# D3.1.1 Protocol for setting-up the pilot VRT systems

WP3.1 – Very-high-resolution variable rate (VRT) nitrogen management

***Leading author: Stamatis Stamatiadis***

***Participating teams of GNHM, ELGO, AUA, RedCoast, SIGMA***

Horizon 2020
European Union funding
for Research & Innovation

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 633945.

## Document Information

| | | | |
|---|---|---|---|
| **Grant Agreement Number** | 633945 | **Acronym** | FATIMA |
| **Full Title of Project** | Farming Tools for external nutrient inputs and water Management | | |
| **Horizon 2020 Call** | SFS-02a-2014: External nutrient inputs (Research and innovation Action) | | |
| **Start Date** | 1 March 2015 | Duration | 36 months |
| **Project website** | www.fatima-h2020.eu | | |
| **Document URL** | (insert URL if document is publicly available online) | | |
| **REA Project Officer** | Aneta RYNIAK | | |
| **Project Coordinator** | Anna Osann | | |
| **Deliverable** | D3.1.1 Protocol for setting-up the pilot VRT systems | | |
| **Work Package** | WP3.1 – Very-high-resolution variable rate (VRT) nitrogen management | | |
| **Date of Delivery** | Contractual 15 Dec 2015 | Actual | 15 Dec 2015 |
| **Nature** | R - Report | Dissemination Level | CO |
| **Lead Beneficiary** | 13_GNHM | | |
| **Lead Author** | Stam Stamatiadis (GNHM) | Email | stam@gnhm.gr |
| **Contributions from** | N. Derkas, L. Evangelou, A. Glampedakis, N. Spyropoulos, C. Tsadilas | | |
| **Internal Reviewer 1** | Vicente Bodas | | |
| **Internal Reviewer 2** | Heide Spiegel | | |
| **Objective of document** | To describe the procedures for setting-up a ground system of variable-rate N application and evaluation of its performance through field trials | | |
| **Readership/Distribution** | All FATIMA Regional Teams; All WP leaders and other FATIMA team members; European Commission / REA | | |
| **Keywords** | nitrogen, water balance, variable-rate, Chlorophyll Index | | |

## Document History

| Version | Issue Date | Stage | Changes | Contributor |
|---|---|---|---|---|
| Draft v00 | 25/09/2015 | Draft | | |
| v02 | 1/11/2015 | Submission | To contributors | |
| V03 | 20/11/2015 | Submission | internal reviewers' and integrated | |
| | | | | |

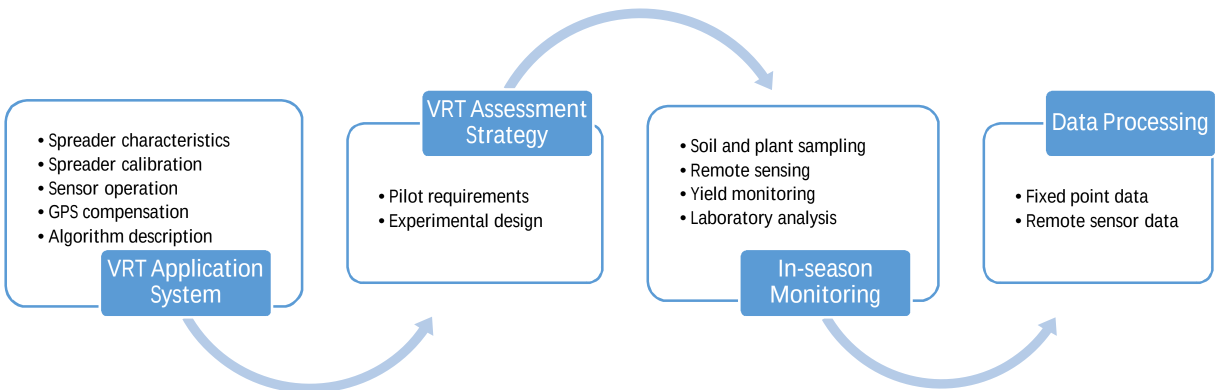
## Disclaimer

Any dissemination of results reflects only the authors' view and the European Commission is not responsible for any use that may be made of the information it contains.

## Copyright

# Executive summary

Scientific knowledge and the advent of new technologies have allowed progress towards variable-rate N application for more effective implementation of site-specific management. Procedural methods are described for the development and field-testing of a mechanized variable-rate (VRT) fertilizer application system for site-specific nitrogen (N) management of major field crops. The VRT system is based on the ability of ground-based sensors to detect canopy N content, to translate the spatial information into fertilizer N requirement and to convey a rate signal to a variable-rate spreader for application of granular fertilizer with inter-row precision of placement under real–time conditions. The concept is a prototype, some fine-tuning adjustments and communication protocols between electronic devices are under development and some may be considered to be of confidential nature. The experimental design allows the comparison of VRT N to conventional management practices under full-scale field conditions by using field strips of 8 rows wide at field-length as experimental units. The strip design accommodates the operation of 4 or 8 row VRT applicator and harvester equipped with yield monitor. In addition to yield monitoring at harvest, dynamic soil properties, crop nutrients and stable isotopes, evapotranspiration and water balance are monitored within the season. These measurements will assist to interpret N management decisions and to calculate environmental and economic performance indicators, i.e., nutrient-use efficiency, water-use efficiency and energy-use efficiency. Statistical analysis of the data is based on standard mixed-model analysis of variance with fixed effects (such as N management and location) and random effects (such as blocks and years) for randomized complete block designs. Finally, high-resolution satellite imagery is examined as an alternative to ground VRT N management with associated pros and cons. Ground sensor data are compared to those produced by WV-2 satellite imagery as the mechanized VRT fertilizer application system has the versatility to also operate with near real-time raster maps of fertilizer N requirement.



# Table of Contents



# List of Tables



# List of Figures

# 1 Introductory concepts of VRT relative to N management

Over-application of nitrogen (N) fertilizer to agricultural crops started about a century ago with the commercial production of anhydrous ammonia in the attempt by producers to attain increased yields. The environmental consequences of this practice are evident today in nitrate contamination of ground and surface waters. Improved management schemes to reduce nitrate loss via runoff and leaching include advanced irrigation systems, reduced tillage and in-season side-dress application of N fertilizer to improve synchronization between crop N need and soil N supply. Yet, fertilizer N recommendation remains an imperfect science because current mass-balance or flat-rate approaches have limited accuracies of estimation. The reason is that optimal N rates vary spatially across a field due to variability of the soil properties. Therefore, innovative N management strategies are needed to address this factor and increase crop nitrogen-use efficiency.

Scientific knowledge and the advent of new technologies have allowed progress towards variable-rate N application for more effective implementation of site-specific management. Variable-rate N application addresses in-field variation in N response, but has been limited by the lack of reliable diagnostic criteria for varying N rate. For example, mapped historic yields, variation in soil organic matter and nitrate content, soil type or drainage classes are properties that can be used for the delineation of management zones within fields, but are of limited usefulness in high-precision variable-rate application. In contrast, indirect plant measurements have been shown to provide the diagnostic criteria and the high spatial resolution needed for variable-rate N application. Ground-based active crop sensors at preselected wavelengths provide measurements that are strongly correlated to canopy N content and direct in-season N application rates. Typically, sensor measurements are normalized to reduce the effects of cultivar, canopy structure (i.e., growth stage and leaf architecture), and differences in the sensor/plant distance relationships, thus allowing the developed model to be applied across many different fields and types of crop. The performance of variable-rate systems has also been improved through the development of hydraulic pressure spreaders, highly responsive control devices and geospatial N models for variable-rate application under real-time conditions.

Work package WP3.1 aims to take advantage of state-of-the-art developments in remote sensors, simulation models and material delivery systems to demonstrate the ability of variable-rate systems to reduce N inputs while increasing nitrogen-use efficiency and crop productivity. In addition, WP3.1 intends to investigate alternative methods of VRT inputs based on best-available high resolution satellite imagery. The strategy of the assessment methodology under full-scale field conditions is shown in Fig. 1.

