected soil min + 86 kg N ha^{-1} from chicken manure and pig slurry as starter + additional 56-76 kg N ha^{-1} as liquid NtS 24-6 guided by sensor monitoring according to Zhou et al. (2017)).

Fertilizer N response plots were also established:
N0, N100, N180, N240 and N300, corresponding to 0, 100, 180, 240 and 300 kg N ha^{-1} as calcium ammonium nitrate.

Observations

In situ soil observations per observation plot: weekly measurements of soil water (SWC).

In situ plant observations per observation plot: weekly measurements crop phenological development, leaf area index (LAI) and canopy reflectance. One measurement of stomatal conductance (LSC) due to wet year.

Plant sampling: one in-season and one at-harvest sampling of fresh and dry weight and N content of aboveground biomass and tubers.

Drone and satellite images: few images were collected using drone and Sentinel2 (for cloud-free days), which were very few in 2017 due to much precipitation.

Lay out of the field

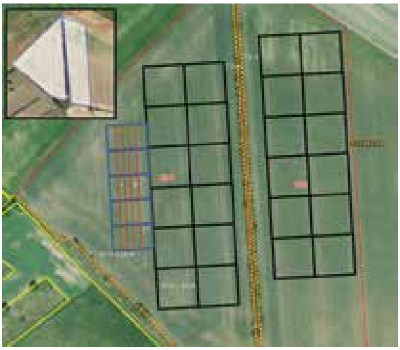


Figure 10 lay out of the experimental field

FIELDNR	YEAR	LOCATION	FARMER	POTATO VARIETY	GROWING PERIOD
6	2018	Belgium	Peurteners	Fontane	03/05/2018-27/09/2018

AIM — **Achieve maximal variation in water and N status in the crop trough the field**

Treatments

Four treatments were set up with a variation on irrigation and N-fertilizer dose, with as aim to achieve a variation in water and N-status trough the field:

- **No mineral N-fertilizer**, only organic fertilizer (35 ton cattle slurry (0.41%N)) and **full irrigated** (210 mm spread over 7 irrigation events)
- **Optimal N-fertilization**, organic fertilizer (35 ton cattle slurry (0.41%N)) combined with 500 kg CAN (Calcium ammonium nitrate (27% (w/w) total nitrogen of which 13.5% (w/w) NO_3-N and 13.5% (w/w) NH4-N)) and **deficit irrigated** (no irrigation)
- **Optimal N-fertilization**, organic fertilizer (11 ton pig slurry (0.0053%N)) combined with 500 kg CAN and **full irrigated**
- **Excessive N-fertilization**, organic fertilizer (11 ton pig slurry (0.0053%N)) combined with 1000 kg CAN and **full irrigated**

Treatments were set up in a split plot design, with five observation plots in each treatment.

Observations

In situ soil observations per observation plot: Soil water retention characteristics, %C content, pH, soil moisture (7 time steps), NO_3-N content in soil (7 time steps)

In situ plant observations per observation plot: Stomatal conductance (5 time steps)

Potato yield per plot. N exported by the crop, by measuring N content in the foliage and the tubers.

Drone flights were organized at 6 moments during the season whereby images were taken with a RGB and multispectral camera. At 1 moment hyperspectral and thermal images were acquired as well. The following indices were derived: fCover, NDVI, NDRE, OSAVI, CIgreen and CIrededge, and a DSM was generated.

Sentinel-2 satellite images were obtained every 2-3 days during the season via the Terrascope platform. The following indices were derived: CIgr, CIr, CWC, LAI, CCC, fCover, fAPAR, MSI, NDVI, NDWI and NDRE.

EMI Soil scan: The field was scanned using EMI (CMD-MiniExplorer and CMD-MiniExplorer Special Edition GF-Instruments, Czech republic). The combination of these two devices in measures the apparent electrical conductivity (ECa) simultaneously over nine depth ranges between 0-0.25 m and 0-2.7 m. Preliminary ERT measurements on 1 transect to assess feasibility and experimental design necessary

Lay out of the field

Figure 11 Map with indication of 20 observation plots,
4 plots per treatment lay out in a split plot design as indicated above

FIELDNR	YEAR	LOCATION	FARMER	POTATO VARIETY	GROWING PERIOD
7	2018	Belgium	Van Eyck	Zorba	14/04/2018-10/08/2018
AIM	**Study spatial variation in the field, similar as field 2**				
Treatments	No specific treatments, fertilization and irrigation (190 mm spread over 7 irrigation events) according to farmers practices.				
Observations	**In situ soil observations** per observation plot: Texture analysis, Soil water retention characteristics, %C content, pH, soil moisture (7 time steps), NO_3-N content in soil (7 time steps). **Potato yield** per observation plot. N exported by the crop, by measuring N content in the foliage and the tubers. **Drone flights** were organized at 4 moments during the season whereby images were taken with a RGB and multispectral camera. The following indices were derived: fCover, NDVI, NDRE, OSAVI, CIgreen, CIrededge and temperature, and a DSM was generated. **Sentinel-2 satellite images** were obtained every 2-3 days during the season via the Terrascope platform. The following indices were derived: CIgr, CIr, CWC, LAI, CCC, fCover, fAPAR, MSI, NDVI, NDWI and NDRE. **EMI Soil scan:** The field was scanned using EMI (CMD-MiniExplorer and CMD-MiniExplorer Special Edition GF-Instruments, Czech republic). The combination of these two devices in measures the apparent electrical conductivity (ECa) simultaneously over nine depth ranges between 0-0.25 m and 0-2.7 m. Preliminary ERT measurements on 1 transect to assess feasibility and experimental design necessary. In addition EMI transects were scanned regularly. **Resin cores** were buried on 4 plots to study leaching of nitrogen. **ERT observations on 4 transects** (ridge, furrow) + 1 transversal to ridges). Soil water monitoring with sensors close to ERT transects. **Yara N plant scan** executed 8/06/2018.				
Lay out of the field	 Figure 12 **Map with indication of 10 observation plots scattered over the field**				

FIELDNR	YEAR	LOCATION	FARMER	POTATO VARIETY	GROWING PERIOD
8	2018	The Netherlands	Van Den Borne	Fontane	28/04/2018-26/10/2018

AIM	Demonstrate potential of variable rate application of water and N-fertilizer sidedress

Treatments

Three treatments were set up with a variation on irrigation and N-fertilizer dose

- **Variabel dose (80, 100 and 120%) of water and mineral N-fertilizer**
  Standard dose of water was 7 irrigation events with total of 160mm/ha.
  Fertilizer was organic fertilizer (50 ton cattle slurry) and 160 kg N mineral fertilizer, combined with a standard topdress dose of mineral (=100%) 23 kg N/ha fertilizer
- **Standard dose (100%) of water and N-fertilizer**
- **Variable dose (80 and 120%) of water, standard dose of mineral N-fertilizer**
- **No irrigation and standard dose of mineral N-fertilizer**

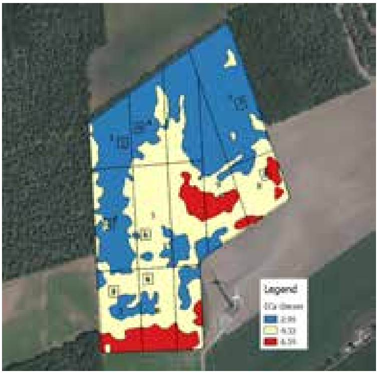
Treatments were set up as a demo in one repetition and with 3 observation plots in each treatment.

Observations

Similar to field 1, although potato yield was automatically registered on the harvesting machine. Drone information was assembled with a Micasense, instead of a eBee as used by VITO by the experiments on field 1, 2 and 3.

Lay out of the field

T=N-top dress, I= Irrigation



PLOT	OBJECT	RATE%	N-TOPDRESS
1	VRA I+T	120	41
2	VRA I+T	100	23
3	VRA I+T	80	35
4	Standard I+T	100	29
5	Standard I+T	100	29
6	Standard I+T	100	29
7	VRA I+T	120	29
8	VRA I+T	80	29
9	No I	0	29

Figure 13 **Map of experimental field with indication of the treatments**

FIELDNR	YEAR	LOCATION	FARMER	POTATO VARIETY	GROWING PERIOD
9	2018	Denmark	AU-Foulum	Oleva	04/05/2018-07/11/2018

AIM	Study and disentangle N and water stress and design variable rate irrigation and fertilization scheme for potato crop on coarse sandy soil

Treatments

Five treatments were set up with a variation on irrigation and N-fertilizer dose in a randomised factorial design (Irrigation x Fertilization, I x F), plot size 30 m x 32 m, four replicates:

- I0 = **full irrigation** (205 mm), when 90% of available soil moisture (pF2.0 – pF3.0) has been depleted (irrigated when soil water content is ca. 25 mm below field capacity)
- I1 = **low irrigation** (15 mm), when available soil moisture pF2.0 – pF2.4 has been depleted
- I2 = **variable rate** (135), as I0 but site-specific, accounting for differences in available soil water content between subplots.
- N1 = **full fertilization**, 241 kg N ha^{-1} (45 kg N ha^{-1} expected soil min + 56 kg N ha^{-1} from pig slurry as starter + additional 140 kg N ha^{-1} as calcium ammonium nitrate to fill max legal quota)
- N2 = **variable rate**, 161 (-201) kg N ha^{-1} (45 kg N ha^{-1} expected soil min + 56 kg N ha^{-1} from pig slurry + additional 60 kg N ha^{-1} as calcium ammonium nitrate as starter + 40 kg N ha^{-1} liquid NtS 24-6 guided by sensor monitoring according to Zhou et al. (2017)).

Fertilizer N response plots also established: N0, N100, N180, N240 and N300, corresponding to 0, 100, 180, 240 and 300 kg N ha^{-1}.

Observations

In situ soil observations: weekly measurements of soil water (SWC), bi-weekly measurements of soil nitrate contents

In situ soil observations: weekly measurements crop phenological development, leaf area index (LAI), canopy reflectance, and water potential (LWP), stomatal conductance (LSC) in July-August.

Plant sampling: Dry matter and N content of aboveground material and tubers (four times during growth season and at final harvest).

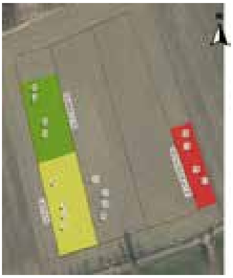
Plant scan: bi-weekly measurements with tractor mounted sensor for SWC, canopy reflectance and LAI.

Drone and satellite images: weekly to bi-weekly multispectral and thermal images collected in parallel using drone and Sentinel2 (downloaded for cloud-free days).

Lay out of the field

Figure 14 **Lay out of experimental fields in Denmark in 2017, 2018 and 2019**

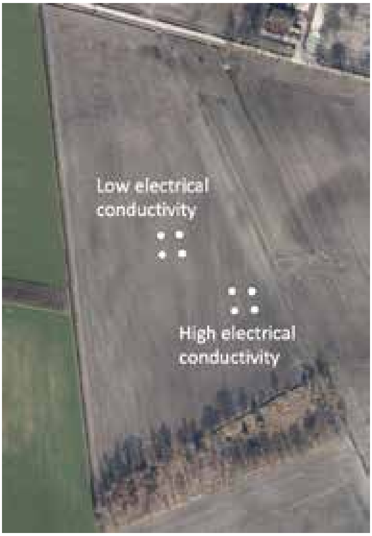
FIELDNR	YEAR	LOCATION	FARMER	POTATO VARIETY	GROWING PERIOD
10	2019	Belgium	Van Eyck	Felsina	1/04/2019-8/08/2019

AIM	Achieve maximal variation in water and N status in the crop trough the field
Treatments	Four treatments were set up with a variation on irrigation and N-fertilizer dose, with as aim to achieve a variation in water and N-status trough the field: • **No mineral N-fertilizer**, organic fertilizer (15 ton cattle slurry and 30 ton cattle manure) and **full irrigated** (147.5 mm spread over 5 irrigation events) • **Optimal N-fertilization**, organic fertilizer (15 ton cattle slurry and 30 ton cattle manure) combined with 380 kg Urea (30% (w/w) total nitrogen of which 7.3% (w/w) NO_3-N, 7.3% (w/w) NH4-N and 15.4% (w/w) Urea-N)) and 122 kg CAN (Calcium ammonium nitrate (27% (w/w) total nitrogen of which 13.5% (w/w) NO_3-N and 13.5% (w/w) NH4-N)); **deficit irrigated** (no irrigation) • **Optimal N-fertilization**, organic fertilizer (15 ton cattle slurry and 30 ton cattle manure) combined with 380 kg Urea and 122 kg CAN; **full irrigated** • **Excessive N-fertilization**, organic fertilizer (15 ton cattle slurry and 30 ton cattle manure) combined with 760 kg Urea and 244 kg CAN; **full irrigated** Treatments were set up in a split plot design, with four observation plots in each treatment.
Observations	**In situ soil observations** per observation plot: Soil water retention characteristics, %C content, pH, soil moisture (7 time steps), NO_3-N content in soil (7 time steps) **In situ plant observations** per plot: Stomatal conductance (4 time steps) Potato yield per observation plot. N exported by the crop, by measuring N content in the foliage and the tubers. **Drone flights** were organized at 8 moments during the season whereby images were taken with a RGB and multispectral camera. The following indices were derived: fCover, NDVI, ReNDVI, OSAVI, CIgreen and CIrededge, and a DSM was generated. **Sentinel-2 satellite images** were obtained every 2-3 days during the season via the Terrascope platform. The following indices were derived: CIgr, CIr, CWC, LAI, CCC, fCover, fAPAR, MSI, NDVI, NDWI and NDRE. **EMI Soil scan**: The field was scanned with EMI systems that measure simultaneously apparent electrical conductivity (ECa) [mS/m], i.e., weighted average over 9 depth ranges between 0-0.25 m and 0-2.7 m. **Yara N plant scan** executed 10/06/2019.
Lay out of the field	 Figure 15 **Map with indication of 16 observation plots, 4 plots per treatment lay out in a split plot design as indicated above**

