Field-level model approach to assess water and nutrient use efficiencies

WaterFARMING project
Report for deliverable 2.1.

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Progress summary

- Two models have been chosen for field-level assessment of crop yields and water- and nutrient use efficiencies: WOFOST and DAISY.
- For WOFOST a post-doc (João Vasco Silva), who is an expert in this modelling approach has been added to the team. He is also the lead author of this report.
- For DAISY, a brief description of the model and data requirements are provided as a guide for the consortium on data needs.
- For WOFOST calibration and evaluation protocols and associated data needs have been worked out. Detailed templates have been developed and distributed in the team.
- For sites in Germany and the Netherlands detailed experiments have been chosen that are ideally suited for model calibration and evaluation. The quality and detail of the data available is very high. In Denmark, data are available from a combined food and energy system for the modelling task.
- Finding suitable experimental data for the other countries is ongoing, there being some challenges in this regard. In view of this we aim to find experimental data for at least one site in South Europe and one in North Africa.

1. Introduction

The WaterFARMING project aims at enhancing the water and nutrient retention capacity and improve resource use efficiencies in different arable production systems in Europe and North Africa. This is important given current concerns about limited availability and pollution of water resources and calls for an assessment of the potential to improve water (WUE) and nutrient use efficiency (NUE) in these regions. In addition, it is important to understand to which extent the scope for enhancing WUE and NUE differs across these regions, preferably along a gradient of water scarcity.

An important tool at to assess and analyse these efficiencies and the chosen field level approach in WaterFARMING is crop growth modelling, which describes crop development and growth in a mechanistic way given a well-defined environment and management conditions (van Ittersum et al., 2003). They are thus highly suitable to explore different genotype x environment x management interactions in a cost-effective way. However, proper model calibration and evaluation is necessary prior to model application in other environments. Model calibration encompasses the fine-tuning of model parameters to the crop observations obtained in a field experiment. Model evaluation comprises the testing of the calibrated parameters against independent data so that model accuracy and uncertainty can be assessed. A comprehensive database of crop-specific field experiments is thus required to perform both steps, but detailed and high quality data are especially important for model calibration.

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Once crop models are properly parametrized, they can be applied to estimate WUE and NUE for the crops and production systems of interest given that daily weather data is available and soil profiles are described. WUE expresses the amount of crop biomass produced per unit of water available in a specific environment. This is informative to understand how different crops are able to make use of the available water and what is the contribution of different water sources for crop growth. NUE indicates the yield obtained per unit of N taken up by the crop. This allows the quantification of potential nutrient losses to the environment, depending for example on the source of nutrients used (i.e., mineral or organic).

The current report describes the field-level approach chosen to assess WUE and NUE at field scale, as part of the Working Package 2 (WP2) of the WaterFARMING project. First, the background theory and concepts required to study crop WUE and NUE are presented. Second, the crop models considered for the project, and their data requirements, are specified. Third, the database of field experiments available for crop modelling purposes is documented. The next steps required to estimate the WUE and NUE within the network of production systems of the WaterFARMING project are presented in the last section.

2. Background theory

2.1. Concepts of production ecology

In agronomy, three different yield levels can be specified to capture the importance of defining factors, limiting factors and reducing factors for crop growth (van Ittersum and Rabbinge, 1997). These are the potential yield, water- or nutrient-limited yield and actual yield (Figure 1):

- ✓ Potential yield: plant growth is defined by growth-defining factors such as CO_2-concentration in the air, solar radiation and temperature, and intrinsic plant characteristics (physiology, phenology and canopy architecture). Potential growth can by definition only occur if the crop is amply supplied with water and nutrients and free of weeds, pests and diseases.

- ✓ Water- or nutrient-limited yield: plant growth rate may be limited by growth-limiting factors such as water (i.e., water shortage during at least part of the growing season) and nutrients (i.e., nutrient shortage during at least part of the growing season). In all kinds of environments, shortages of especially nitrogen (N) and phosphorus (P) may occur. A period of water shortage may or may not overlap with a period of nutrient shortage.