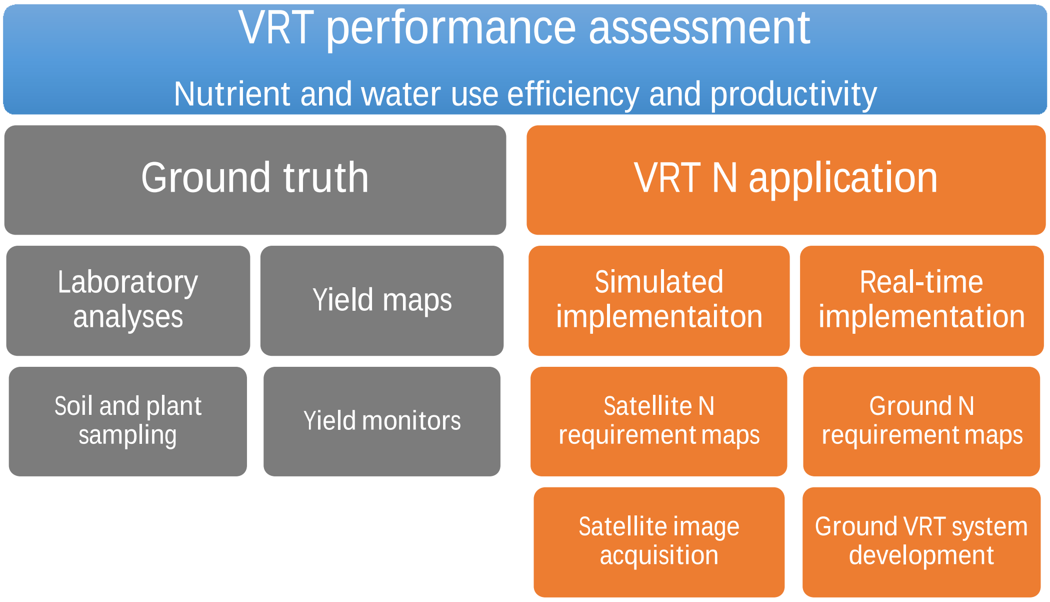



***Figure 1.*** *Schematic of field operations and measurements leading to the assessment of variable-rate nitrogen application technologies*

# 2 Ground-sensing VRT application system

A mechanized variable-rate (VRT) fertilizer application system for site-specific nitrogen management is based on the ability of ground-based sensors to detect canopy N content, to translate the spatial information into fertilizer N requirement and to convey a rate signal to a variable-rate spreader for application of granular fertilizer with inter-row precision of placement under real–time conditions (Fig. 2). The system is based on sensor and spreader components that are commercially available by independent vendors. But the concept is a prototype because these components have not previously operated together, thus requiring the modification of communication protocols and various adjustments between electronic devices.

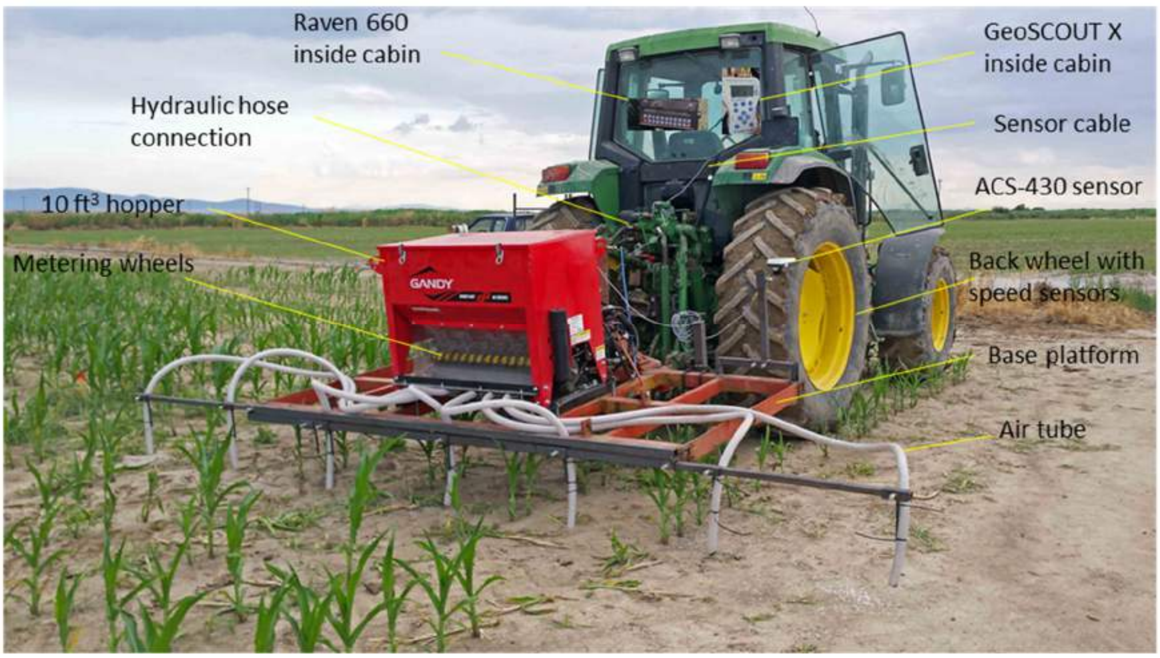



***Figure 2***. *Various components of the VRT application system after installation*

## 2.1 Spreader characteristics and fertilizer distribution

Most all air delivery fertilizer systems on the market today are available for large-scale operations. They involve carts that are pulled behind a tractor and carry multiple tons of fertilizer or are self-propelled machines (Montag, Amity, Terra Gator, Rugged Applicator, 810 Flex-Air by Case IH, Hiniker, New Holland). None of these are designed for small-scale side-dress operations or for strip research studies.

The Gandy Orbit Air 66FSC (photo 4 of Annex 1) holds 3.5 $m^3$ of granular fertilizer applied by an air delivery system to 16 crop rows maximum and is powered by a hydraulic motor with Raven speed-control compensation. It is designed to provide uniformity of spray and granular applications between crop rows regardless of the vehicle's speed (photo 3 of Annex 1). Utilizing a computer-based console, a wheel drive speed sensor (photo 10 of Annex 1), a flow meter, an encoder and a control valve, the Raven SCS 660 Control System also functions as an area, speed and volume monitor. The operator sets the target volume per area to be applied and the control system automatically maintains application. A manual override switch allows the operator to manually control the flow for spot-applications. When used in conjunction with crop sensors, it can provide variable-rate applications based on sensor readings.

## 2.2 Spreader calibration

The wheel drive speed sensor (photo 10 of Annex 1) that is mounted on a wheel of the tractor relates the speed of the tractor to the fertilizer delivery of the applicator. The speed calibration is achieved by measuring the distance travelled during a specific number of full rotations of the wheel. The GPS receiver of the sensor data logger is not used for speed calibration, but rather for depicting the coordinates at the time of the controller signal to the spreader.

The Valve Cal option on the console controls the response time of the Control Valve Motor to the change in the vehicle's speed. The valve speed has a range of 9 speeds. The system comes with an initial recommended control valve value but after operating the system, this value may be refined (a setting of 2123 is recommended in the manual, but users of the spreader found that a setting of 0743 is more responsive).

A photographic description of system assembly, calibration and field trials during the summer of 2015 is presented in Annex 1.