FIELDNR	YEAR	LOCATION	FARMER	POTATO VARIETY	GROWING PERIOD
11	2019	Belgium	Peurteners	Zorba	13/04/2019-5/08/2019

AIM	Study spatial variation in the field, similar as field 2
Treatments	No specific treatments, fertilization (25 ton pig slurry combined with 400 kg CAN) and irrigation (148 mm spread over 5 irrigation events) according to farmers practices.
Observations	**In situ soil observations** per observation plot: Soil water retention characteristics, %C content, pH, soil moisture (8 time steps), NO_3-N content in soil (8 time steps) **In situ plant observations** per observation plot: Stomatal conductance (3 time steps) **Potato yield** per plot. N exported by the crop, by measuring N content in the foliage and the tubers. **Drone flights** were organized at 8 moments during the season whereby images were taken with a RGB and multispectral camera. The following indices were derived from the drone images: fCover, NDVI, ReNDVI, OSAVI, CIgreen and CIrededge, and a digital surface model was generated. **Sentinel-2 satellite images** were obtained every 2-3 days during the season via the Terrascope platform. The following indices were derived from the Sentinel-2 satellite images: CIgr, CIr, CWC, LAI, CCC, fCover, fAPAR, MSI, NDVI, NDWI and NDRE. **EMI Soil scan**: The field was scanned with EMI systems that measure simultaneously apparent electrical conductivity (ECa) [mS/m], i.e., weighted average over 9 depth ranges between 0-0.25 m and 0-2.7 m. **Yara N plant scan** executed 10/06/2019.
Lay out of the field	 Figure 16 **Map with indication of 12 observation plots scattered over the field**

FIELDNR	YEAR	LOCATION	FARMER	POTATO VARIETY	GROWING PERIOD
12	2019	The Netherlands	Van Den Borne	Fontane	05/05/2019-24/10/2019

AIM	Study potential of different irrigation management zones
Treatments	Two treatments were set up with a variation on irrigation • **Zone with low electrical conductivity with higher water demand:** 6 irrigation events and total 180 mm • **Zone with high electrical conductivity with lower water demand:** 6 irrigation events and total 165 mm Treatments were set up as a demo in one repetition and with 4 observation plots in each treatment.
Observations	Similar to field 1, although potato yield was automatically registered on the harvesting machine. Drone information was assembled with a Micasense, instead of a eBee as used by VITO by the experiments on field 1, 2 and 3.
Lay out of the field	 Figure 17 **Map of experimental field with indication of zone with high and low conductivity**

FIELDNR	YEAR	LOCATION	FARMER	POTATO VARIETY	GROWING PERIOD
13	2019	Denmark	AU-Foulum	Oleva	07/05/2019-31/10/2019

AIM	Study and disentangle N and water stress and design variable rate irrigation and fertilization scheme for potato crop on coarse sandy soil
Treatments	Five treatments were set up with a variation on irrigation and N-fertilizer dose in a randomised factorial design (Irrigation x Fertilization, I x F), plot size 30 m x 30 m, four replicates: • I0 = **full irrigation** (154 mm), when 90% of available soil moisture (pF2.0 – pF3.0) has been depleted (irrigated when soil water content is ca. 25 mm below field capacity) • I1 = **low irrigation** (30 mm), when available soil moisture pF2.0 – pF2.4 has been depleted • I2 = **variable rate** (103), as I0 but site-specific, accounting for differences in available soil water content between subplots. • N1 = **full fertilization**, 237 kg N ha^{-1} (41 kg N ha^{-1} expected soil min + 56 kg N ha^{-1} from pig slurry as starter + additional 140 kg N ha^{-1} as calcium ammonium nitrate to fill max legal quota) • N2 = **variable rate**, 177 kg N ha^{-1} (41 kg N ha^{-1} expected soil min + 56 kg N ha^{-1} from pig slurry as starter + additional 40 and 40 kg N ha^{-1} as liquid NtS 24-6 guided by sensor monitoring according to Zhou et al. (2017)). Fertilizer N response plots also established: N0, N100, N180, N240 and N300, corresponding to 0, 100, 180, 240 and 300 kg N ha^{-1}.
Observations	**In situ soil observations**: weekly measurements of soil water (SWC), bi-weekly measurements of soil nitrate contents **In situ plant observations**: weekly measurements crop phenological development, three measurements of leaf water potential (LWP) and stomatal conductance (LSC) in July. **Plant sampling**: dry matter and N content of aboveground material and tubers (four times during growth season and at final harvest). **Plant scan**: bi-weekly measurements with tractor mounted sensor (time-domain reflectometer probes) for SWC, canopy reflectance (RapidScan, Holland Scientific, USA) and LAI. **Drone and satellite images**: weekly to bi-weekly multispectral and thermal images collected in parallel using drone and Sentinel2 (downloaded for cloud-free days).
Lay out of the field	**See Figure 14 for layout of the field**

6 //

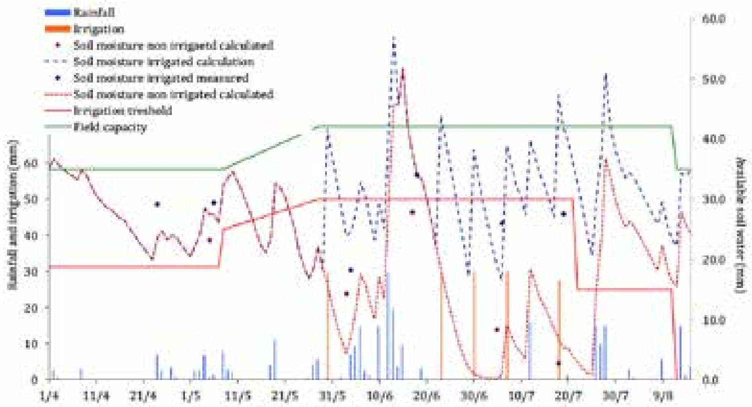
Quantification of the water and N deficit at the experimental fields using in-situ measurements

6.1 QUANTIFICATION OF THE WATER DEFICIT WITH IN-SITU MEASUREMENTS

6.1.1 Belgium

Irrigation on the trial fields was scheduled using the soil water balance, as described in paragraph 3. The difference in soil moisture between the irrigated and non irrigated treatments was clearly visible in 2017, 2018 and 2019 (Figure 18). In al years total evapotranspiration exceeded total rainfall during the growing season.

Figure 18 Soil water balance of irrigated and non irrigated treatment of field 10 in Belgium in 2019.



For comparison with drone and satellite imagery water deficit was quantified by observations of stomatal conductance. Stomatal closure is a crop response related to water deficit in the soil. Stomatal closure was monitored with a porometer (Decagon Devices, 2010) in experimental Fields 1, 4, 6, 10 and 11 (see paragraph 5). During the POTENTIAL project stomatal closure could be related to soil moisture content (Figure 19) and to crop yield (Figure 20).

Figure 19 Relation between average soil moisture and average stomatal conductance on Field 1 (Belgium, 2017). Average was calculated over four observations during the growing season (a); Relation between average soil moisture and average stomatal conductance on Field 6 (Belgium, 2018). Average was calculated over four observations during the growing season (b) and Relation between average soil moisture and average stomatal conductance on Field 10 (Belgium, 2019). Average was calculated over four observations during the growing season (c).

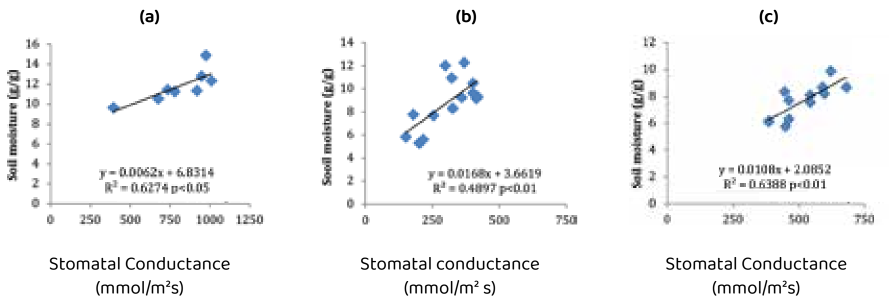
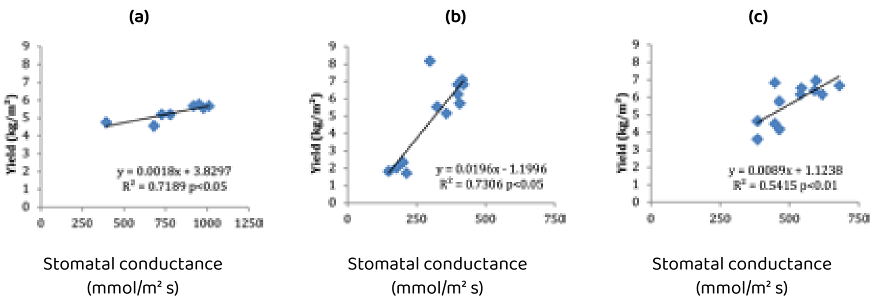


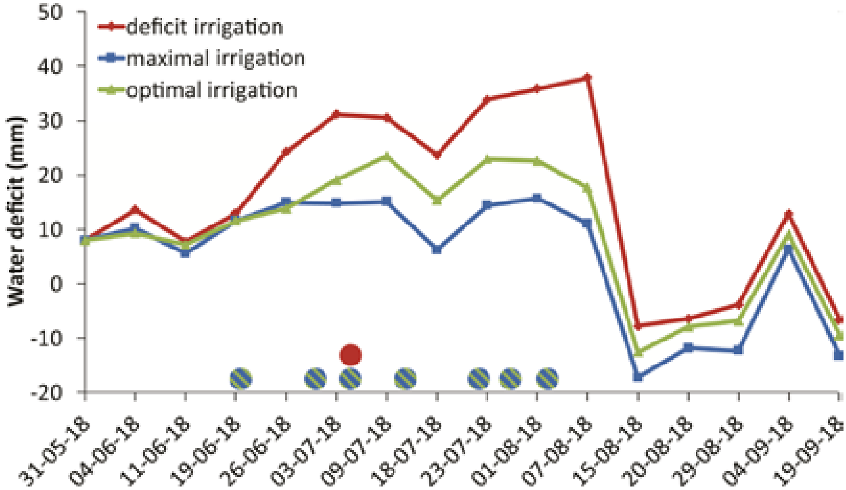
Figure 20 Relation between yield and average stomatal conductance on Field 1 (Belgium, 2017). Average was calculated over four observations during the growing season (a); relation between yield and average stomatal conductance on Field 6 (Belgium, 2018). Average was calculated over four observations during the growing season (b) and relation between yield and average stomatal conductance on Field 10 (Belgium, 2019). Average was calculated over four observations during the growing season (c).



6.1.2 Denmark

In the Danish potato field trials, water deficit was quantified as the difference between the measured soil water content throughout the season and the soil water content at field capacity measured before the start of the experiment. Maximal (control, farmers practice) irrigation aimed to maintain field capacity and was applied when actual soil water was about 80% of the field capacity. Optimized irrigation aimed to apply smaller but more strategic amounts of water and was applied if actual soil water is about 70% of field capacity (spatially variable). Water stressed trials included irrigation only when soil water deficit does not change, i.e., when soil water content approached wilting point (Figure 21). The decision when to irrigate was also complemented with the weather forecast offered by the Danish Meteorological Institute.

Figure 21 **Average soil water deficit (difference between soil water content during the season and at field capacity) for the potato trials in Denmark in 2018. Irrigation decision was based on whether soil water deficit is about 90% of field capacity (maximal irrigation), about 30% of field capacity (optimized spatially variable irrigation), or towards reaching wilting point (deficit irrigation). Circles on x-axis (color according to trial) denote irrigation events.**

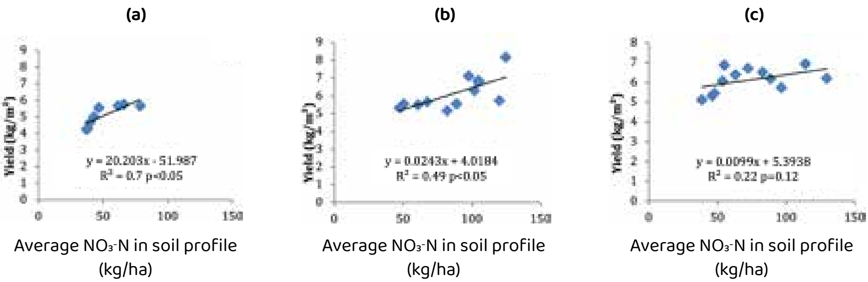


6.2 QUANTIFICATION OF THE NITROGEN DEFICIT

6.2.1 Belgium

In Belgium nitrogen deficit was quantified by NO_3-N concentration in the soil. NO_3-N content in the soil was measured 5 times during the growing season. Average NO_3-N concentration in the soil profile was correlated to tuber yield in Field 1, Field 6 and Field 10 in Belgium (Figure 22). These were the fields where fertilization experiments were set up.

Figure 22 Correlation between potato yield and average NO_3-N concentration, measured on 5 to 6 moments during the growing season, in the soil profile for Field 1 (a) in Belgium in 2017; for Field 6 (b) in Belgium in 2018 and for Field 10 (c) in Belgium.