- ✓ Actual yield: further reduction of the water- or nutrient-limited yield by growth-reducing factors such as weeds, pests, diseases and/or other pollutants leads to the so-called actual yield. This is the common situation for the majority of the world's agricultural production systems.

Yield gap analysis is useful to understand the relative contribution of defining, limiting and reducing factors to actual yields. The yield gap is defined as the difference between the potential yield and the

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actual yield in case of irrigated systems and between the water-limited and the actual yield in case of rainfed production systems. As explained below, yield gaps provide an indication of how inefficiently land is used e.g., due to inefficient use of inputs such as water and nutrients.

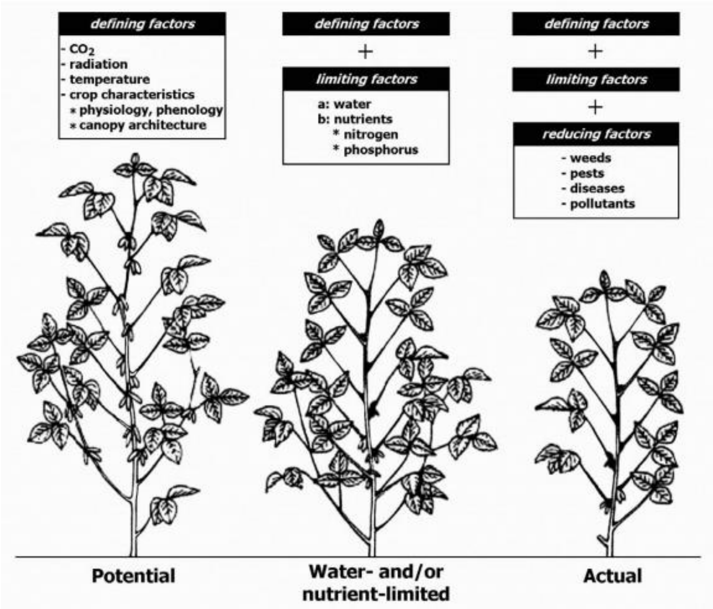

Figure 1. Concepts of production ecology highlighting the contribution of growth-defining factors, growth-limiting factors and growth-reducing factors to crop yields (potential yield, water- or nutrient-limited yield and actual yield). Source: van Ittersum et al. (2003).

2.2. Resource use efficiency

The yield levels depicted in Figure 1 reflect differences in crop performance regarding WUE and NUE (Figure 2). Actual yields by definition entail reductions in water- and nutrient-use efficiencies that would be achieved under maximum water- and nutrient-limited yields. Crop models allow the quantification of the WUE and NUE under potential, water- and nutrient-limited situations depending on whether or not the routines describing soil water and soil nutrient dynamics are considered in the simulations. However, crop models usually do not assess actual yields, and their inherent WUE and NUE, as simulation of the effects of growth-reducing factors is quite difficult. Empirical data from field trials and/or farmers' fields is thus needed for that purpose.

Water use efficiency (WUE, kg/mm) is defined as the amount of output produced per mm of water supplied (Figure 2A; e.g., Grassini et al., 2011). WUE can be further decomposed as the product of transpiration efficiency (i.e., the amount of output produced per mm transpired by the crop) and water capture efficiency (i.e., the mm of water transpired per mm of water available during the growing season). However, assessing the different components of WUE requires a detailed description of the water balance for individual crops. Differences in WUE between different fields can be explained by multiple factors such as the amount of water available for crop growth in a specific moment of time or differences in nutrient management between the fields.

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Nutrient use efficiency (NUE, kg/kg) is defined similarly to WUE as the amount of output produced per unit of nutrient applied (Figure 2B). Following de Wit (1992), nutrient use efficiency can be further conceptualized as the product of physiological efficiency and nutrient capture efficiency using a three-quadrant diagram. Physiological efficiency refers to the amount of output (e.g. yield or biomass) produced per unit of nutrient uptake, which relates mostly to plant architecture (harvest index) and physiology (photosynthetic rate). Nutrient capture efficiency stands for the amount of nutrient uptake per unit of nutrient applied and it is affected by for example the amount, time, space and form of the nutrients applied. Differentiating these components is useful to identify management practices which can best improve NUE.