## 2.3 Sensor operation

The Crop Circle ACS-430 active crop canopy sensor (photo 1 and 13 of Annex 1) provides vegetation index data (NDVI, SRI and others) as well as basic reflectance information from plant canopies and soil. For on-the-go applications, the sensor can be mounted to virtually any type of vehicle to remotely sense and/or map plant or crop canopy biomass while driving through a field. The ACS-430 simultaneously measures three optical channels at 670 nm, 730 nm and 780 nm. A unique feature of the ACS-430 sensor is its ability to make height independent spectral reflectance measurements. This means each spectral reflectance band is scaled as a percentage and will not vary with sensor height above a target. This opens the possibility of using literally dozens of vegetative indices that do not use ratio-based calculations. Sensors operate by generating modulated light that pulses at the speed of 40,000 Hz. The photodetectors and related circuitry are able to separate natural light from the modulated light that is reflected. As such, the sensor works equally well under any light conditions. Reflectance values for each waveband are recorded along with spatial information and several vegetation indices (Table 1). The foot-print of the sensor increases in size as the distance from the target crop increases. At a height of 1-m above the crop, the foot-print is ~10-cm wide and 75-cm long. Sensors are generally positioned in front of the tractor so that the reflectance information can be processed and immediately acted upon by the spreader that is attached to the rear of the tractor. Sensor-based fertilizer recommendations are updated each second.

The GeoSCOUT X data logger equipped with an internal GPS receiver (photo 2 of Annex 1) is a tool for collecting geospatial data from Holland Scientific sensors and other sensors that provide RS-232 text-based data streams. Geospatial sensor data are stored on an internal, 2GB, SD flash card. Data is stored in files that are organized with a comma-separated-variable text format for easy import into third-party GIS mapping and analysis software (Table 1). The GeoSCOUT X can support 4 sensors plus two additional RS-232 serial devices. Position offsets for each sensor can be readily configured. The GeoSCOUT X can be operated in a MAP mode or a VRT (variable rate) mode. While in the VRT mode, users have the option to set a uniform rate, a variable rate based on sensor data, a rate generated by a regression equation provided by the user, or a rate extracted from a table that is generated by the user. Nitrogen rate recommendations are made at 1 Hz which amounts to about every 1.2 m when traveling at 4 km/h.

While the Crop Circle sensor - GeoSCOUT X system has been tested to work reliably in the field when operated in the VRT mode, communication issues were identified between GeoSCOUT X and the Raven SCS 660 controller. This problem is conceivable since the two electronic devices are made by different companies with untested communication protocols and a solution could not be found within the narrow time frame imposed by the early start of the project. Thus, real-time VRT was not applied in corn and cotton in the Greek pilots in the summer of 2015. Instead, a manual method of VRT fertilizer application in cotton was devised to overcome current operational problems of the VRT prototype (photo 19 of Annex 1). To some extent, the manual method is equivalent to the VRT prototype in that it uses sensor maps of N-requirement to differentially apply fertilizer across VRT strips by a manually-operated linear spreader (photo 20 of Annex 1).

***Table 1**. Example of geospatial sensor output in an Excel file format*

| LAT | LNG | COURSE | SPEED | ELEV | HDOP | FIX | UTC_DATE | UTC_TIME | SENSOr | NDRE | NDVI | Red-Edge | NIR | Red |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 39.65518007 | 22.60411743 | 158 | 0 | 63.5 | 0.9 | GPS | 210615 | 91432 | 1 | 0.342 | 0.718 | 19.226 | 6.446 | 6.446 |
| 39.65518007 | 22.60411743 | 158 | 0 | 63.5 | 0.9 | GPS | 210615 | 91432 | 2 | 0.334 | 0.735 | 19.331 | 5.902 | 5.902 |
| 39.65518007 | 22.60411743 | 158 | 0 | 63.5 | 0.9 | GPS | 210615 | 91433 | 1 | 0.352 | 0.735 | 19.114 | 6.089 | 6.089 |
| 39.65518007 | 22.60411743 | 158 | 0 | 63.5 | 0.9 | GPS | 210615 | 91433 | 2 | 0.333 | 0.711 | 19.338 | 6.519 | 6.519 |
| 39.65518007 | 22.60411743 | 158 | 0 | 63.5 | 0.9 | GPS | 210615 | 91434 | 1 | 0.341 | 0.716 | 19.237 | 6.478 | 6.478 |
| 39.65518007 | 22.60411743 | 158 | 0 | 63.5 | 0.9 | GPS | 210615 | 91434 | 2 | 0.32 | 0.668 | 19.495 | 7.531 | 7.531 |

## 2.4 Sensor calibration: reference method and vegetation index selection

Before delivery, the dual sensors of the system were cross-calibrated so as to provide duplicate analysis of the crop canopy when used in the field. Sensing crop chlorophyll status and the amount of biomass is reliable because the sensor is monitoring the crop at 40,000 Hz and recording the data at 10 Hz. Crop biomass is an expression of accumulated photosynthates and as such is a long term (weeks) assessment compared to hourly or daily photosynthesis that is largely influenced by plant nutrient and water status.

### 2.4.1 Virtual strip approach

Before using N sensors to estimate fertilizer requirements in a field, the sensors need to be normalized to a reference crop that is managed the same as the rest of the field except for having received enough N so that the crop is not N deficient (reference strip). This field situation is referred to as being “N-rich” and was used to guide sensor-based fertilizer N recommendations in the USA. Normalization involves dividing field crop readings by the reading from the reference plants and the resulting quotient is termed the “Sufficiency Index” (SI). Extending the normalization concept to whole-field situations raises questions related to using the appropriate reference value, convenience and year-to-year repeatability as it is imperative that the N-rich strips be moved to a new area each year.

Recent advances in sensor calibration refer to a more convenient, reliable and dynamic method to systematically determine the vegetation index value of reference plants (Holland and Schepers 2011) without using an N-rich strip that requires special attention by the producers. This approach is termed a “virtual reference strip” because it statistically identifies field plants that demonstrate a level of vigor comparable to those commonly found within an N-rich strip, but without the hassle of applying extra N fertilizer, a practice that is restricted in some countries or situations. This approach uses the Crop Circle active canopy sensor to monitor a portion (strip) of the existing crop that is intended to represent the range in crop vigor within the field and then statistically identifies plants that are deemed to be non-N limiting and thus comparable to many of those that might be found in an N-rich strip. The vegetation index value for these non-N limited plants is used as the reference when calculating the sufficiency index for plants in the remainder of the field as variable-rate N fertilizer is applied.

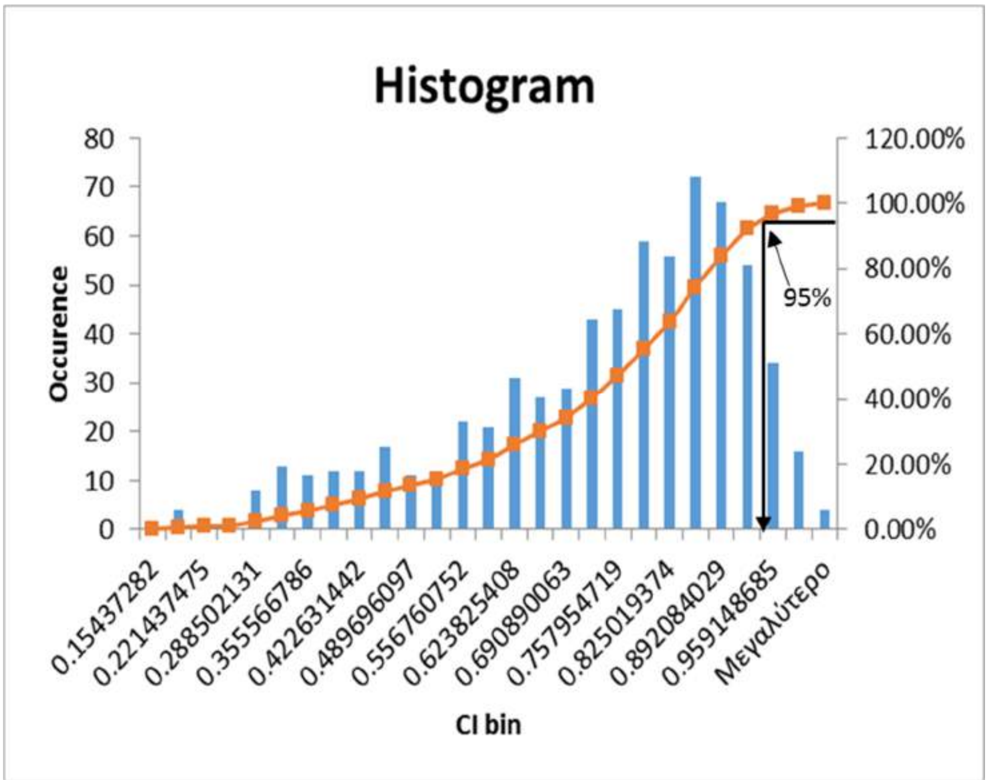



***Figure 3**. Sampled data distribution with cumulated percentile overlay for cotton at 70 days after planting in the Larisa pilot (2015). The 95-percentile value was utilized as the calibration point for the N application model.*