Soil sampling

6.2.2 Denmark

For the field trials in Denmark, N deficit was quantified by the relationship between two canopy indices, ratio vegetation index (RVI) and leaf area index (LAI). A previous study showed that the RVI-LAI relationship developed for potato on field scale can be used to detect N stress and to guide N fertilization (Figure 23; Zhou et al., 2017). The RVI-LAI relationship was established from field measurements during the season in "N fertilizer response" trials (fertilizer range from 0 to 300 kg N ha^{-1}) and RVI was measured with a handheld multispectral sensor RapidScan C45 (Holland Scientific, USA), whereas LAI was measured by a LAI-2000 instrument (Li-Cor, Inc, Lincoln, NE, USA). The RVI-LAI relationship at field scale is shown on Figure 24, and this approach was used to guide fertilization decision (time and amount). However, the approach cannot be upscaled on drone- or satellite level because both LAI and RVI would be derived from the same reflectance data, thereby imposing the collinearity issue. Therefore, other indices from drone and Sentinel-2 data were investigated, as elaborated in the next chapters.

Measurements with the leaf porometer to determine stomatal conductance.

Figure 23 **Relationship between ratio vegetation index (RVI) and leaf area index (LAI) for potato trials in Denmark (Zhou et al., 2017). The relationship curve is flanked by ±95% confidence intervals, below which is the N deficiency area (as indicated by the red point).**

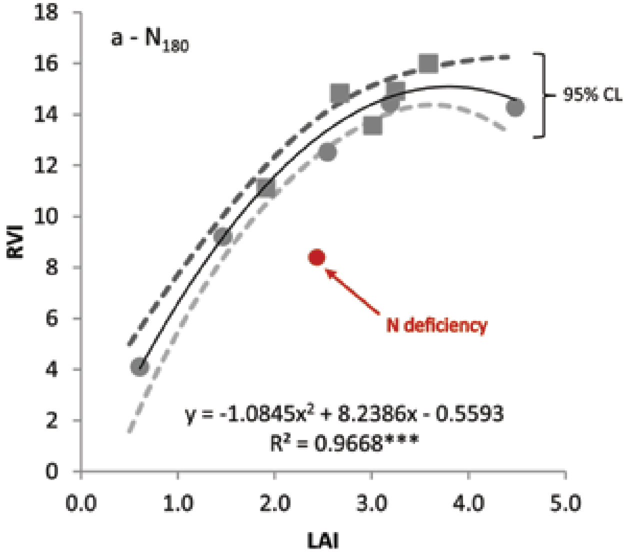
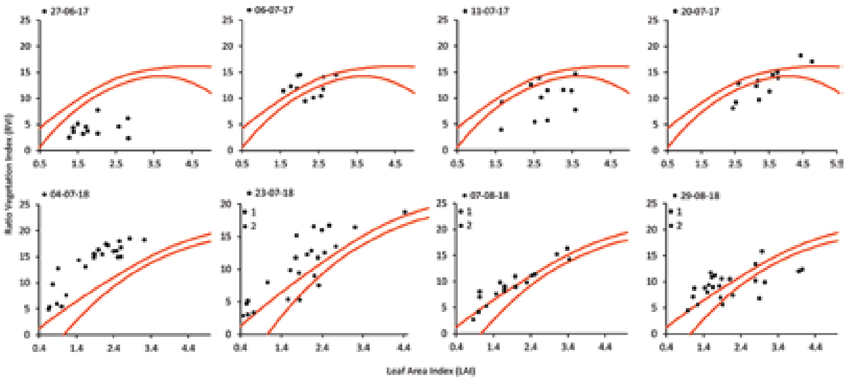


Figure 24 **Relationship between ratio vegetation index (RVI) and leaf area index (LAI) for the POTENTIAL field trials in Denmark in 2017 (upper plots) and 2018 (lower plots). The dots represent the experimental plots, the red line is the ±95% confidence levels of the relationship, below which is the N deficiency area. Fertilizer was applied 13-Jul 2017 and 03-Aug 2018.**



7 //
Potential of multispectral drone imagery

7.1 TYPES OF DRONES AND CAMERAS

7.1.1 The use of drones in agriculture

Practical applications for UAVs (unmanned aerial vehicles) or RPAS (Remotely Piloted Aerial Systems), commonly referred to as "drones", have progressed significantly in recent years. In particular for the agriculture sector, drones offer a range of opportunities.
Drones permit farmers to obtain a "birds-eye-view" of their fields "on-demand". Drone flights are carried out at low altitude, even in the event of cloud cover. The highly detailed images taken by the drones allow farmers to detect subtle, local changes in crop growth within the field that cannot always be identified by regular field visits at ground level. The changes in crop growth observable by drone imagery can be related to water stress or excess, nutrient deficiencies, pest infestations, crop diseases, or other conditions affecting crop development.
Drones can be equipped with various types of cameras to capture the light reflected by the crop below:

- **RGB cameras:**
  - Multipurpose, cheap cameras, capturing Red, Green, and Blue light.
  - The images are similar to what is seen with the human eye, meaning they are easy to interpret.
  - RGB images are useful to detect zones within the field with emergence problems or zones affected by pests, diseases or extreme weather events such as strong winds, hail (when damage is visible by the human eye).

    - RGB images can be used to count plants, calculate the percentage of soil cover (fCover) or get an idea of the crop's development stage.
    - RGB images have a better spatial resolution (compared to other image types discussed below, from the same flight height). This means that finer details are visible, and denser and more accurate 3D models can be derived from RGB imagery.

- **Multispectral cameras:**
    - Multispectral cameras capture light not only in the visible (RGB) but also in the infrared part of the light spectrum (the Red Edge and Near-InfraRed (NIR)). The infrared part of the light is not visible to the human eye, but is interesting for plant studies, as plants reflect more light in the infrared than they do in the visible part.
    - Multispectral refers to the fact that images are captured in a limited number of spectral bands, mostly between 3 and 6 bands of which the most common are the Red, Green, Red Edge and NIR bands.
    - Multispectral drone images reveal variation within the field in a quantitatively reliable way and can be used to generate variable rate prescriptions for nitrogen, pesticides, irrigation of other applications.
    - Well calibrated multispectral camera systems deliver images which can be compared over time.
    - The resolution of multispectral images (pixel size) is usually between 5 and 10 cm and hence slightly lower than for RGB images (< 3 cm).
    - By combining multispectral images "vegetation indices" can be derived. A simple and popular index computed from Red and NIR images is the NDVI. This index provides information on the crop's greenness or health. Other indices such as the red edge NDVI (NDRE) or red edge chlorophyll index (CIre) are particularly useful for early stress detection.
    - The position of the spectral bands differs between multispectral cameras. This is especially important for the very narrow red edge bands and can affect the interpretation of the resulting vegetation index maps based on these bands.

- **Hyperspectral cameras:**
  - Mostly experimental cameras, and today still rather expensive.
  - Hyperspectral cameras also capture images in the visible and infrared part of the light spectrum but compared to multi-spectral imaging, hyperspectral imaging involves a greater number of narrower spectral bands, sometimes more than 2000.
  - Hyperspectral images offer more opportunities to detect diseases in an early stage or to identify weeds by using information from very specific parts of the light spectrum.

- **Thermal cameras:**
  - Thermal sensors can read the radiated temperature of an object.
  - Plants with access to more water appear cooler in an image. As such a thermal sensor can help identify how plants are using water and detect drought stress.
  - Interpreting thermal images may be challenging though. Temperature variations within the image are sometimes minor and it may be difficult to distinguish drought stress from the other factors that might heat or cool the plant, such as breezes, sun exposure, etc.

Many types of drones are available today. Those suitable for agricultural applications fall into three categories: fixed-wing, multi-rotor and hybrid drones.

- **Fixed-wing drones:**
  - Small planes in the form of a non-movable wing and a propeller that facilitates forward movement.
  - These drones have long-range flight capacity, an advantage when a large area is to be covered.
  - They fly 2-3 times faster than multi-rotors and take much less time to cover a field compared to a multi-rotor at the same resolution and overlap
  - Fixed wing drones generally require more open space for take-off and landing. In practice, this often means that a neighboring grass field is needed for take-off and landing.
  - Fixed wing drones are generally more expensive than multi-rotors.

- **Multi-rotors:**
  - Small helicopters with 4 to 8 rotors
  - Multi-rotor drones can take off and land vertically and are therefore easier and faster to use within the field of interest itself.
  - Multi-rotors [KP6] can fly at lower altitudes to capture extremely detailed images.
  - Flight time is often limited to 15-20 minutes by the drone's battery life. Hence, only small areas can be covered in a single flight.

- **Hybrid drones:**
  - These drones resemble fixed wing drones but can take off and land vertically, by using tilting rotors or using a tail structure to stand vertically and transition into a horizontal cruise flight.
  - They combine the advantages of large coverage and within-field operation.
  - Being more complex, hybrid drones are still more expensive and are not yet fully recognized by Belgian law.

Operating a drone in Belgium is regulated by law. When flying a drone for non-recreational purposes, the Belgian law imposes a set of obligations on the drone operator and pilot that differ from the recreational restrictions. Drone pilots must be in possession of either a certificate or a remote pilot license, depending on whether the flight is in "class 2" (low risk: flights with light-weight drones < 5kg at low altitude <45m) or "class 1" (moderate / high risk: flights with heavier drones <150kg at higher altitude < 90m). For class 2 flights, a drone needs to be registered and the operators needs to be insured. Additionally, for class 1 flights an operations manual needs to be prepared and the flight must be notified to the BCAA before take-off.

Due to these strict regulations, the complexity that goes with the organization of a drone flight (defining the flight plan, setting correct flight parameters, …) and the relatively high cost price of a drone, few farmers purchase and operate their own drone. Most drone flights are carried out by professional drone operators who are paid by the farmer to perform the drone flights, process the images and deliver actionable information such as variable rate application maps to the farmer. The cost price of such a service – usually a fixed price per hectare per season – may be considerable and often 10 to 100 times more expensive than the cost of satellite data.

Most agriculture drone operators use standard (often cloud-based) processing tools to turn the hundreds of images captured by the drone camera into useful information for the farmer. Image processing can be complex, however, especially when flights took place under suboptimal weather conditions (partly cloudy or windy days) and may need some manual finetuning in order to get high quality results.

Summarized, the usage of drones can be relevant but merely for high value crops and small-holder farms, where it is required to have a high spatial resolution, and the average farm size is no more than 50-100 hectares (due to organizational constraints).

7.1.2 Drone images used in POTENTIAL

In the frame of POTENTIAL the following drone systems / cameras were used:

- **Belgium:**
    - RGB: SenseFly eBee + SODA camera, 2 cm GSD in ortho – 4 cm GSD in DSM
    - Multispectral: SenseFly eBee + Sequoia camera, 8 cm GSD[KP1]
    - Hyperspectral: AT Zenith + Cubert S 199 ButterflEYE LS camera: 91 bands from 475 to 925 nm (VIS-NIR), 5 cm GSD in DSM & hypercube
    - Thermal: AT Zenith + Workswell WIRIS camera 2,5 cm GSD

- **Netherlands:**
    - Multispectral: Micasense Multispec camera, 8 cm GSD
    - Thermal: FLIR camera

- **Denmark:**
    - DJI Matrice 100 drone with mounted RGB and multispectral camera Micasense Sequoia or Micasense Rededge
    - DJI Matrice 100 drone with mounted TAU 2 Thermal Camera

Processing using default settings in popular image processing software packages or using automated online processing services can be of interest to quickly generate some products to get a general understanding of a field for a specific date. However, processing datasets in a standardized way to enable consistent analyses over time and to ensure geometric and spectral data quality in every step requires expert knowledge.

The following products / indices were derived from the drone images:

- **Belgium:**
  - From RGB images: digital surface model (DSM), orthophoto's and fCover
  - From multispectral images: OSAVI
  - From multispectral and hyperspectral images: NDVI, ReNDVI, CIgr, CIre
  - From thermal images: temperature map

- **Denmark:**
  - From RGB images: digital surface model (DSM), orthophoto's and fCover
  - From multispectral images: numerous vegetation indices (NDVI, RVI, ReNDVI, CIgr, CIre and others)
  - From thermal images: temperature map

- **The Netherlands:**
  - From RGB images: digital surface model (DSM), orthophoto's
  - From multispectral images: numerous vegetation indices (NDVI, WDVIg, CIr, CCCI, NDRE)
  - From thermal images: temperature map

The drone images of the Belgian fields were made available via beta.mapeo.be

For each drone based index statistics were calculated for each plot by the average index value. These drone statistics with compared with field measurements.

7.2 POTENTIAL OF DRONE IMAGERY FOR VARIABLE RATE IRRIGATION, RELATION BETWEEN DRONE INDICES AND IN SITU MEASUREMENTS

7.2.1 Belgium

In Belgium at high vegetation cover spectral indices including NIR reflectance such as NDVI and OSAVI correlated with stomatal conductance (Figure 25, Figure 26, Figure 27). At low vegetation cover correlation could be inverse for vegetation indices which include Rededge reflectance such as ReNDVI and Cired (Figure 25).

Figure 25 Correlation between vegetation indices, derived from a drone platform, and stomatal conductance observed on the same day. (Significant correlations at level p<0.05 are marked with *) Correlation analysis was conducted over 8 plots in Field 1 (Belgium 2017) which received the same N-fertilization dose.