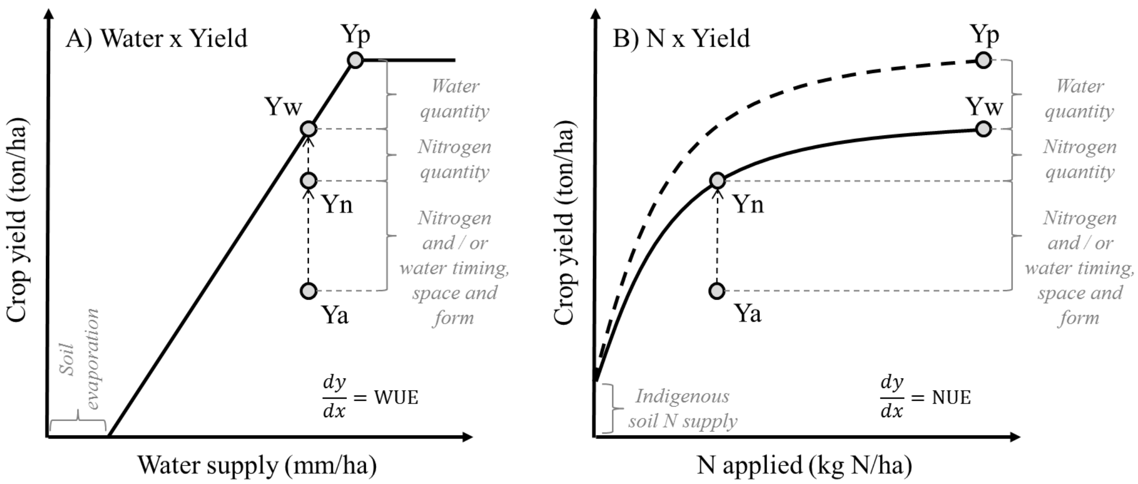

Figure 2. Conceptual framework to analyse A) water use efficiency and B) nitrogen use efficiency within the network of production systems of the WaterFARMING project. For exemplification purposes, it is assumed that the only limiting factors to production are water and nitrogen. Yp = potential yield; Yw = water-limited yield; Yn = nutrient-limited production; Ya = actual yield. Adapted from Silva (2017).

Interactions between different inputs, and their management, are central in the analysis of yield gaps, WUE and NUE in a specific production system. This is depicted in Figure 2 while assuming that water and nitrogen (N) are the only limiting factors to production. For Yp and Yw, WUE is at its optimum and NUE depends on the amount of water supplied. Differently, the fact that Ya is below the response curve to water and N indicates that both inputs are used inefficiently. Supplying water and N at the right time, form and space results in the projection of Ya on the response curve to N, but not to water. Increasing the amount of N is needed to further narrow the yield gap between Yw and Ya, and to fully project Ya on the response curve to water. Finally, achieving Yp requires that additional water is supplied which leads to gains in NUE by shifting the response curve to N upwards.

The aforementioned indicators of WUE and NUE are a useful first step to distinguish between crop and soil processes but other indicators can also been applied to assess WUE and NUE. Regarding WUE, van Halsema and Vincent (2012) differentiate between irrigation efficiency, water use efficiency and water productivity to examine water use across different scales. Regarding NUE (particularly nitrogen),

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a comprehensive framework was developed to summarize the relationship between Ninputs, Noutputs, N use efficiency and N surplus (EUNEP, 2015). This framework can be applied across different scales and can be used to derive policy interventions balancing production and environmental aspects of farming systems.

3. Crop modelling approach

The two models used in WP2 are WOFOST and DAISY each of which is shortly described. These two models were chosen because partners responsible for the modelling work are familiar with these models and because they capture the relevant processes we aim to study in the context of the WaterFARMING project.