A histogram of the red-edge Chlorophyll Index values ($CI_{red\text{-}edge}$) was constructed to examine the shape of the distribution function (Fig. 3). The 95-percentile cumulative value (CI=0.945) from the histogram was selected as the reference to make SI calculations and simulate fertilizer N applications. Accumulation was performed from the lowest CI bin to the highest CI bin. The 95-percentile point was determined from the histogram data (Fig. 3) via linear interpolation and used to calculate SI values. Fertilizer N recommendations were calculated using the algorithm of Holland and Schepers (2010) below (section 2.4.3).

### 2.4.2 Vegetation index selection

Having access to reflectance data from three wavebands makes it possible to calculate several vegetation indices. Calculation of NDVI (normalized difference vegetation index) is the most appropriate for early-season growth conditions before the crop canopy closes, but thereafter the chlorophyll index (CI) or NDRE (red-edge vegetation index) is more responsive to crop N status. This is supported by published data (Gitelson et al., 2005) showing that a model based on red edge reflectance (720-730 nm) of the form CI = (NIR/red edge)-1 accurately estimates chlorophyll contents ($r^2$=0.95) in very contrasting species in terms of LAI, chlorophyll, canopy architecture and leaf structure for different crops such as soybean and maize. The wide range of canopy conditions studied suggests that the developed model may also be applied to estimate the canopy chlorophyll status for other crops and under a mixed pixel scenario.

### 2.4.3 Algorithm description and in-season adjustments

$$N_{APP} = \left(N_{opt} - N_{pre} - N_{OM}\right) * \sqrt{\frac{(1 - SI)}{\Delta SI * \left(1 + 0.1e^{m(SI_{thres} - SI)}\right)}}$$

The N application model developed by Holland and Schepers (2010) computes the N application rate ($N_{APP}$) at a specific field location and has two terms: the first term estimates the fertilizer N needed by the crop at the time of application by mass balance and the second provides a spatial adjustment of the mass balance by sensor readings of canopy reflectance.

The terms of the mass balance are the Economic Optimum N Rate or the maximum N rate prescribed by producers ($N_{opt}$), the sum of fertilizer N applied prior to crop sensing and/or in-season N application ($N_{pre}$) and the N credit for the field's average organic matter content ($N_{om}$). In cases where $N_{om}$ is not known, it is omitted by assuming that Nom is equal to previously applied fertilizer losses.

The sensor-adjusted terms are the normalized Chlorophyll Index called the sufficiency index (SI=CI sensed/CI reference), the sufficiency index difference parameter (ΔSI), the back-off rate variable (0< m <100) and the back-off cut-on point (SI threshold). The back-off function was incorporated to conserve N for SI values below 0.65. The rate parameter m determines the rate at which the N application model decreases N supply and the SI threshold determines when the back-off function starts to limit N supply.

As an example, CI values from irrigated cotton in the Larisa pilot (Fig. 3) were used to compute SI values which were inserted into the algorithm to simulate the N application rates (Fig. 4). This algorithm allows users to account for field-specific N sources and reduce N application rates in situations where the yield potential is reduced or additional fertilizer is not likely to achieve full yield. The simulation used a producer N rate of 150 kg N $ha^{-1}$ and a pre-plant N rate ($N_{Pre}$) of 50 kg N $ha^{-1}$. The back-off function was implemented to limit N application for SI values less than a SI threshold of 0.65.

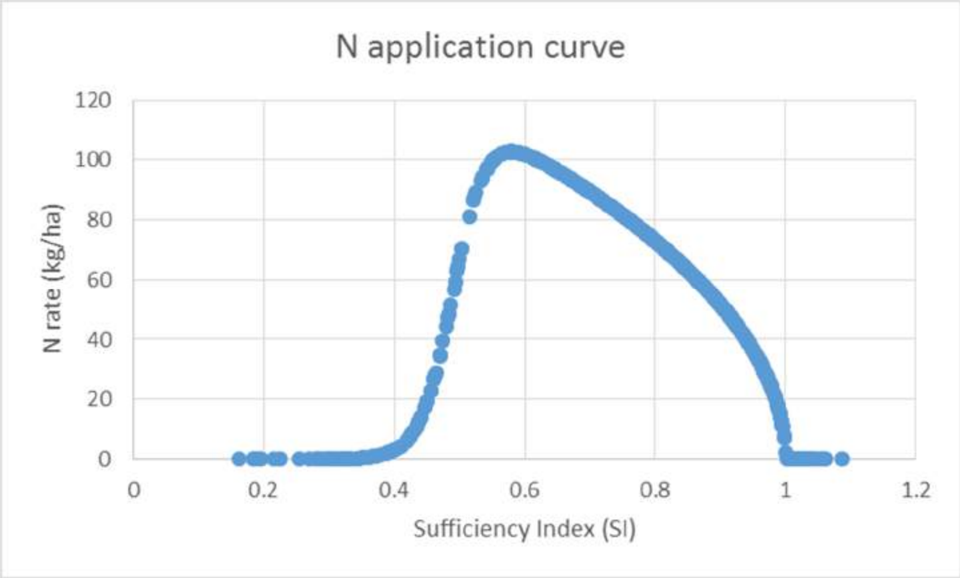



***Figure 4.*** *Recommended application rates using the N application model for irrigated cotton at 70 days after planting in the Larisa pilot (2015).*

# 3 VRT assessment strategy under real field conditions

## 3.1 Pilot requirements

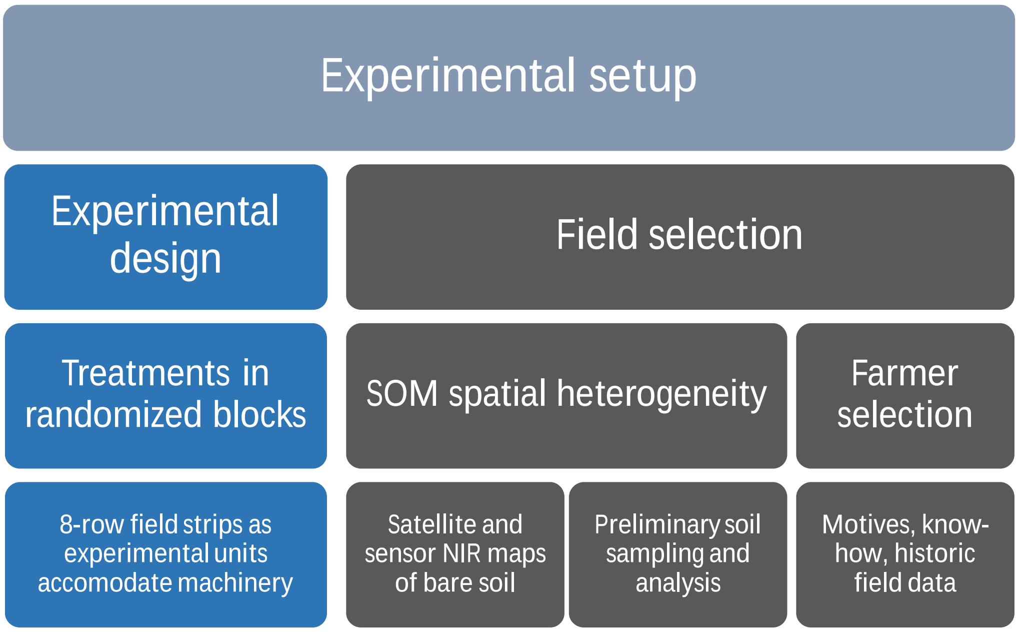



***Figure 5****. Schematic of procedures for pilot field selection and experimental setup*

A number of prerequisites apply to the selection of appropriate fields for the assessment of VRT systems. These include spatial heterogeneity in soil organic matter and associated crop growth patterns that are representative of the area in question, lack of current flooding and salinity problems, absence of past flooding-fire events and manure application, ease of access to field location and field dimensions that can accommodate our experimental design. A preliminary screening for spatial heterogeneity is possible through the examination of airplane or regular satellite imagery and, whenever available, through the analysis of