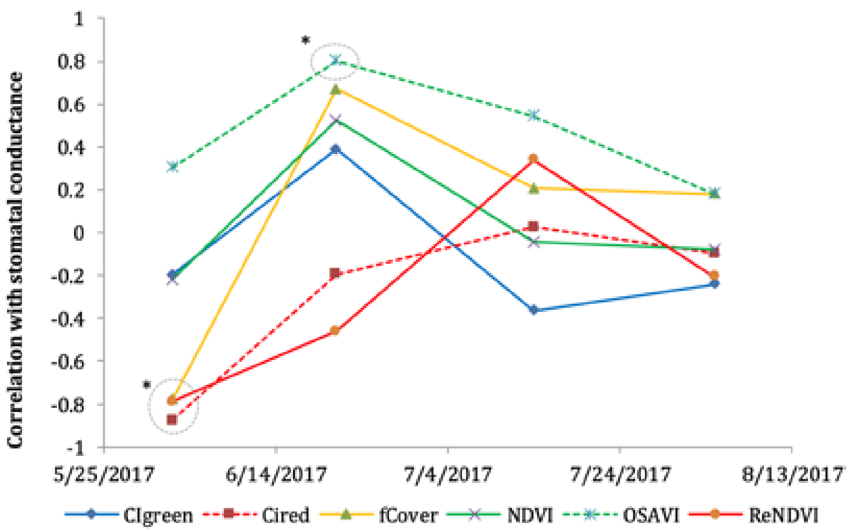


Figure 26 Correlation between vegetation indices, derived from a drone platform, and stomatal conductance observed on the same day. (Significant correlations at level p<0.05 are marked with *) Correlation analysis was conducted over 15 plots in Field 6 (Belgium 2018) which received an organic and mineral N fertilization.

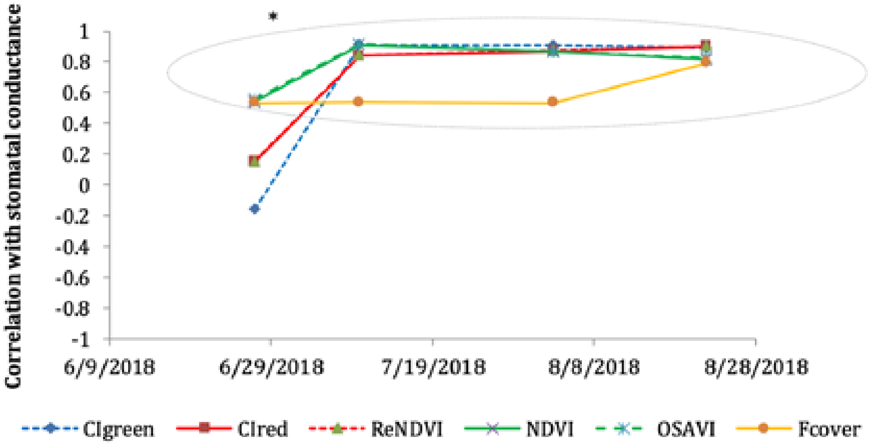
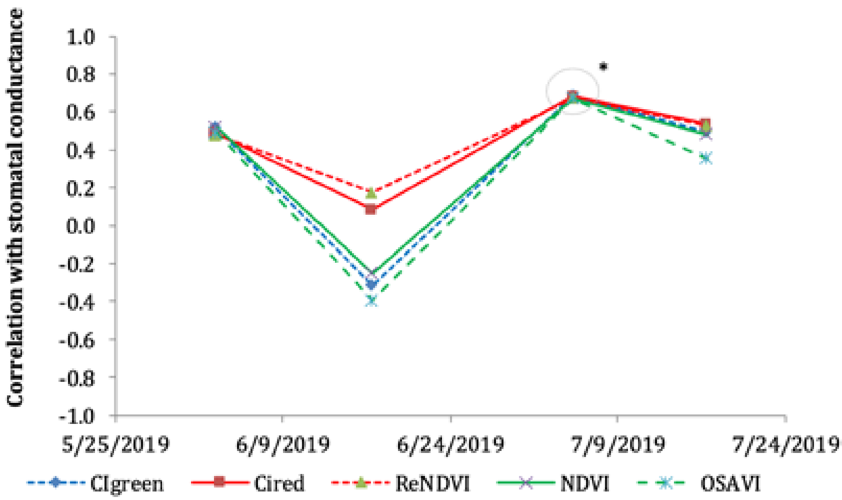


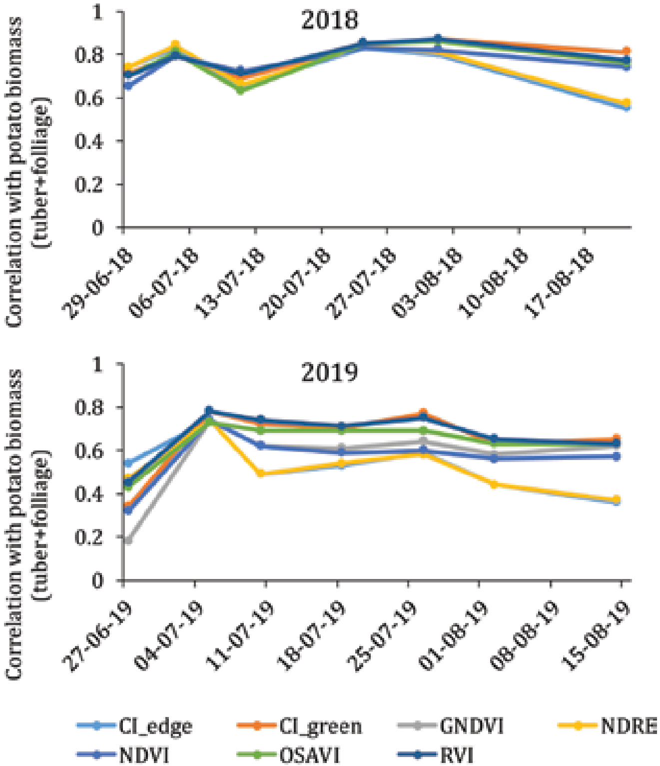
Figure 27 Correlation between vegetation indices, derived from a drone platform, and stomatal conductance observed on the same day. (Significant correlations at level p<0.05 are marked with *) Correlation analysis was conducted over 12 plots in Field 10 (Belgium 2019) which received both organic and mineral N fertilization.



7.2.2 Denmark

In Denmark several indices were calculated from the multispectral drone images and were correlated with potato dry matter (foliage and tuber) for the experimental plots in 2018 and 2019 (Figure 28). For both years, and especially 2018, when drought occurred, the correlation was relatively high for the indices derived in the peak season, i.e., from early July to mid-August, coinciding with the largest water stress effect (largest differences in vegetation cover).

Figure 28 Correlation between vegetation indices, derived from a drone platform, and potato biomass (dry matter at harvest, tuber and foliage) observed on the same day. (All correlations are significant at level $p<0.05$ and lower) Correlation analysis was conducted over 24 plots in the field (Denmark 2018 and 2019) that received both organic (starter) and mineral N fertilization.



Regarding variable rate irrigation, the overall approach is to calculate the drought stress index CWSI from surface temperature obtained from drone thermal imagery (Figure 29) to guide timing of irrigation (Figure 30). Alternatively, more complicated method involves calculating potato ET as a function of canopy temperature obtained from drone thermal imagery, leaf area index, canopy height and fCover obtained from drone multispectral imagery, according to the TSEB model (Hoffmann et al., 2016).

Figure 29 Spatio-temporal variation in crop water stress index (CWSI) for well-irrigated and drought-stressed potato in July 2018 in Denmark. The difference between the two irrigation treatments is consistent throughout the day.

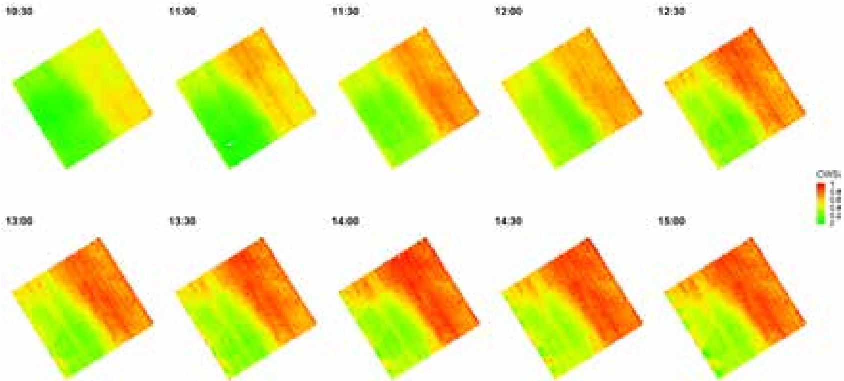
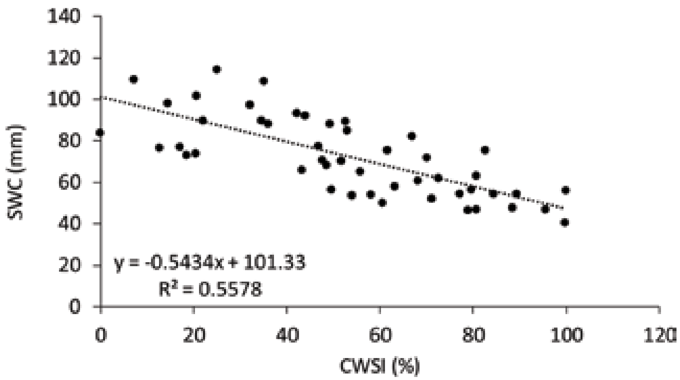


Figure 30 Relation between crop water stress index (CWSI) and measured soil water content in July and August 2018 in Denmark. Values are on plot scale.



7.3 POTENTIAL OF DRONE IMAGERY FOR VARIABLE RATE FERTILIZATION, RELATION BETWEEN DRONE INDICES AND IN SITU MEASUREMENTS

7.3.1 Belgium

In Belgium late in the growing season there was a positive correlation between nearly all vegetation indices and NO_3-N content in in soil (Figure 31, Figure 32 and Figure 33). In 2017 on Field 1 in Belgium a negative correlation was observed between CIgreen, NDVI, OSAVI and fCover early in the growing season. In 2018 correlation between vegetation indices and in situ measurements was always positive, throughout the entire growing season. In 2019 correlation increased towards the end of the growing season.

Figure 31 **Correlation between vegetation indices, derived from a drone platform, and average NO_3-N content in the soil at the time of the observation. (Significant correlations at level $p<0.05$ are marked with *) Correlation analysis was conducted over 8 plots in Field 1 (Belgium 2017) which received the same irrigation dose.**

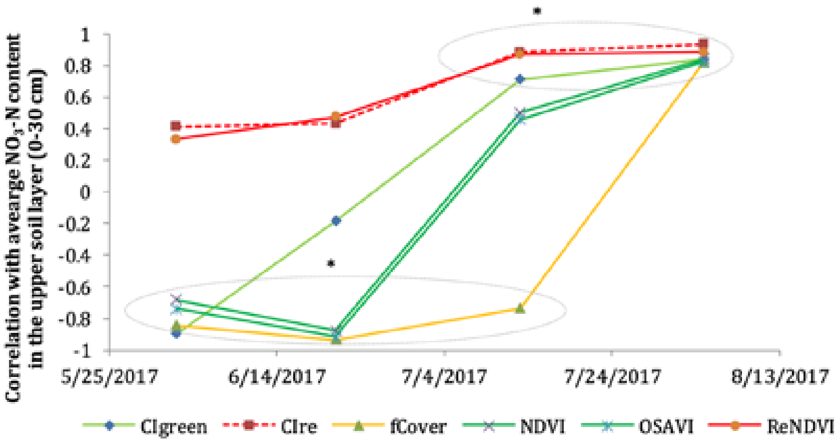


Figure 32 Correlation between vegetation indices, derived from a drone platform, and average NO_3-N content in the soil at the time of the observation. (Significant correlations at level p<0.05 are marked with *) Correlation analysis was conducted over 12 plots in Field 6 (Belgium 2018) which received the same irrigation dose.