3.1. WOFOST v7.1

3.1.1. Model description

WOFOST (WOrld FOod STudies model) is a member of the family of Wageningen crop models (van Ittersum et al., 2003). The model was originally developed to assess the potential yield of various annual crops in tropical countries, but since then it has also been widely applied in temperate conditions (Boogaard et al., 2013). More recently, WOFOST was applied in different parts of the world to simulate the potential and water-limited yields of different cereals and other annual crops as part of the Global Yield Gap and Water Productivity Atlas (GYGA, www.yieldgap.org). As part of GYGA, the model was used to compute WUE, in addition to the simulated water-limited yields, but there are relatively few applications of the model in NUE assessments (Groenendijk et al., 2016).

WOFOST is a semi-deterministic crop simulation model of physiological processes such as crop phenology, light interception, photosynthesis (i.e., assimilation of carbohydrates), respiration, assimilate partitioning, leaf area dynamics, evapotranspiration and soil water balance (Figure 2). Crop growth and development is simulated with WOFOST on a daily time step from sowing to physiological maturity. Crop growth over time takes into account the amount of assimilates produced through photosynthesis and the amount of assimilates required for maintenance respiration. The difference between both rates is then partitioned to the different crop organs (i.e., roots, stems, leaves and grain) using partitioning coefficients specified according to the development stage of the crop. The development stage is calculated by integrating the daily development rate over time, which is a function of temperature.

The main processes modelled in WOFOST to simulate potential and water-limited production are presented in Figure 2. Simulations of potential production consider only the response of the crop to weather conditions, while simulations of water-limited production also take into account crop responses to soil moisture conditions. The growth-defining factors considered to simulate potential production include temperature, day-length, solar radiation and a set of crop parameters describing leaf area dynamics, assimilation characteristics and dry matter partitioning. Daily crop growth is estimated as the difference between the daily gross CO_2 assimilation rate and the respiration rate. The

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former is calculated from the absorbed solar radiation assuming a photosynthesis light response curve of individual leaves.

For water-limited conditions, the soil moisture content determines whether or not crop growth is limited by drought stress. For this purpose, a soil water balance is simulated over time applying a tipping bucket approach in the rooted zone. The soil water balance considers rainfall and irrigation as inputs and water losses by surface runoff, soil evaporation, crop transpiration and downward percolation as outputs. Soil evaporation and crop transpiration are estimated based on the potential evapotranspiration and considering both soil moisture content and light interception in the canopy. Reduction in growth by water limitation occurs in parallel to the reduction in actual transpiration relative to potential transpiration. We refer to Boogaard et al. (1998) and Supit et al. (1994) for further details about model structure and modelled processes.