World View 2 satellite imagery which involves quantification of soil organic matter content at high resolution by an algorithm of bare soil NIR waveband (Stamatiadis et al. 2013) verified by laboratory analysis of field samples. A visual inspection and discussion with the farmer is always an important step. Also, soils of high $\delta^{15}N$ signature are preferred as they allow an assessment of fertilizer N uptake by the crop.

In the absence of suitable long-term experiment stations for this purpose, the selection procedure also includes farmer cooperation and involvement, know-how, motives, the possession of suitable equipment and machinery (irrigation systems, fertilizer applicators, yield monitors). As a final step, ELGO communicates with selected farmers to reach an agreement on the legal terms of collaboration. Meetings of the involved parties will define the areas of collaboration, obligations, and motives. The areas of collaboration will include the use of their facilities and equipment for undertaking the tasks of N management, irrigation and plant protection. Motives provided to farmers include training, technical scientific advising on crop management, and financial reimbursement for expenses that are additional to their normal management practices.

## 3.2 Assignment of treatments and experimental design

The experimental design allows implementation of VRT N management under full-scale field conditions by using field strips of 8 rows wide at field-length as experimental units. An additional benefit of this design is to accommodate the operation of 4 or 8 row VRT applicator and a harvester equipped with a yield monitor. Under P and K sufficiency and optimal irrigation, real-time VRT N application is compared to uniform farmer N application (single or segmented in-season N application) and to a preplant N control (Table 2). The randomized complete block design has thus 4 N treatments x 4 blocks (16 field strips per crop) with treatments randomized within each block. However, in the case of winter wheat the FARM1 treatment is not applicable because the main fertilization occurs in-season (early March). Fixed sampling positions (circles in Fig. 6) are arranged in three horizontal lines to add another blocking factor to the experiment for soil and plant analysis within the growing season. Whenever applicable, a 0-N control will be included in the experimentation of 2016.

***Table 2.*** *Treatment rates of fertilizer-N (%) and their distribution within the growing season*

| Timing | Preplant application CONTROL | Farmer single application FARM1 | Farmer split application FARM2 | Variable-rate application VRT |
|---|---|---|---|---|
| | --------------------Uniform ------------------------ | | | VRT |
| Preplant | 40% | 40% | 40% | 40% |
| Early-season | 0% | 60% | 0% | 0% |
| Mid-season | 0% | 0% | 30%+30% | VRT |
| Total N applied | 40% | 100% | 100% | 40% + VRT |

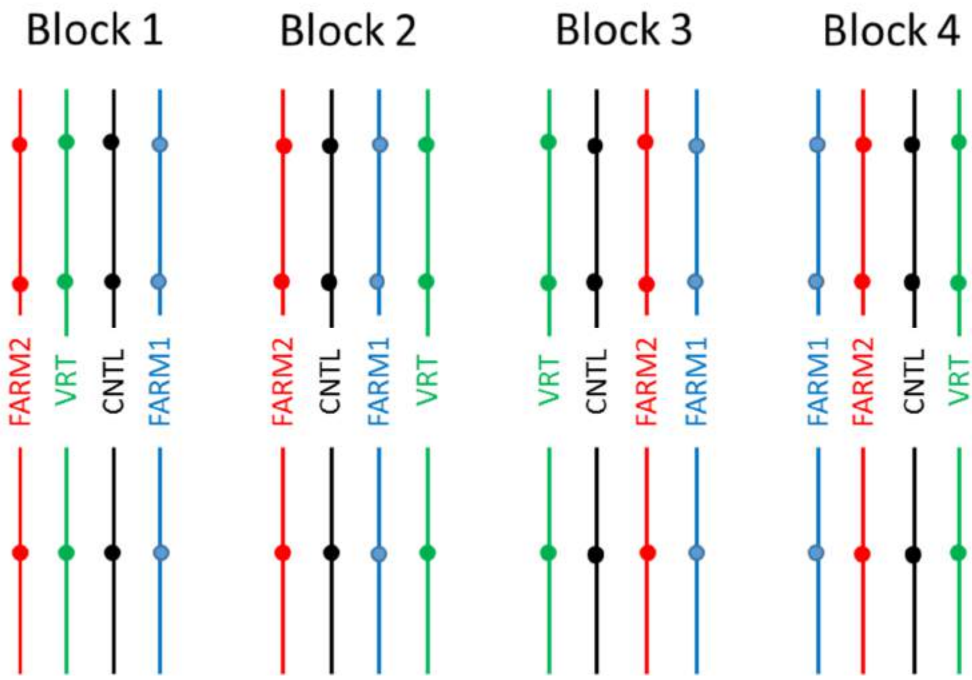



***Figure 6**. Schematic of the experimental design for the cotton pilot field (2015). Each line represents one treatment strip of 8 rows wide and an entire field length. Circles represent fixed sampling positions in three horizontal lines as a second blocking factor.*

## 3.3 Within-season monitoring

### 3.3.1 Ground truth

#### 3.3.1.1 Soil quality and crop nutrients

Non-dynamic soil properties such as soil organic matter was determined by the Walkley–Black method of wet oxidation (Nelson 1982), soil texture was determined by physical fractionation (Bouyoukos 1951) and carbonate content, as an estimate of inorganic C, was determined by using a Bernard calcimeter to measure the released carbon dioxide (CO2) after addition to soil of dilute hydrochloric acid (HCl) solution (Nelson 1982). In order to assess soil condition (EC, pH, nitrates) and plant nutrient deficiencies or stress (C, N, P, K, $^{13}C$ and $^{15}N$), composite samples on two soil depths (0-20 and 20-40 cm) are taken at 3 fixed sampling positions in each strip or management practice and two dates within the growing season: one sampling event at the time of in-season VRT fertilizer application (soil, leaves) and another prior to harvest (soil, grain). Soil samples for EC, pH and nitrates are analyzed in the laboratory on a 1:1 soil to water ratio by pH-EC meters and by a Nitracheck colorimeter (FIAstar 5000 analyzer by Foss, Laurel, Md.) in soil extracts of 2M KCl (Keeney and Nelson 1982), respectively. An example of in-season soil data for the corn pilot field in 2015 is given in Annex 4. Plant samples for C, N, $^{13}C$ and $^{15}N$ are analyzed in the laboratory by an automated combustion elemental analyzer interfaced with a continuous-flow isotope ratio mass spectrometer (PDZ Europa, UK). Samples were prepared as described by Schepers et al. (1989) and 2.8 ± 0.1 mg of each was used for the analysis. The isotopic signature of the leaves provided information of plant stress relative to water shortage (δ13C) and fertilizer N uptake (δ15N). K and P plant concentrations were determined with a flame photometer and spectrophotometer, respectively, after ground samples were heated at 500 °C for 5 h and ash was digested with 1 N HCl (Benton Jones Jr et al. 1991). The obtained data are necessary to interpret nutrient status and management decisions at the time of fertilizer application and to interpret nitrate leaching potential, nutrient-use efficiency, water-use efficiency and product quality at the time of harvest for VRT and conventional management practices.