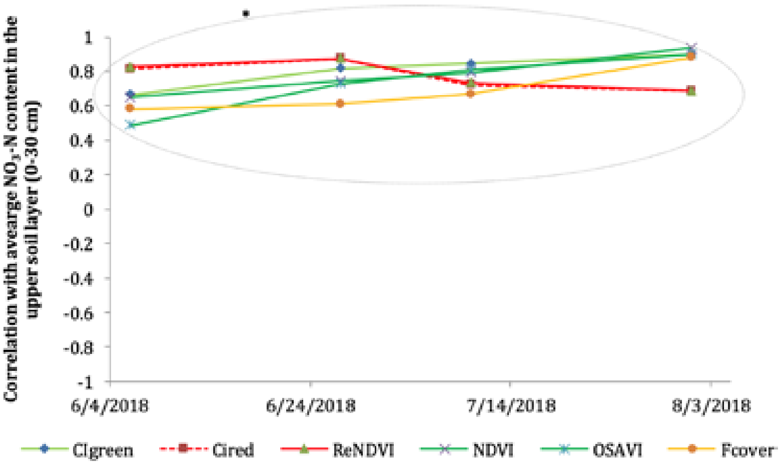
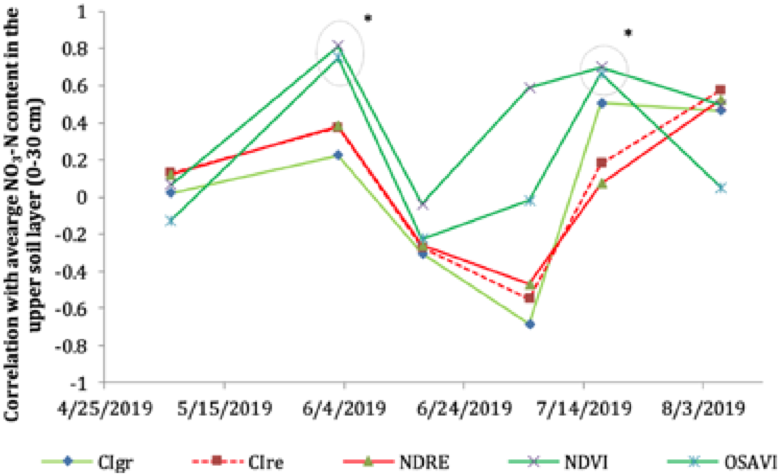


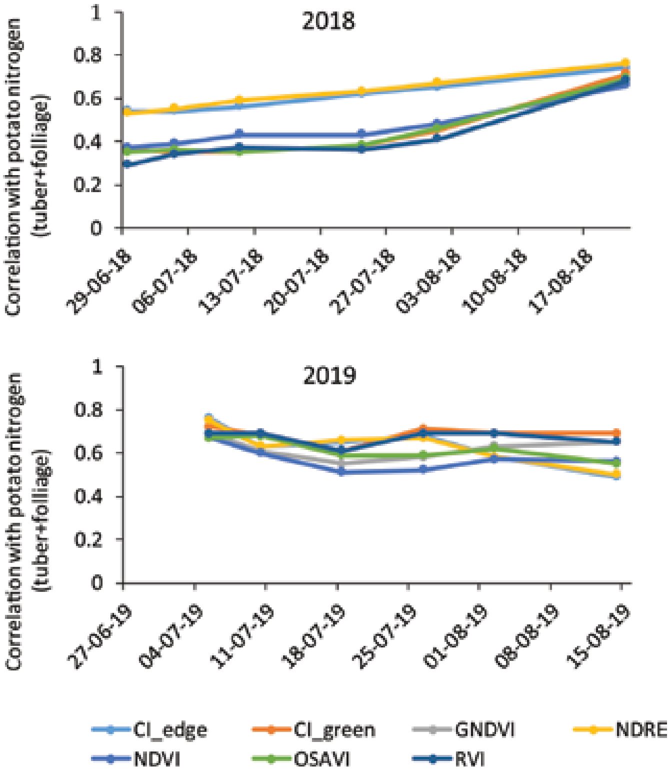
Figure 33 Correlation between vegetation indices, derived from a drone platform, and average NO_3-N content in the soil at the time of the observation. (Significant correlations at level p<0.05 are marked with *) Correlation analysis was conducted over 12 plots in Field 10 (Belgium 2019) which received the same irrigation dose.



7.3.2 Denmark

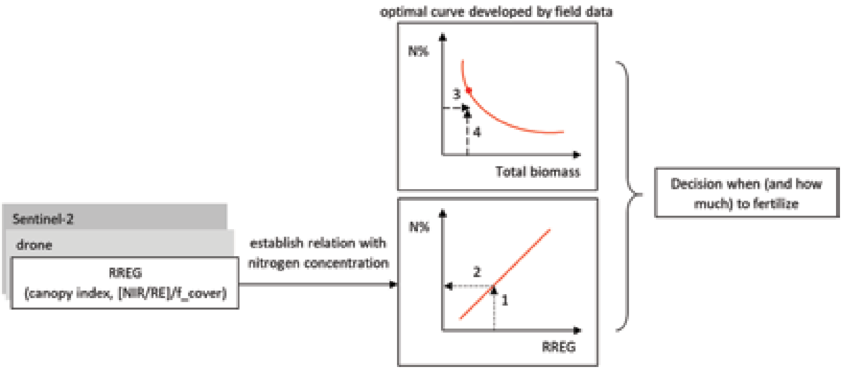
The correlation analysis showed that some indices derived from the drone multispectral data throughout the growth season in 2018 and 2019 are more correlated to potato N (foliage + tuber) compared to other (Figure 34). The indices containing the red edge (CI_edge and NDRE) showed better correlation with potato N, compared to the others, probably because red edge is well correlated with chlorophyll content, which also reflects N.

Figure 34 Correlation between vegetation indices, derived from a drone platform, and potato nitrogen (in dry matter at harvest; tuber and foliage). (All correlations are significant at level $p<0.05$ or lower) Correlation analysis was conducted over 24 plots in fields (Denmark 2018 and 2019) that received both organic (starter) and mineral N fertilization.



Hence, a developed relation between some indices with N content/concentration can be utilized to assess potato N status and guide fertilization. For instance, once a N dilution curve is developed, it can be used to locate N concentration derived from RREG (CI_edge/fCover) (Figure 35).

Figure 35 Proposed approach to assess nitrogen status and guide nitrogen fertilization for potato. The actual relationships (ongoing task) are shown on the next figure. Numbers from 1 to 4 on the plots indicate the start and the end of the procedure.



7.4 GUIDELINES FOR USING DRONE IMAGERY FOR VARIABLE RATE IRRIGATION AND FERTILIZATION

- With the help of drones images with **high resolution** can be acquired. Keep in mind that **flight arrangements and image processing can be time-consuming** and therefore expensive.
- Real time **drone images are useful to detect historic and real-time spatial variation within the field**. This helps for example to highlight zones where crop growth is lagging. Although early in the growing season there is a risk of false perception since potato emerge faster in warmer soils, but these soils also dry out faster later in the growing season having a negative effect on crop growth. Keep in mind that drone-derived plant indices are the result of different, interacting conditions affecting the plant (water, nutrient status, soil structure, disease, ...).

- Patterns in the fields may change in the course of the season. From the trials it was found that **correlation between the drone indices and final yield is higher in the second half of the season**.
- When potato suffers from water stress, it stops assimilating nitrogen. Water stress and a deficiency of nitrogen uptake are strongly entangled. This makes it **hard to distinguish between water and nitrogen shortage based only on spectral indices**. Nearly all spectral indices responded similar between water and nitrogen shortage.
- Due to the strong relation between water uptake and nitrogen uptake **additional tools need to be used to identify the true reason of retarded crop growth**. Soil sensors can measure water status, although they need to be properly calibrated. A soil water balance, calibrated with soil samples can reveal water stress. Laboratory analysis of soil, or plant nitrogen status can reveal nitrogen shortage. This information needs to be linked to the spectral images derived from drone's to apply variable rate irrigation or fertilization.
- **Thermal camera's on drone's could help by distinguishing between water and nitrogen shortage**. Stomatal closure, related to water stress, will induce a significant increase in crop temperature. The acquisition of thermal images is more complicated than the acquisition of spectral images since wind and clouds will interfere with the signal.

8 //
Potential of Sentinel satellite imagery

8.1 TYPES OF SATELLITE SENSORS

8.1.1 The use of satellites in agriculture

Since the 1970s satellites have been taking detailed images of the Earth from space. Initially, these satellite systems were large and expensive, owned and operated by governments or public organizations and tailored to their needs. In the past few decades, however, a (r)evolution took place, with the rise of new constellations of (often small and cheap) satellites offering highly detailed images with high revisit frequency. Start-ups but also big web actors such as Google and Amazon entered the field, aiming to transform space into a commodity. Since the early 2000s, many governments have opened up satellite imaging databases to the public and offer satellite images for free. This has boosted the use of satellite data for all kinds of downstream applications, including agricultural monitoring.

Satellites are very suitable for crop monitoring as they gather information over large areas with high revisit frequency. Drones may be ideal to get a 'micro' view of fields but in most cases the satellite-provided 'macro' view provides more than enough detail. Satellite images with a pixel size of 10-20m are usually detailed enough to reveal variability within a field.

Just like drones, satellites provide information on a crop's growth, its reaction to water or nutrient stress, pests or diseases or other conditions affecting its development by measuring the intensity of the radiation emitted by the crop in a particular range of the electromagnetic spectrum.

Satellites can carry various sensors. Basically, the following types can be discerned:

- **Passive sensors:**
    - "Passive" sensors rely on an external source of energy (e.g. the sun or artificial light), and record the radiation reflected by the Earth's surface to produce an image. There are two main types of passive sensors:
        1. "Optical" sensors measure the sunlight being reflected (visual and near-infrared light).
            - Most of the optical satellites sensors used for day-to-day crop monitoring are "multispectral" sensors:
            - Multispectral mages are captured in a limited number of spectral bands, mostly between 3 and 6 bands in the visual and NIR/SWIR part of the light spectrum.
            - By combining multispectral images "vegetation indices" (NDVI, chlorophyll indices, ...) and "biophysical parameters" (LAI, fAPAR, fCover, ...) can be derived. These indices provide information on the crop's greenness or health.
            - Multispectral satellite images reveal variation within the field and can be used to generate variable rate prescriptions for nitrogen, pesticides, irrigation of other applications.
        2. "Thermal or microwave" sensors measure radiation being emitted from the earth's surface.
            - Thermal sensors can read the "surface temperature", being the radiated temperature of an object.
            - Surface temperatures combined with spectral reflectances are essential components for calculating evapotranspiration and water stress and to optimize irrigation.
            - The spatial resolution of thermal satellite images is generally somewhat lower than the resolution of optical images.
    - Passive sensors produce images that are recognizable and easily interpreted.
    - Passive sensors, however, do not provide information in the case of cloud coverage.

- **Active sensors (radar):**
  - These sensors are independent from the sun's illumination because they have their own energy source (usually microwave) directed towards the earth's surface). A radar, for example, sends microwave radiation at a specific polarization (horizontal or vertical), which is backscattered from (bounced off) the earth's surface and recorded again by the sensor.
  - Radar sensors respond to moisture content, orientation, surfaces and volume of objects in their field of view.
  - Radar images are more difficult to interpret than optical images.
  - The key advantage radar sensors, however, is that images can be acquired at any time of the day and in cloudy weather conditions as the radar can see" through (penetrate) the clouds.

After acquisition, "raw" (Level 1) satellite images need to be "processed". This may include corrections for atmospheric disturbances, geometric adjustments, removal of clouds and cloud shadows, image enhancements, etc. This is done by the satellite data provider or by third parties. The corrected (Level 2 or 3) satellite images are then picked up by service providers specialized in precision agriculture that turn them into useful information for the farmer by combining the satellite data with weather, soil and plant data or by generating prescription maps for variable rate applications.

Summarized, satellites are very useful for systematic monitoring of agricultural land on a large scale. They provide a cost effective solution for precision agriculture, where 10m resolution is acceptable.

8.1.2 Satellite images used in POTENTIAL

In the frame of POTENTIAL Sentinel-2 satellite images are used. The Sentinel-2 constellation launched by ESA consists of two high resolution satellites, Sentinel-2A and 2B, that provide high resolution (10-20m) optical images on a 5-day basis.

Sentinel-2 images are made available free of charge by the EU's Copernicus program. To maximize the usability and uptake of Copernicus satellite data, ESA has set up partnerships or "collaborative ground segments" in its member states. VITO operates the collaborative ground Segment for Belgium, called "Terrascope" (https://terrascope.be/en). Sentinel images are processed by VITO. Belgian users can get free access to these data.

In the frame of POTENTIAL the following Sentinel-2 products were downloaded from Terrascope:

- NDVI: Normalized Difference Vegetation Index
- fAPAR: fraction of Absorbed Photosynthetically Active Radiation
- fCover: fraction of vegetation cover
- LAI: Leaf Area Index

In addition, Sentinel-2 reflectances, also available from Terrascope, were processed to derive the following products:

- ReNDVI: Red edge NDVI
- CIgr: green chlorophyll index
- CIre: red edge chlorophyll index
- CCC: Canopy Chlorophyll Content
- CWC: Canopy Water Content
- MSI: Moisture Stress Index
- NDII: Normalized Difference
- RVI: Ratio Vegetation Index

For each satellite based index statistics were calculated with for each plot the average index value. These drone statistics were compared with field measurements.
The POTENTIAL fields were also monitored with www.watchitgrow.be

8.2 POTENTIAL OF SATELLITE IMAGERY FOR VARIABLE RATE IRRIGATION, RELATION BETWEEN SATELLITE INDICES AND IN SITU MEASUREMENTS

8.2.1 Belgium

In Belgium early in the growing season there was a negative correlation between the gravimetric soil water content and the vegetation indices (Clgreen, Clred, CWC, fCover, NDVI and ReNDVI) derived from the Sentinel-2 satellite (Figure 36). At the end of the growing season – potatoes were harvested 20/08/2018 – there was a positive correlation between the gravimetric soil water content and the vegetation indices (Clgreen, Clred, CWC, fCover, NDVI and ReNDVI) derived from the Sentinel-2 satellite. However in 2019 correlation decreased sharply at harvest in 2019 (Figure 37).

Figure 36 Correlation between vegetation indices, derived from the Sentinel-2, and average gravimetric soil water content in the soil at the time of the observation. (Significant correlations at level p<0.05 are marked). Correlation analysis was conducted over 15 plots in Field 6 (Belgium 2018) which received both organic and mineral N fertilization.