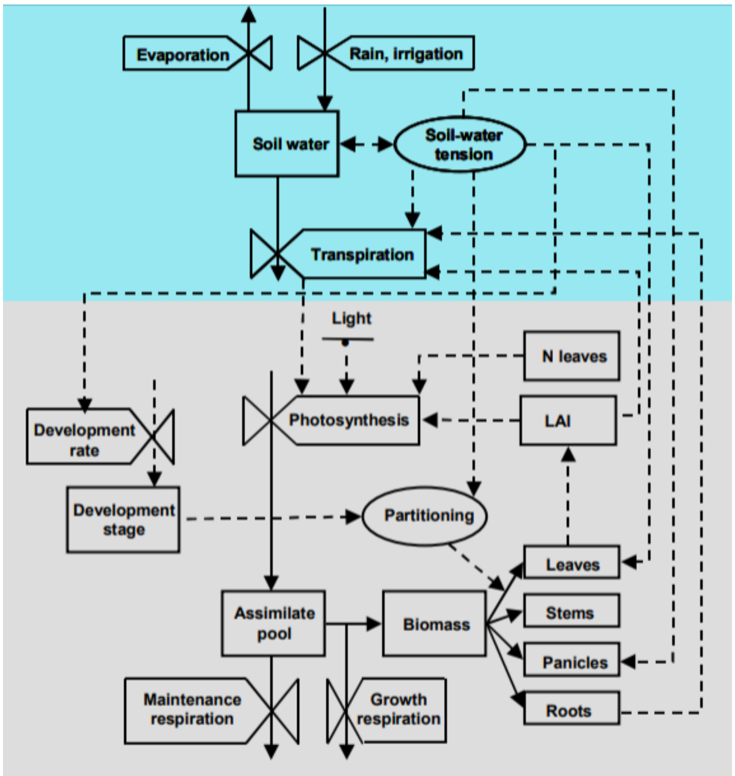

Figure 3. Relational diagram depicting the state variables and rates required for simulation of potential yield (grey box: crop development and growth) and water-limited yield (blue box: soil water balance) with WOFOST. Source: van Ittersum et al. (2003).

3.1.2. Data requirements

The complete set of input data required for calibration and evaluation of WOFOST is provided in Table 1, but the model can still be parameterized even if not all information is available. Climatic data on a daily basis can be obtained from a weather station provided this station is within a reasonable distance from the experimental site. How far is reasonable depends on local spatial weather variation. Soil data

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Table 1. Complete set of input data required to parametrize WOFOST by category (location, climatic, edaphic, management, crop phenology, crop growth, yield components). Input data which are strictly required for model parameterization are indicated with 'X' in the column 'Priority'. The spatial and temporal resolution of the data are indicated in column 'Resolution'. An example is provided for a wheat crop.

Variables	Units	Priority	Source	Resolution
Site description				
Latitude	decimals	X	GPS	Field and season
Longitude	decimals	X	GPS	Field and season
Altitude	m		GPS	Field and season
Slope	%		Observation	Field and season
Climatic conditions				
Temperature	degree C	X	Weather station	Region and day
Solar radiation	MJ/m^2	X	Weather station	Region and day
Precipitation	mm	X	Weather station	Region and day
Wind speed	m/s	X	Weather station	Region and day
Relative humidity	%	X	Weather station	Region and day
Edaphic conditions				
Clay content	%	X	Soil analysis	Soil layer and season
Silt content	%	X	Soil analysis	Soil layer and season
Sand content	%	X	Soil analysis	Soil layer and season
Organic matter content	g/kg	X	Soil analysis	Soil layer and season
Depth soil layer	cm	X	Soil profile	Soil layer and season
Bulk density	g/kg		Soil analysis	Soil layer and season
Total-N	g/kg		Soil analysis	Soil layer and season
P-Olsen	g/kg		Soil analysis	Soil layer and season
Exchangeable K	g/kg		Soil analysis	Soil layer and season
pH	-		Soil analysis	Soil layer and season
Crop management				
Previous crop	-		Trial protocol	Field and season
Sowing density	# $plants/m^2$	X	Trial protocol	Field and season
Variety planted	name	X	Trial protocol	Field and season
Irrigation applied	mm/ha	X	Trial protocol	Field and day
Irrigation timing	date	X	Trial protocol	Field and day
Irrigation method	-	X	Trial protocol	Field and day
N applied	kg/ha	X	Trial protocol	Field and day
P applied	kg/ha	X	Trial protocol	Field and day
K applied	kg/ha	X	Trial protocol	Field and day
N timing	date	X	Trial protocol	Field and day
P timing	date	X	Trial protocol	Field and day
K timing	date	X	Trial protocol	Field and day
N application method	-	X	Trial protocol	Field and day
P application method	-	X	Trial protocol	Field and day
K application method	-	X	Trial protocol	Field and day
Pest incidence	score		Observation	Field and season
Disease incidence	Score		Observation	Field and season
Weed incidence	score		Observation	Field and season
Crop phenology				
Sowing	date	X	Observation	Field and season
Emergence	date	X	Observation	Field and season
Flowering	date	X	Observation	Field and season
Physiological maturity	date		Observation	Field and season
Harvesting	date	X	Observation	Field and season
Crop growth (five measurements)				
Leaf area index	m^2/m^2	X	Measurement	Field and day
Leaf weight	g/plant		Measurement	Field and day
Stem weight	g/plant		Measurement	Field and day
Head weight	g/plant		Measurement	Field and day
Grain weight	g/plant		Measurement	Field and day
N in aboveground biomass	g N/kg		Measurement	Field and day
N in leaves	g N/kg		Measurement	Field and day
N in harvested product	g N/kg		Measurement	Field and day
Yield components (at harvest)				
Number of tillers	#/plant		Measurement	Field and season
Number of spikes	#/tiller		Measurement	Field and season
Number of grains	#/spike		Measurement	Field and season
1000 grain weight	g/plant		Measurement	Field and season
Grain moisture content	%	X	Measurement	Field and season
Grain yield	t/ha	X	Measurement	Field and season