#### 3.3.1.2 Water balance and spatial distribution of soil moisture

Water balance is used to estimate the amount of available water to the crop and to assess irrigation practices that may impact the utilization rate of nitrogen either through deficit irrigation or through excessive percolation and associated nutrient losses. Soil water content and meteorological data (rainfall, evapotranspiration) were monitored during the growing season (May 29 to September 19 2015) for the estimation of soil water balance. The soil moisture sensors (EC-5 and 10-HS, Decagon Devices, Inc.) were installed in three positions on a central planting row of each of the 4 treatment strips of a single block, a total of 15 sensors per crop (Fig. 1 of Annex 2). Of those, eleven sensors were placed to a depth of 30 cm as representative of the root zone (Soulis et al., 2014) and readings were taken twice a week before and after irrigation events with the portable Pro Check device. The remaining 4 sensors were placed to depths 15, 30, 60 and 90 cm in order to monitor the whole profile of soil moisture in a single position (middle position of VRT treatment) every two hours via an EM50 data logger. Using the soil moisture data at 30 cm depth, the soil moisture distribution was determined for every measurement date (Annex 2). The average soil moisture for sampling positions during the growing season was also determined to establish the spatial distribution of the soil moisture (Fig. 2 of Annex 2).

For monitoring irrigation volumes, each drip irrigation network was equipped with its own hydrometer. Prior to the installation of the drip irrigation system in late June or early July, irrigations were made with a sprinkler system and volumes of water granted were recorded with a hydrometer.

Meteorological data from a station in the city of Larisa (Latitude: 390 38' 00'' N, Longitude: 220 25' 00'' E, ground elevation 263 feet) were used to estimate the reference evapotranspiration with the combined Penman – Monteith equation (FAO) as follows:

$$ET_r = \left[0.408\Delta(R_n - G) + \gamma\frac{900}{\mathrm{T}+273}u_2\left(e_z^0 - e_z\right)\right]\left[\Delta + \gamma(1 + 0.34u_2)\right]^{-1}$$

Where:

*$ET_r$ = Reference evapotranspiration of grass (mm $d^{-1}$)*

*$\Delta$ = Rate of change of saturation specific humidity with air temperature. (kPa $^oC^{-1}$)*

*$R_n$ = Net irradiance (MJ $m^{-2}$ $d^{-1}$), the external source of energy flux*

*G = Ground heat flux (MJ $m^{-2}$ $d^{-1}$)*

*$\gamma$ = Psychrometric constant (kPa $^oC^{-1}$)*

*T = Mean temperature ($^o$C)*

*$u_2$ = Wind velocity at 2m (m $s^{-1}$ )*

*$e_z^0$ - $e_z$ = Vapor pressure deficit, or specific humidity (kPa)*

The crop coefficient was adopted according to the relative FAO table. The potential evapotranspiration was afterwards estimated based on the reference evapotranspiration and the crop coefficients. The actual evapotranspiration was assumed to be equal with the potential evapotranspiration due to the high soil water content throughout the growing season.

The soil water balance was estimated from seedling emergence to harvest for a soil layer of 1 m depth, which is the active root zone of both crops, as follows:

$$ET + D + Q = \Delta S + P + I$$

Where:

*ET is actual evapotranspiration (mm)*

*D is drainage (or leaching) (mm)*

*Q is runoff (mm) (in our case neglected due to the local topography)*

*ΔS is the soil water content change (mm)*

*P is precipitation (mm)*

*I is irrigation (mm)*

Estimates of water balance for the two summer crops of 2015 are presented in Annex 2 (Tables 1 and 2).

#### 3.3.1.3 Yield monitoring

Yield monitoring at the time of harvest is necessary in order to assess yield potential and nutrient-use efficiency for VRT and conventional management practices. Yield monitor is a device coupled with sensors to calculate and record crop yield "on the go" as a harvester machine operates. Yield monitors utilize multiple signals derived by sensors that differ among crop categories. In cotton, for example, optical sensors measure cotton volumetric flow rate in the chutes, which convey cotton from the picking units to the basket of a cotton picker. Volumetric flow rates from the rows of the cotton picker are measured and are communicated to a yield monitor unit in the cab of the picker over a serial communication bus. The device combines cotton volume with accumulated harvest areas, weight calibration values, and estimated percent lint turnout to calculate total weights and average yields for both fields and loads within fields. For grains, the yield monitoring system consists of an impact plate sensor for measuring grain mass flow and an electronic control unit for converting the voltage output of the impact plate into a numerical representation of yield for the combine operator. The impact plate is strategically placed at the top of the clean grain elevator and grain directly strikes the impact plate giving an output voltage signal. The voltage signal is then converted into a usable format that outputs directly to the combine display. When coupled to a GPS receiver, the yield monitor can also record data on a memory card for producing yield maps with desktop PC software.

Yield monitors for wheat, corn and cotton will be employed in the 2016 growing season by overcoming cooperation issues with the farmer as it turned out to be the case for corn in the fall of 2015. Just after corn harvest, an unusually extended rainy period did not allow the use of the yield monitor for cotton harvest. In both cases and as an alternative, harvesting was performed at three predefined (fixed) sampling positions per field strip in order to obtain yield data.

### 3.3.2 Satellite imagery

#### 3.3.2.1 World View-2 satellite imagery

During the 2015 growing season, three high-resolution World View-2 satellite images were processed in order to produce maps of canopy reflectance and Chlorophyll Index. Pre-processing methods were applied such as atmospheric and radiometric corrections of the multispectral and panchromatic images. In addition, geometric correction of the images was performed by utilizing a dataset of ground control points derived from a differential GPS receiver. Main data processing includes:

a) Pan sharpening of the panchromatic (0.5 m spatial resolution) and multispectral (2 m spatial resolution) data.
b) The computation of several vegetation indices using both multispectral (2m) and pan sharpened (0.5m) data such as:
    - [NIR(2)-Red Edge]/[NIR(2)+Red Edge]
    - Red/Red Edge
    - NIR(2)/Green
    - [NIR(2)/Red Edge]-1

The selection of the vegetation indices focuses on wavelengths of the Chlorophyll Index due to its relevance to the N application model (see section 2.4.2). The vegetation knowledge is structured on the second NIR, red edge and green channels of the WV-2 satellite. The second NIR channel is less affected by the atmosphere and this is why it is used by the FPAR, LAI and SAVI algorithms in most remote sensing software packages.

Concerning pan sharpening, merging of the panchromatic and multispectral images generates another set of multispectral channels that preserve the spectral information but in higher spatial feature space of 0.5m, thus enhancing the information integrity and clarity. Images that have been acquired simultaneously (WV-2) are preferred due to the lack of atmospheric differences. It is also recommended that the ratio of ground sample distances between the multispectral and panchromatic images should not exceed 5:1. For example, WV-2 data with 2m MS and 0.5 m Pan have a ratio of 4:1, which is acceptable. A number of image fusion algorithms have problems with color distortion and operator and data set dependency. The image fusion technique implemented in PANSHARP2 (developed by Dr. Yun Zhang, Department of Geodesy and Geomatics Engineering University of New Brunswick) diminishes greatly those deficiencies. The PANSHARP2 algorithm produces best results for multispectral image channels whose wavelengths lie within the frequency range of the panchromatic image channel. Multispectral channels outside the wavelength range of the high resolution panchromatic image channel will still look good but may have reduced physical meaning. In the PAN-SHARPENING process we used all eight multispectral channels of WV-2 such as Coastal Blue, Blue, Green, Yellow, Red, Red Edge, NIR (1) and NIR (2), knowing that only R, G, B, Y and Red Edge channels are suitable for this transformation. We experimented with NIR (1) and NIR (2) whose wavelengths are outside the panchromatic channel range.