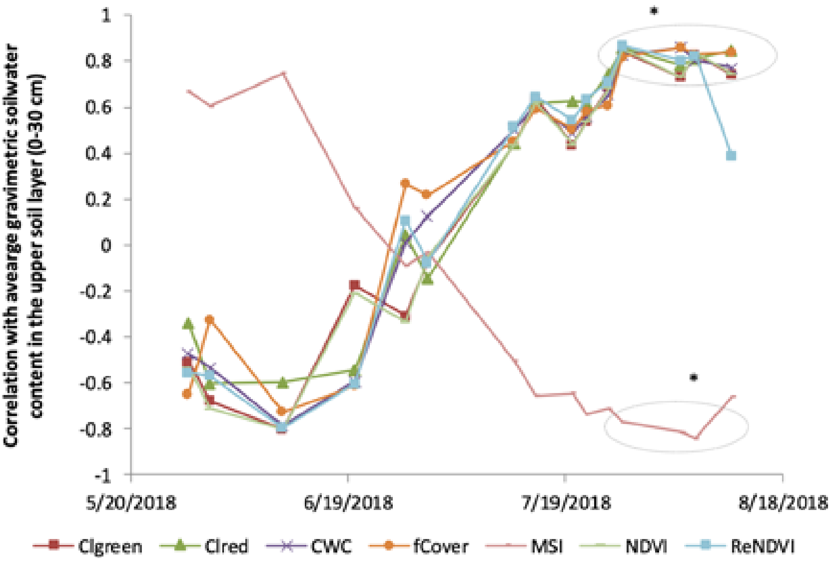
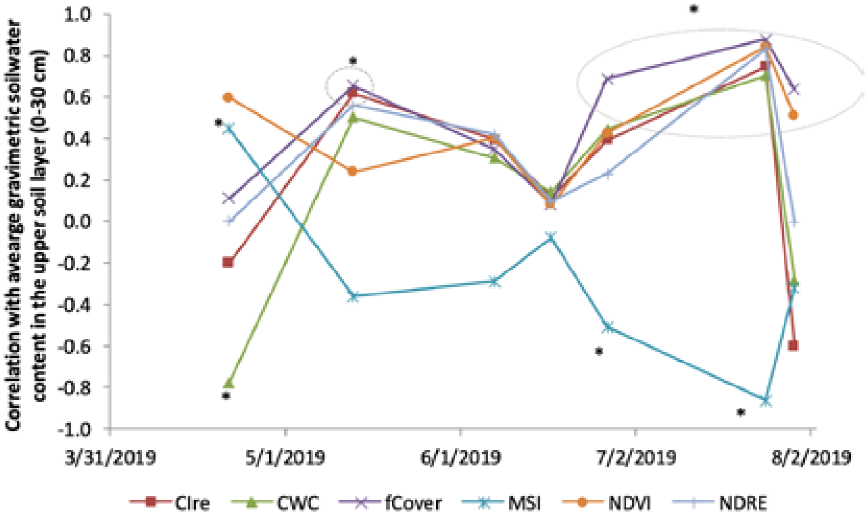
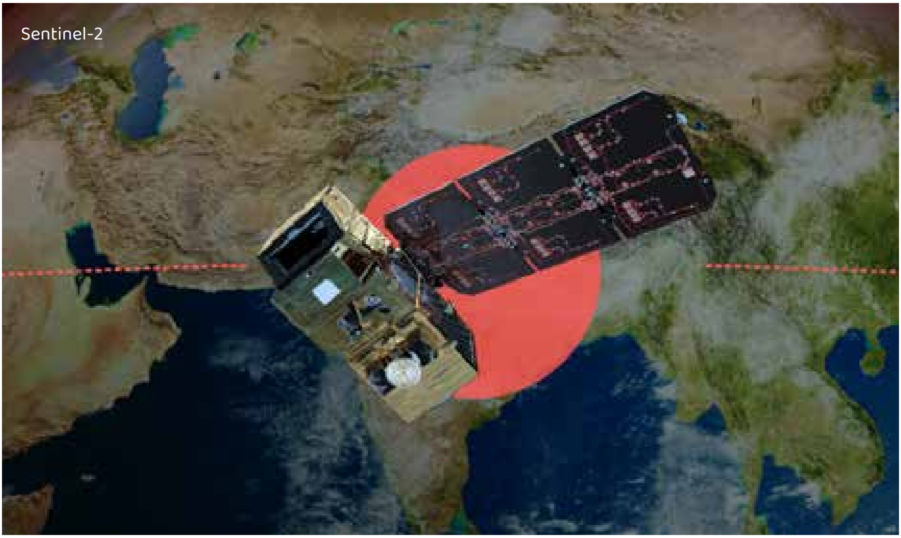


Figure 37 Correlation between vegetation indices, derived from the Sentinel-2, and average NO_3-N content in the soil at the time of the observation. (Significant correlations at level $p<0.05$ are marked). Correlation analysis was conducted over 12 plots in Field 10 (Belgium 2019) which received both organic and mineral N fertilization.

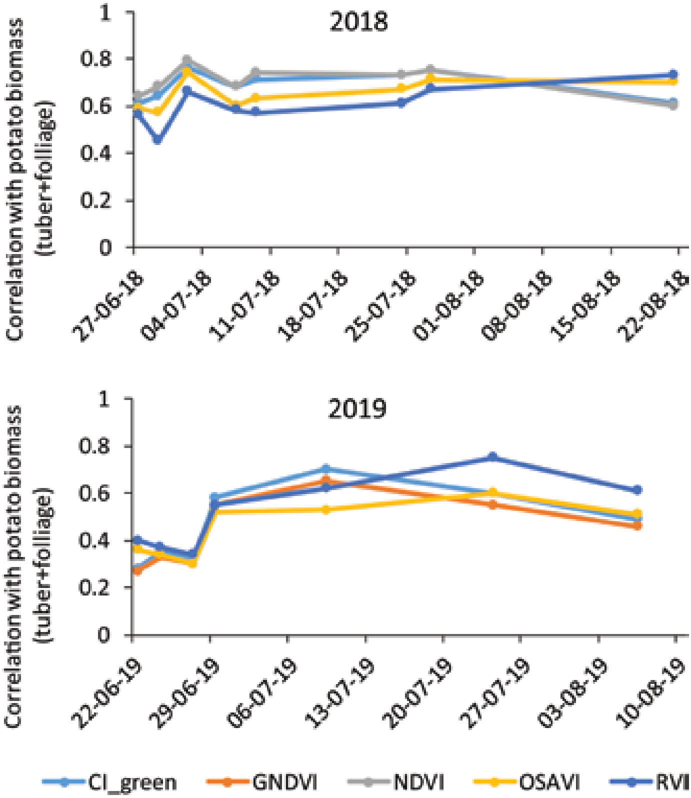




8.2.2 Denmark

Several indices were calculated using the Sentinel-2 multispectral imagery collected during the 2018 and 2019 potato season in Denmark and their relation with harvested potato tuber was assessed (Figure 38). The correlation was overall medium to high during the major part of the season (July and August).

Figure 38 Correlation between vegetation indices, derived from Sentinel-2, and potato biomass (dry matter at harvest; tuber and foliage). (All correlations are significant at level $p<0.05$ or lower). Correlation analysis was conducted over 24 plots in fields (Denmark 2018 and 2019) that received both organic (starter) and mineral N fertilization.



8.3 POTENTIAL OF SATELLITE IMAGERY FOR VARIABLE RATE FERTILIZATION, RELATION BETWEEN SATELLITE INDICES AND IN SITU MEASUREMENTS

8.3.1 Belgium

Figure 39 and Figure 40 show the correlation between the NO_3^-N content in the soil and the calculated vegetation indices CIgreen, CIred, CWC, fCover, NDVI, ReNDVI and MSI from the Sentinel-2 satellite at different times during the growing season at field 6 (2018) and field 10 (2019) in Belgium resp. In both fields correlation between NO_3^-N content in the soil and spectral indices increases towards the end of the growing season.

Figure 39 Correlation between vegetation indices, derived from the Sentinel-2, and average NO_3^-N content in the soil at the time of the observation. (Significant correlations at level $p<0.05$ are marked). Correlation analysis was conducted over 15 plots in Field 6 (Belgium 2018) which received the same irrigation dose.

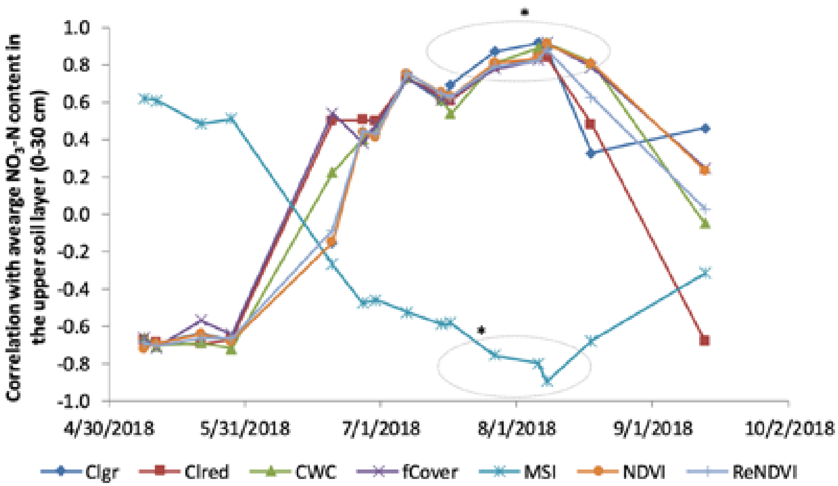
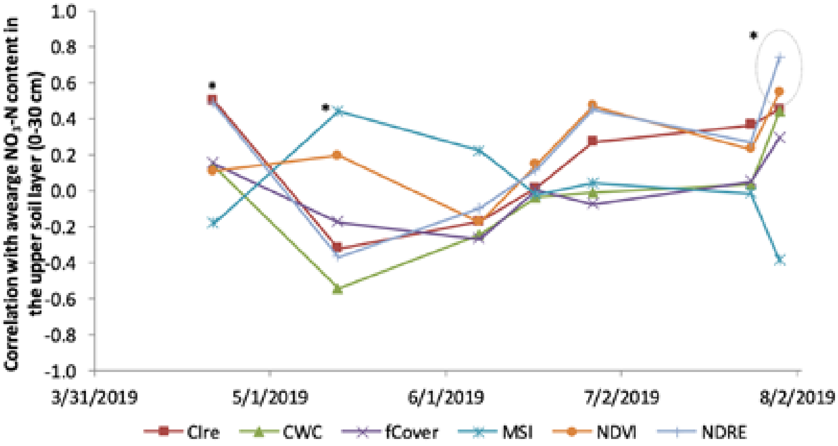
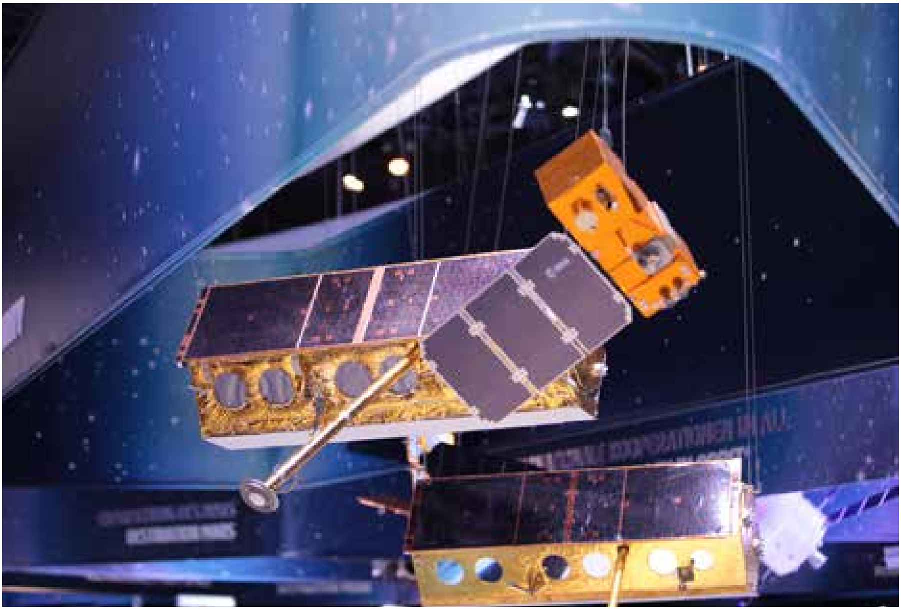


Figure 40 **Correlation between vegetation indices, derived from the Sentinel-2, and average NO_3-N content in the soil at the time of the observation. (Significant correlations at level $p<0.05$ are marked). Correlation analysis was conducted over 15 plots in Field 10 (Belgium 2019) which received the same irrigation dose.**



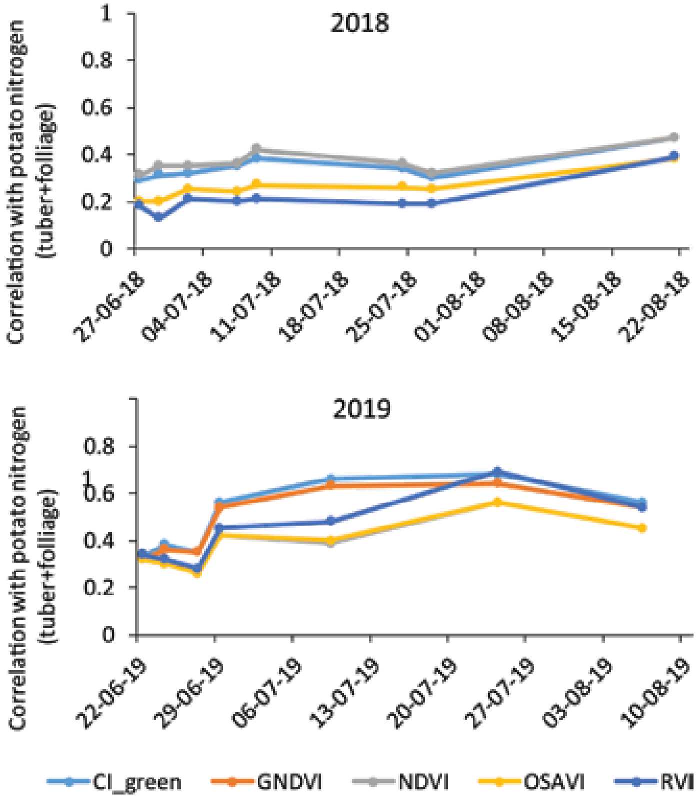


Models of the ESA spacecrafts Sentinel-2, TanDEM-X und TerraSAR-X / Sentinel-2, TanDEM-X and TerraSAR-X at the Space Pavilion at ILA 2014 (Credit ILA Berlin)

8.3.2 Denmark

Figure 41 shows the correlation between the indices derived from Sentinel 2 throughout the potato growth season 2018 and 2019 and potato nitrogen (foliage+tuber at harvest). It can be seen that the correlations are rather weak and work is ongoing to assess the potential of other variables derived from Sentinel-2 (e.g., fCover) for guiding N fertilization.