#### 3.3.2.2 Free Landsat imagery

As water conditions are particularly important in order to assess the ability of the crop to use nitrogen, it is important to ensure that the crop does not suffer from water deficit and can utilize the nitrogen applied. The objective of 3.3.2.2 is to examine whether Landsat images provide the necessary information to reliably estimate evapotranspiration for improvement of crop water and nutrient management under the small-acreage conditions of Greek agriculture. Two OLI Landsat 8 high resolution satellite images were obtained, free of charge, from the United Stated Geological Survey (USGS) archive (http://glovis.usgs.gov/) at Level-1T processing, meaning that they were already geometrically corrected, resampled and registered to a UTM 34N WGS84 ellipsoid with elevation correction applied. The image acquisition dates (June 14 and August 1, 2015) were selected to be in close proximity to those of WorldView-2 images (June 13 and July 29, 2015) for comparative purposes.

Pre-processing involved the conversion of Digital Number values of each Landsat image spectral band (except the thermal bands, bands 10-11) to Top of Atmosphere reflectance and then to surface reflectance. Subsequently, the processing steps were the following:

- The creation of the Normalized Difference Vegetation Index (NDVI)
- The calculation of the Photosynthetically active radiation (PAR)
- Crop coefficient (Kc)-based estimation of crop evapotranspiration

According to FATIMA deliverable D2.2.2 (Methodology manual for EO-based crop water requirements forecast), it is possible to estimate the water irrigation need of a crop by calculating ET from satellite data by using the Kc coefficient derived from a vegetation index. The full ET estimation equation is based on:

$$ET = (Ks\ Kcb + Ke)\ ETo$$

The basal crop coefficient (Kcb) is defined as the ratio of the crop evapotranspiration over the reference evapotranspiration (ETc/ETo) when the soil surface is dry but transpiration is occurring at a potential rate, i.e., water is not limiting transpiration. Therefore, 'Kcb ETo' represents primarily the transpiration component of ETc. The Kcb ETo does include a residual diffusive evaporation component supplied by soil water below the dry surface (Ke) and by soil water from beneath dense vegetation (Ks). Kcb is a spectral basal crop coefficient that is taking values between 0.15 and 1.15:

$$Kcb = 1.44 * NDVI - 0.1$$

An approximation to a single spectral crop coefficient Kc taking values between 0.15 and 1.20 is:

$$Kc = 1.25 * NDVI + 0.10$$

In this report the Kc is calculated from an NDVI of Landsat-8 free satellite images (see Fig. 9a and 9b of Annex 2) which is a modified version of the following equation built in Pleiades EU project:

$$Kc = 0.15 * NDVI + 0.17$$

# 4 Data analysis and interpretation

## 4.1 Assessment of the efficiency of real-time and VRT N management

This section is designed to assess the efficiency of the applied VRT N management with (1) other conventional practices within the same field (Table 2), (2) between different crops (corn, cotton, wheat) within the same geographical area and (3) between different geographical areas. For each of the above three levels of evaluation, the input and product output balances will be used to estimate environmental performance indicators such as internal NPK-use efficiency, NPK recovery efficiency, water-use efficiency and energy-use efficiency. Ground truth measurements are necessary for the purpose of interpreting nutrient status and management decisions at the time of fertilizer application and to estimate nutrient-use efficiency and product quality at the time of harvest for VRT and conventional management practices. Univariate and multivariate statistical analysis will be performed by using the Statistical Analysis System (SAS) and expert consultancy. Univariate analysis for a randomized complete block design will be based on standard mixed-model analysis of variance, mean comparisons and contrast procedures to compare VRT N management with the other treatments regarding yield, efficiency, soil and plant properties. The use of mixed model analyses will be necessary since models used in all experimental analyses will contain both fixed effects (such as N management treatments and location) and random effects (such as blocks and years). Combined analyses will be conducted across two sites and two years for each crop. Analyses will also be combined across crop to compare the crops regarding NUE and water use efficiency.

Soil moisture, irrigation and meteorological data are used to calculate water balance of the pilot fields and, thus, to assess the amount of available water during the growing season, its sufficiency to meet the maximum evapotranspiration requirements or the prevalence of deficit irrigation that would impact the utilization rate of nitrogen (a measurable variable in this experiment). On the other hand, any losses due to deep percolation lead to leaching of nutrients and therefore the water balance is essential for the calculation of the corresponding nutrients balance. Furthermore, water balance together with soil and plant sample analysis can be exploited to create a model concerning the hydraulic behavior of the pilot fields in order to improve the irrigation practices. If irrigation is properly controlled and leaching below the root zone is avoided, the water balance would allow us to estimate the maximum evapotranspiration (which would be the actual ET) and re-compute the plant Kc coefficients (the FAO factors adapted to the local conditions). On the other hand, Kc determination from free Landsat images enables the evapotranspiration calculation on a large scale. Assessment of the reliability of this method may provide a shortcut in the field ET calculation when the VRT method for the nitrogen application will be ultimately established in an operational way.

Finally, the direct economic benefits of VRT fertilizer application are not a negligible factor in order for this new management practice to receive wider acceptance amongst the farming community. Although a comprehensive economic analysis is not an objective of this deliverable, a 40% reduction of nitrogenous fertilizer inputs without yield losses as a result of VRT application would bring about significant economic benefits. Assuming the current market price of €0.45/kg of ammonium nitrate in Greece, the savings equate to €91 and €54/ha per growing season of corn and cotton, respectively (Table 3). Projecting to a medium European farm of 300 ha for five consecutive growing seasons, these savings equate to approximately €137.000 and €81.000 for corn and cotton, respectively, which may far exceed the capital required for the purchase and implementation of VRT technologies.

***Table 3**. In-season fertilizer amounts, costs and savings assuming a 40% reduction of inputs due to VRT application.*

| Parameter | CONVENTIONAL | | VRT | | Savings | |
|---|---|---|---|---|---|---|
| | Corn | Cotton | Corn | Cotton | Corn | Cotton |
| N, kg/ha | 170 | 100 | 102 | 60 | 68 | 40 |
| Fertilizer quantity, kg/ha | 507 | 299 | 304 | 179 | 203 | 119 |
| Fertilizer Costs, €/ha | 228 | 134 | 137 | 81 | 91 | 54 |

## 4.2 Assessment potential of WV2 imagery as an alternative to real-time VRT N management

World View 2 satellite imagery during the growing season is processed for the purpose of producing maps of canopy reflectance and the Chlorophyll Index (CI), evaluating spatial fertilizer N requirement and comparing to that of the ground sensors at the time of in-season fertilizer application.

The comparison of satellite and ground measurements necessitates the transformation of all ground inputs into a common projection system. More than 10.000 point measurements have been collected from both fields and the data were geostatistically analyzed to create solid raster representations/bitmaps and to create index defined zones. All the point measurements collected in long/lat format and in WGS 84 Ellipsoid are re-projected to TM projection (EGSA'87) taking into account that the EGSA transformation model shifts the 24 Meridian to 500m east thus securing the compatibility of the data with all national geospatial data sets.

Preliminary analysis (Annex 3) indicated that the red edge and NIR channel spectral signatures of the ground sensors compared with the corresponding vegetation indices and channels of WV-2 satellite data in multispectral 2m and pan-sharpened 0.5m modes. The dates of July 24 (field data collection) and July 29 WV-2 image acquisition provided the ideal comparison set. The 95-percentile value was utilized as the reference value of the CI in the N application model (see sections 4.1, 2.4.2 and 2.4.3.). There was a strong correlation between multi and pan-sharpened satellite data (similar 95- and 20-percentile CI values) despite that pan-sharpened data produced ~70.000 measurements against the ~4.500 of multispectral and the 2.700 of ground sensors over the same cotton field (~1.8 ha). There was also a correlation between ground reflectance measurements and satellite data. There are zones of N application in the cotton field that correspond exactly to each different data set in the high or low values. The linear pattern of the ground sensor data occurred because measurements took place along the canopy rows from a northwest to southeast direction and influenced the algorithm that rasterizes the point measurements (Fig. 9 of Annex 3).