Figure 41 **Correlation between vegetation indices, derived from Sentinel-2, and potato nitrogen (in dry matter at harvest; tuber and foliage). (All correlations are significant at level $p<0.05$ or lower). Correlation analysis was conducted over 24 plots in fields (Denmark 2018 and 2019) that received both organic (starter) and mineral N fertilization.**



8.4 GUIDELINES FOR USING SATELLITE IMAGERY FOR VARIABLE RATE IRRIGATION AND FERTILIZATION

- The resolution of satellite images is low compared to drone images, but the organization of data collection is very easy, especially since the launch of the Copernicus program where Sentinel images of the target area are collected every 5 days, however only observation on cloud free days can be used.
- The resolution of 10 by 10 meter should meets the requirements of variable rate irrigation and fertilization in potato.
- Just as for the use of drone images, lower crop growth due to water stress or nitrogen shortage was clearly visible. Correlation with in situ data were similar between satellite and drone. And also the strong relation between water stress and nitrogen uptake makes it hard to distinguish between both on the spectral images. As mentioned before additional observations of water or nitrogen status in soil or plant are required.
- Task maps could be made based on historical images collected in dry periods such as for example the summer of 2018. Based on these maps it could be decided to apply less fertilizer on dry spots, or to increase the irrigation dose.
- Platforms like Watch it grow make satellite images easy accessible for farmers and should open the door to variable rate irrigation or fertilization.

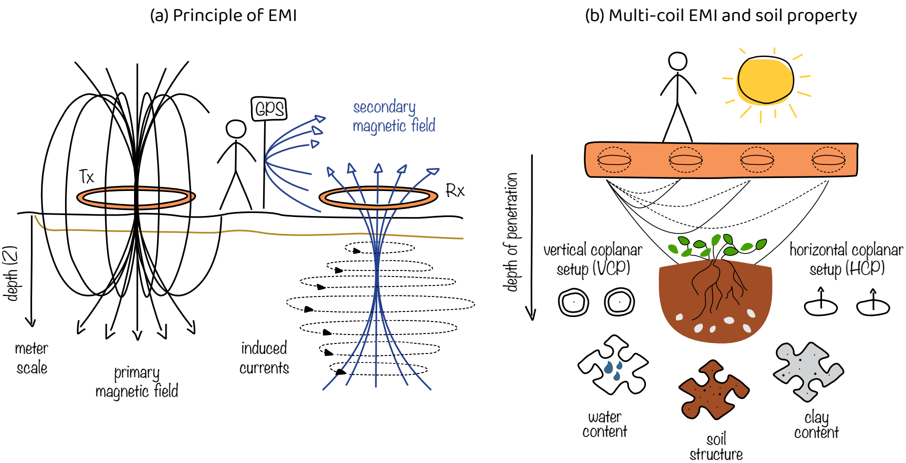
9 //
Potential of soil scanning using electromagnetic induction systems

9.1 ELECTRICAL CONDUCTIVITY AS INDICATOR FOR DIFFERENT SOIL UNITS

The electrical conductivity of the soil is classically an indicator for soil quality, nutrient status and soil moisture depending on the sample type taken or sensor technology used. Since a few decades it is also possible to map these properties at field scale and produce field maps of electrical conductivity, revealing in-field heterogeneity using geophysical techniques such as Electromagnetic Induction (EMI) or Electrical Resistivity Imaging (ERI). Nevertheless, the electrical conductivity of bulk soil is influenced by a series of soil properties (porosity, clay content, ...) and states variable (soil moisture, pore water ion concentration, temperature, ...). Maps of electrical conductivity therefore contain much information, but always have to be complemented with other ground-truth data to disentangle the impact of each individual factor. Nonetheless, the imaged patterns at field scale give direct info on spatial heterogeneity at soil level, which is complementary to aerial data mostly revealing plant responses. In this chapter, we explain how EMI data can be obtained and how they relate to classical soil information, such as soil maps.

EMI system: Multi-coil electromagnetic induction (EMI) systems use a transmitter coil and multiple receiver coils to transmit and measure magnetic fields as shown in Figure 42a. The received secondary magnetic field is related to the apparent electrical conductivity. The multi-coil EMI systems carry multiple receiver coils (Rx) with increasing separation to a transmitter coil (Tx) in a rigid boom as displayed in Figure 42b. Such rigid-boom multi-coil EMI systems investigate different depth ranges simultaneously. The investigated volume (from surface to depth) depends on the coil geometry. Geometry means the separation between Tx and Rx and their orientation to each other. The two rigid-boom multi-coil EMI systems used here carry three and six Rx coils, respectively. The multiple Rx are spaced by 0.3 m up to 1.8 m to the Tx and are oriented vertical coplanar (VCP) or horizontal coplanar (HCP).

Figure 42 (a) Principle of electromagnetic induction (EMI). Primary magnetic field induces currents in the subsurface that generate a secondary magnetic field, which is measured at the receiver coil and related to the apparent electrical conductivity (ECa). (b) Multi-coil EMI systems simultaneously measure apparent electrical conductivity values of multiple depth ranges of investigation and the ECa depends on soil properties like water content, structure, and clay content beside others. Figure after Jonard et al., 2018



EMI systems typically demand an investment of 20 000 - 60 000 euros. For efficient and reproducible measurements, an adapted sled is required to pull/guide the device over the entire field, which is an additional investment. Up till now, only a few commercial applications exist. A similar map of electrical conductivity can be produced using the electrical resistivity imaging technique, as commercially provided by VERIS for example. This technique was tested as well in the POTENTIAL project and yielded similar results as the EMI measurements.

Apparent electrical conductivity: Due to the multiple Rx in a rigid boom, multi-coil EMI systems simultaneously measure an integrative value of the electrical conductivity of a large, variable measurement volume, which is called the apparent electrical conductivity (ECa). This measurement volume is different for each depth range associated to each distinct coil separation and orientation in the device. For the smallest coil separation oriented in VCP, a depth range of ~ 0-0.2 m is measured while the largest coil separation in HCP measures the average electrical conductivity of a depth range of ~ 0-2.7 m.

The ECa distributions of an entire field typically mainly reflect soil textural changes within the field. As stated above, the ECa can generally be correlated to other dominant soil properties like soil water content, soil pH, organic matter, soil salinity, and/or soil compaction as indicated in Figure 42b. In order to determine the main contribution factors to the measured ECa values, ground-truth data is essential.

Measurement procedures: EMI systems measure non-invasively. Due to its inductive nature, meaning that multi-coil EMI systems generate electrical currents in the soil due to a transmitted magnetic field (magnetic fields cause currents to flow), i.e. they do not require contact with the soil. Because of their high mobility, multi-coil EMI systems are particularly useful to scan the soil of relatively large areas. When mounted in sleds, the EMI systems can be dragged over the entire field using an all-terrain-vehicle, e.g., a quad-bike or small tractor, while performing up to 10 measurements per second. Several hectares can be measured per day with track distances of 2 to 5 m, which obtains spatially highly resolved field-specific ECa maps. Unlike satellite data which can show changing patterns over time, the big structures found with soil scans are typically rather stable. Absolute values of the measured ECa change of course considerably under different conditions (soil moisture changes, temperatures, fertilisation, ...). The retrieved patterns are much more detailed than a classical soil map. Nevertheless, through statistical or mechanistic models obtained with analyses on soil samples at specific locations, these properties can be upscaled to the entire field to obtain texture maps, for example. Also, the ECa maps can be related to plant index data obtained by satellite or drone images, which helps explaining the soil and plant interactions.

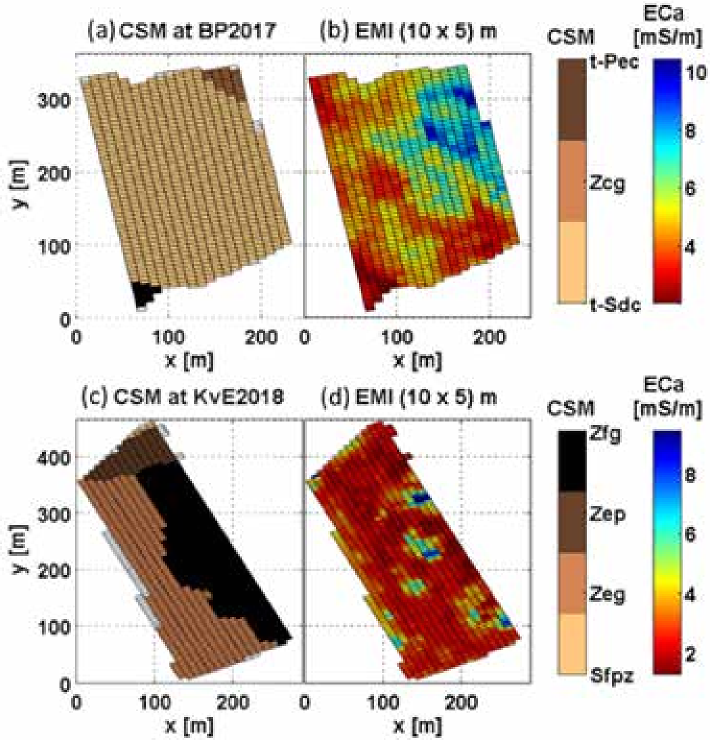
9.2 COMPARISON EMI AND CLASSICAL SOIL MAP

Figure 42 shows classical soil maps (CSM) in comparison with apparent electrical conductivity, which were downscaled to a rotated farming-grid. The rotation was parallel to the crop rows and grid has a resolution of 10 m in the x-direction and 5 m in the y-direction. This grid size is a compromise between resolution and track distances suitable for land machinery. In principle, any size can be used together with the rotation in our semi-automatic downscaling and rotation approach.

The CSM shown in Figure 43a essentially shows a loamy sand with two small edges of sand and sandy loam in the north-eastern and south-western corners, respectively. The rotated and downscaled EMI data Figure 43b roughly showed south-west to north-east directed gradient with increasing ECa values. According to the CSM, the soil in Figure 43c can be classified as sand with a negligible area of loamy sand in the northern part. At the field shown in Figure 43d, relatively small distinct areas of increased ECa values were distributed as a matrix of low electrical conductivity. Consequently, the EMI maps provide detailed insights into the soil that a classical soil map is not able to deliver. Such EMI ground-based EMI information may drastically improve interpretations of above-surface crop performances in different zones that can be observed with drone and or satellite images.

EMI measurement setup as used in POTENTIAL: the quad simultaneously pulls 2 sleds containing one EMI device and GPS antenna each. Design of the sleds: Forschungszentrum Jülich GmbH.

Figure 43 Classical soil maps (CSM) and EMI map at farm scale resolution using a semi-automatic rotation and downscaling approach in Field 2 and Field 7. Legend corresponding to (a) CSM with following legend. t-Pec: sandy loam, Zcg: sand, t-SDc: loamy sand. (b) shows the EMI map of that test site. (c) CSM of a test site with following legend. Zfg: very wet sand podzol, Zep: wet sand podzol. Zeg: wet sand, Sfpz: very wet loamy sand. (d) shows the EMI map of that site.



9.3 GUIDELINES FOR USING ELECTROMAGNETIC INDUCTION DATA FOR VARIABLE RATE IRRIGATION AND FERTILIZATION

- EMI data give insights into heterogeneity of soil properties at field scale.
- EMI data alone are not adapted to drive irrigation or fertilisation management. However, when combined with ground-truth data, a detailed assessment of soil properties can be conducted and spatially variable management can be guided.
- The combination between EMI and groundtruth data combined with soil and crop modelling, can lead to promising applications such as yield predictions and spatially variable management, but is currently not yet commercially implemented.

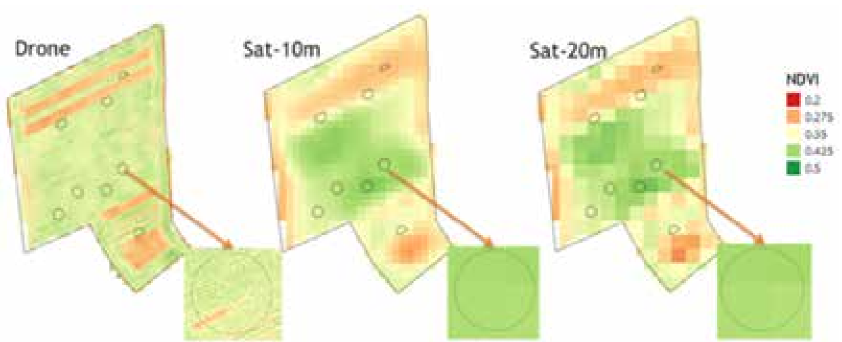
The quad driver uses the high-precision GPS equipment to plan and follow his/her measurement track.