Further quality control and statistical analysis is needed to standardize the procedures for the comparison between the ground and satellite reflectance data. The two measurements are naturally differing in terms of degree of soil interference, field and crop row coverage, reflectance penetration depth of the optics, wavebands of modulated vs natural light, etc. The fact, however, that data are standardized both during conversion to vegetation indices and to sufficiency index values gives optimism that the relation between N model parameters (Fig. 8 of Annex 3) and VRT fertilizer recommendation maps will be similar.

# 5 Literature cited

Barbagallo S, Consoli S, Russo A (2008). Estimate of evapotranspiration using surface energy fluxes from Landsat TM. In : Santini A. (ed.), Lamaddalena N. (ed.), Severino G. (ed.), Palladino M. (ed.). Irrigation in Mediterranean agriculture: challenges and innovation for the next decades. Bari : CIHEAM, p. 105-114. (Options Méditerranéennes : Série A. Séminaires Méditerranéens; n. 84). International Conference on Irrigation in Mediterranean Agriculture: Challenges and Innovation for the Next Decades, Naples, Italy.

Benton Jones J Jr, Wolf B and Mills H (1991). Plant analysis handbook: a practical sampling, preparation, analysis, and interpretation guide. Micro-Macro Publishing Inc. 213 pp.

Blanta A, Dalezios RN, Maliara A, Spyropoulos N (2011). Monitoring cotton crop evapotranspiration based on satellite data. Proceedings of the International Conference on Information and Communication Technologies for Sustainable Agri-production and Environment (HAICTA 2011), Skiathos.

Bouyoukos GH (1951). A recalibration of the hydrometer method for making mechanical analysis of soils. Agronomy Journal 43:434–438.

Gitelson AA, Viña A, Rundquist DC, Ciganda V & Arkebauer TJ (2005). Remote estimation of canopy chlorophyll content in crops. Geophysical Research Letters, 32, doi:10.1029/2005Gl022688.

Hansen J, Sato M, & Ruedy R (2012). Perception of climate change. Proceedings of the National Academy of Sciences of the United States of America 109: E2415–E2423.

Holland KH, Schepers JS, Shanahan JF (2006). Configurable multi-spectral active sensor for high-speed plant canopy assessment. In: Mulla DJ (ed) Proc. 8th International Conference on Precision Agriculture (CD). University of Minnesota, Minneapolis

Holland KH & Schepers JS (2010). Derivation of a variable rate nitrogen application model for in-season fertilization of corn. Agronomy Journal, 102: 1415-1424.

Holland KH & Schepers JS (2011). Active-crop sensor calibration using the virtual reference concept. P. 469-479. In J.V. Stafford (ed.) Precision Agriculture 2011. Czech Centre for Science and Society, Prague, Czech Republic.

IPCC (2013). Working Group I contribution to the IPCC Fifth Assessment Report Climate Change 2013. The Physical Science Basis, Final Draft Underlying Scientific-Technical Assessment (http://www.ipcc.ch/report/ar5/wg1/

Irons JR, & Loveland TR (2013). Eighth Landsat satellite becomes operational. Photogrammetric Engineering and Remote Sensing, 79: 398–401.

Keeney DR and Nelson DW (1982). Nitrogen – inorganic forms, Page, A.L., R.H. Miller, and D.R. Keeney, (Eds.), Methods of Soil Analysis Part 2 Chemical and Microbiological Properties. 2nd Ed. No 9 Series Agronomy, ASA, SSSA, Publisher, Mad, WI, pp. 643-698.

Lauer DT, Morain SA, & Salomonson VV (1997). The Landsat program: Its origins, evolution, and impacts. Photogrammetric Engineering and Remote Sensing, 63: 831–838.

Lindquist JL, Arkebauer TJ, Walters DT, Cassman KG & A Dobermann (2005). Maize radiation use efficiency under optimal growth conditions. Agronomy Journal, 97: 72-78.

Loveland TR, & Dwyer JL (2012). Landsat: Building a strong future. Remote Sensing of Environment, 122: 22–29.

Meisinger JJ, Schepers JS & Raun WR (2008). Crop nitrogen requirement and fertilization. In Nitrogen in Agricultural Systems. Agronomy Monograph 49. ASA, CSSA & SSSA, Madison WI, p 563-612.

Nafziger ED, Sawyer JE & Hoeft RG (2004). Formulating N recommendations for corn in the Corn Belt using recent data. In Proc. North Central Ext.-Industry Soil Fertil. Conf., Des Moines, IA, 17 – 18 November 2004. Potash and Phosphate Inst., Brookings, SD, p 5-11.

Nelson RE (1982). Carbonate and gypsum. In Methods of soil analysis, part 2, 2nd ed., ed. A. L. Page, 181–197. Madison, Wisc.: ASA and SSSA.

Rafn EB, Contor B, Ames DP (2008). Evaluation of a Method for Estimating Irrigated Crop-Evapotranspiration Coefficients from Remotely Sensed Data in Idaho. Journal of Irrigation and Drainage Engineering, p. 722-729.

Raun WR, Solie JB, Johnson GV, Stone ML, Mullen RW, Freeman KW, Thomason WE & EV Lukina (2002). Improving nitrogen use efficiency in cereal grain production with optical sensing and variable rate application. Agronomy Journal, 94: 815-820.

Roy DP et al. (2014). Landsat-8: Science and product vision for terrestrial global change research. Remote Sensing of Environment, 145: 154-172.

Schepers JS, Francis DD and Thompson MT (1989). Simultaneous determination of total C, total N, and 15N on soil and plant material. Commun. Soil Sci. Plant Anal. 20(9&10), 949-959.

Sogbedji JM, van Es HM, Klausner SD, Bouldin DR & WJ Cox (2001). Spatial and temporal processes affecting nitrogen availability at the landscape scale. Soil Tillage Res. 58: 233-244.

Soulis KX, Elmaloglou S & Dercas N (2015). Investigating the effects of soil moisture sensors positioning and accuracy on soil moisture based drip irrigation scheduling systems. Agricultural Water Management, vol. 148, issue C, pages 258-268.

Stamatiadis S, Evangelou L, Blanta A, Tsadilas C, Tsitouras A, Chroni C, Christofides P, Tsadila E, Samaras V, and Dalezios N (2013). Satellite visible-NIR reflectance correlates to soil N and C content in three fields of the Thessaly Plain (central Greece). Communications Soil Science and Plant Analysis 44:28-37.

Stoorvogel JJ, Antle, JM, Crissman, CC, Bowen, W (2004) The tradeoff analysis model: Integrated bio-physical and economic modeling of agricultural production systems. Agricultural Systems 80: 43-66.

United Nations Population Division (2011). World population prospects: The 2010 revision. New York: United Nations (http://esa.un.org/unpd/wpp/index.htm).

von Blottnitz H, Rabl A, Boiadjiev D, Taylor T, Arnold S (2006). Damage costs of nitrogen fertilizer in Europe and their internalization. Journal of Environmental Planning and Management 49: 413-433.

Williams DL, Goward S & Arvidson T (2006). Landsat: yesterday, today, and tomorrow. Photogrammetric Engineering & Remote Sensing, 72(10): 1171–1178.

Zhang Y (2002). Problems in the fusion of commercial high-resolution satellite as well as Landsat 7 images and initial solutions. In ISPRS, Vol. 34, Part 4, GeoSpatial Theory, Processing and Applications, Ottawa, Canada.

Zhang Y (2002). "A new automatic approach for effectively fusing Landsat 7 as well as IKONOS images". IEEE/IGARSS'02, Toronto, Canada.