10 //
Relation between datasets

10.1 RELATION BETWEEN MULTISPECTRAL IMAGERY DERIVED FROM DRONE AND MULTISPECTRAL IMAGERY DERIVED FROM SENTINEL-2 SATELLITE

Despite the large difference in spatial resolution of the multispectral drone and satellite images acquired over the trial fields (<10 cm vs. 10m, respectively) the images showed similar patterns throughout the growing season (Figure 44). The correlations of drone and satellite derived vegetation indices with measured field parameters were also very similar. In absolute values, however, the drone and satellite indices, in particular the red edge indices, were quite different, even if the same spectral bands (green, red, red edge, NIR, SWIR) were used to derive the indices. This can be explained by the differences in band position and band width of the drone and satellite sensors that were used for the trials.

Figure 44 Illustration of the difference in spatial resolution between a drone image (8cm pixel size) and Sentinel-2 satellite images (10m and 20m pixel size), Field 3 (Belgium, 2017) which was a field with experimental treatments applied.



The choice between drone and satellite for crop monitoring and variable rate applications depends on the required spatial detail, field size and timeliness of the images. Drone images show much more details compared to satellite images and can be acquired in cloudy conditions. However, they also come with a cost and/or with organizational challenges, and can contain local processing artefacts in case of partly clouded or moving cloud conditions.

From the trials (covering three dry seasons) it was found that patterns in the field may change in the course of the growing season and that correlations between satellite and drone based vegetation indices and yield are generally higher in the second half of the growing season. As such these images may be interesting to detect yield patterns in the field. Fertilization, however, takes place in the first half of the season. For fields with unchanged patterns in time, 'real time' drone and satellite images acquired in May/June can be used as input for variable rate fertilization. To check whether or not patterns are stable in time, the satellite image archive can be queried. Sentinel-2 satellite images are available starting with July 2015. For fields with changing patterns, however, it may be safer to use satellite or drone images of previous years to build variable rate application maps, or to use 'stable variability maps', which are generated by analyzing image time series and which show the yearly recurrent patterns in the second half of the season.

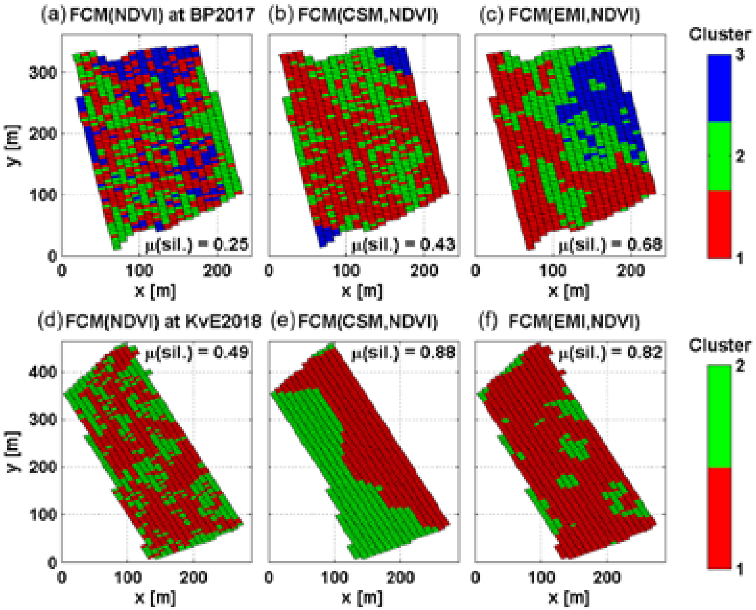
Vegetation indices derived from multispectral drone and satellite images also provide information on water stress and can serve as input to generate variable rate irrigation maps, in case of pronounced drought periods where it is known that the drought is preventing nutrient uptake and is therefore the limiting growth factor. The use of thermal images for water stress detection also looks promising but requires more research. Today, the only operational satellite which offers relatively high resolution (60m) thermal images is Landsat 7-8 but its revisit time is 16 days, which is far too long for water stress detection. Additionally, the relatively large satellite thermal ground sample distance makes it unusable in variable rate application maps. Besides the long revisit time, the relatively large satellite thermal pixel size also results in the presence of mixed information (e.g. coming not only from the field, but potentially also from neighboring trees and buildings), further reducing its value as a source of ancillary drought information in the analyses of multispectral images. Therefore, thermal imagery from drones could be especially interesting. For the trials in Belgium, thermal images were acquired with a heavy multi-rotor drone. However, due to its limited flight time, only part of the field could be covered and hence only limited conclusions could be drawn. On the other hand, thermal cameras mounted on fixed wing drones that can easily cover entire fields are becoming increasingly available, but these are generally less radiometrically stable and calibrated, therefore requiring further research into quantitative analyses for prescription mapping.

10.2 RELATION BETWEEN SOIL SCAN AND MULTISPECTRAL IMAGERY

Plants interact with soil. This is intuitive although typically little is known about the subsurface soil structure and characteristics because we only see the soil surface and sampling is time-consuming. One way to look into the soil is to use electromagnetic induction (EMI) systems that measure the apparent electrical conductivity (ECa) that reflect soil constituents. To investigate the soil and plant interaction, the ECa can be clustered with plant index data derived from satellite or drone imagery.

Figure 45a to f show the results of two test sites where the different data were used and combined in a fuzzy c-means cluster algorithm to delineate management zones, here shown for two different test sites. Clearly, using the spatial EMI data of 9 coils with the temporal NDVI data measured over the growing season, clusters are obtained that reflect the soil (compare Figure 43) interacting with the crops at the different zones. At Field 2 (Belgium, 2017) (Figure 45c), the zones are appropriate in size for variable rate applications. At Field 7 (Belgium, 2018) (Figure 45f), the cluster represents distinct zones of improved crop performance as well as soil with higher contents in fine textured material and thus higher water holding capacity and nutrient availability. For managing these relatively small patches, we highlight that future agricultural practice using robotic-based machinery, for example, can treat the crops differently. Alternatively, such fields may be suited for intercropping systems that probably better utilize the soil and will hopefully replace the common monoculture practice.

Figure 45 Fuzzy C-Means (FCM) cluster results of (a) and (d) only NDVI data, (b) and (e) NDVI and CSM, (c) and (f) EMI and NDVI data of Field 2 (a, b, c) and Field 7 (d, e, f).



11 //
Conclusions and summary of guidelines

11.1 SUMMARY

The objective of the proposed POTENTIAL project was to increase N and water use efficiency in potato by co-scheduling of N and irrigation water. Special attention is paid to the spatio-temporal variation in water and N deficit in potato fields. To meet this objective innovative sensing solutions were used such as drones, satellites and geophysical soil scanners.

During the POTENTIAL project, between 2017 and 2019, 11 experimental fields were set up in Belgium, 3 in the Netherlands and 3 in Denmark. In the experiments two different setups were used. On a part of the experimental fields a variation in water and N status was induced by applying varying doses of irrigation and fertilization. In another experiment the variation in the field was studied, without adding extra degrees of variation in water or nutrient input. In each field in situ data were collected. At the beginning of the growing season soil properties were determined. Soil sampling was conducted every three to four weeks to measure soil water and nitrate content over the growing season. Alongside with the soil observations stomatal conductance was measured using a porometer. This provided indications on plant water stress. Harvest quantity and quality was determined at the end of the growing season by taking yield samples. Regular drone flights were executed during the growing season. Drones were equipped with multispectral and thermal cameras. In addition, Sentinel-2 multispectral satellite imagery was used to schedule irrigation and N-fertilization in potato delivering images on a 5-day basis. From the drone and satellite images various vegetation indices were derived such as NDVI, ReNDVI, CIgr and CIre. The thermal camera permitted to derive temperature maps or calculation of the crop water stress index (CWSI).

Potato and typical sandy soil of the campine area in a trench dug for root observations.

Spectral indices correlated well with stomatal conductance at high vegetation cover in Belgium and Denmark, and with yield. This was the case for both drone and satellite derived indices. This shows the possibility of using spectral indices to **reveal variation in plant stress over the potato field**. However, a similar correlation was found between the same spectral indices and soil N, which is linked to the variation in N status, and thus N fertilizer need. When potato suffers from water stress, it stops assimilating nitrogen. Water stress and a deficiency of nitrogen uptake are strongly entangled. This makes it hard to distinguish between water and nitrogen shortage based only on spectral indices. Nearly all spectral indices responded similarly to water and nitrogen shortage. Only **thermal cameras on drones could help to distinguish between water and nitrogen shortage**. Stomatal closure because of water stress will induce a significant increase in crop temperature. **Additional in situ observations from soil moisture sensors (if properly calibrated) could also be useful**. In the experiments in Belgium and the Netherlands, a soil water balance model was used to reveal possible water stress. In Denmark it was demonstrated that, when water stress can be excluded, side dress N fertilization in potato can be organized according to a three-step procedure. This involves the construction of a N dilution curve (relation between dry matter and N concentration) for potato and the use of this curve to characterize the potato N status during the season, by calculating DM and N concentration from remote sensing data.

Both drone and satellite images can be used to reveal the variation in potato growth. The resolution of satellite images is low compared to drone images, but collecting satellite data is very easy, especially since the launch of the Copernicus program which provides free and open access to Sentinel images of the target area every 5 days. In practice, however, the availability of optical satellite data, e.g. from Sentinel-2, may be lower due to cloud cover. **The spatial resolution of Sentinel-2 satellite images is 10 by 10 meter which generally meets the requirements for variable rate irrigation and fertilization in potato**. Most satellite based decision support tools use the most recent images to generate task maps for variable rate irrigation and fertilization but **historical satellite images** collected in dry periods such as for example the summer of 2018, may also contain valuable information, e.g. on the occurrence of dry spots in the field. From the field work it was found that the correlation between the spectral indices and in situ observations was only significant towards the end of the growing season, and not at the time of fertilization, which hinders the use of actual spectral observations. Based on these historical maps it can be decided to apply less fertilizer on dry spots, or to increase the irrigation dose at these spots. Platforms like WatchITgrow make satellite images easily accessible for farmers and could open the door to variable rate irrigation or fertilization.

Prior to drone and satellite acquisition a non-invasive soil scan was conducted using a rigid-boom, multi-coil electro-magnetic induction device (EMI) mounted on a sled which was dragged over the entire field using a quad-bike. This resulted in a map of the apparent electrical conductivity (ECa) of the field. The ECa patterns of a field typically mainly reflect soil textural changes within the field. Nevertheless, ECa is also related to other soil properties (compaction, clay content, organic matter content) and variables (soil moisture, soil temperature, pore water salinity). There was **no unequivocal relationship between apparent electrical conductivity (ECa), derived from EMI scan and spectral indices acquired from the drone**. However, the acquired EMI data were also combined with the NDVI data in a fuzzy c-means cluster algorithm to delineate management zones. Clearly, when using the spatial EMI data in combination with the temporal NDVI data measured over the growing season, clusters were obtained that reflected the soil interacting with the crops at the different zones.

EMI maps provide **detailed insights into the soil that a classical soil map is not able to deliver**. Such information can drastically improve interpretations of above-surface crop performances in different zones that can be observed with drone and or satellite images and may result in improved management decisions.

11.2 PERSPECTIVES FOR FURTHER RESEARCH

POTENTIAL aimed to bridge the gap between the presence of innovative sensing technology and its actual use in potato farming. While machines for spatially variable application of N fertilizer are now commonly available in agriculture, they are rarely used in a correct way. POTENTIAL showed that spectral indices alone are not sufficient to distinguish between a water and a N deficit and that additional data are required to make correct agronomic management decisions. Applying variable rate fertilization solely based on spectral sensors implies a high risk of overfertilization in dry fields. A consistent framework to determine the risk of water stress on a potato field before deriving task maps for variable rate application of N is recommended. Soil sensors or soil water balance models in combination with detailed soil mapping (e.g. from EMI soil scans) could do the job. Maybe the ET calculation derived from remote sensed energy balances like SEBAL (Bastiaanssen et al. 1998), S-SEBI (Roerink et al., 2000) or TSEB-PT could be used, but the accuracy of these methods needs to be improved. Thermal data derived from drone images have already proved valuable to derive the variation in water stress although a well-watered reference plot is still needed to guide the signal.

Historical satellite images also offer a wealth of information, but the challenge remains to identify the most relevant images. Sentinel images already go back to July 2015. Images collected in the summer of 2018 can tell a lot about variability in the field due to water stress. However, the patterns often shift during the growing season. The incorporation of soil information, collected through soil scanners, for instance, could be used to understand the reasons why patterns are shifting during the growing season, or between seasons. Unsupervised clustering methods may be used to analyze the large amount of data that is generated by satellites, if possible combined with soil or other relevant information, in order to detect stable patterns over time.

This can then lead to more reliable task maps which provide indications of homogenous zones in the field.

Reliable task maps for fertilization will lead to more efficient mineral N fertilization since there are several machines ready to apply N at variable rate over the field. However, farmers also apply organic manure, often 60 to 70% of the total N need, while there is a big variation in N content in the manure. NIR sensing (Saeys et al., 2005) on manure tanks could provide more accurate information of actual manure composition. Knowledge of the N content of the manure could then also enable variable rate application of organic manure.

Whereas advanced machines are available to apply variable rate mineral N fertilization, variable rate irrigation is still a big challenge. Irrigation guns for variable rate application are still under development. Even when they are able to apply water at variable rate, the drift due to the interference of wind will remain an issue, unless the machines could be equipped with a wind meter so that the angle, and pressure at the nozzle can be automatically corrected.

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VARIABLE RATE IRRIGATION AND NITROGEN FERTILIZATION IN POTATO; ENGAGE THE SPATIAL VARIATION (POTENTIAL)