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can be obtained through soil analysis and profile descriptions. Detailed crop observations include crop phenology (e.g., date of flowering), leaf area and biomass accumulation over time and the yield components at harvest time. Independent datasets are required for model calibration and evaluation meaning that data from different locations in the same year or from the same location over multiple years needs to be compiled from the data sources described below.

These data are traditionally obtained through on-station or on-farm field experiments involving detailed field monitoring and crop sampling over time for the most important crops within the different production systems. These may include agronomy trials (e.g., fertiliser or irrigation management) or breeding trials (such as multi-location variety trials) in which detailed crop observations have been performed. Alternatively, it may also be possible to make use of grounded measurements used to validate remote sensing images, to monitor one field during one (or preferably two) year(s) where detailed measurements can be conducted or to obtain the required information through literature review. Templates for gathering data have been shared with the WaterFARMING partners and are available upon request.

3.2. DAISY

3.2.1. Model description

DAISY is a soil-plant-atmosphere system dynamic model for agro-ecosystems, which simulates plant growth and soil processes based on the input of weather data (temperature, precipitation, global radiation and evapotranspiration), soil data (sand, silt and clay content, C:N ratio, bulk density and soil organic matter content), hydraulic parameters, location of ground water and management information. Management data required are crop rotation, tillage, use of fertilizer and manure, irrigation, sowing and harvesting. The model simulates water, heat, carbon and nitrogen flows in a soil-plant system at field scale and provides information on crop productivity, soil carbon, nutrient and water dynamics as a result of management and weather conditions at a particular site of interest. DAISY simulates at field scale and can describe processes like soil water transport and flow, evapotranspiration, crop development and growth dynamics. DAISY model can be linked up to other hydrological models and has been validated in several international comparative validation studies.

3.2.2. Data Requirements for the Daisy model

DAISY requires data about the climate, the crop, the agricultural management and the soil in order to run a simulation. DAISY is to some degree able to adjust to the available data, either by using simpler models internally when less data is available, or by trying to synthesize the missing data from what is available. Generally, local measurements improve the model description of the studied area. For some input parameters, like precipitation, local measurements are particularly important, because local variability is large and the influence on the simulation results is significant.

Climate data

DAISY needs daily values for the following items for the entire simulation period, including the initialization period: a) average air temperature; b) precipitation (local data are important); c) global radiation.

DAISY will also need information about the weather station itself, in particular:

- the name (for reference);
- elevation of the weather station (used for some of the radiation/energy calculations);
- location: longitude and latitude (used for some of the radiation/energy calculations);
- information about the weather data is recorded at the field or on a reference surface (may affect reference evaporation);
- the screen height (influences the Penman Monteith evaporation calculation);
- wet and dry deposition of NH4 and NO3 (usually estimated based on national database-information);
- average temperature for the location (can be derived based on long-term records from the area and is used to calculate the lower boundary condition for the calculation of soil temperature);
- the average amplitude of the temperature variation over the year (can be derived as above) , and the average day where the maximum temperature is reached (can be derived as above);
- the average amplitude of the temperature variation over the year (can be derived as above) , and the average day where the maximum temperature is reached (can be derived as above).

Soil data

In DAISY, the column is a one or two dimensional description of an agricultural system, with the weather at the top and the groundwater at the bottom. A soil column consists of soil horizons. A soil horizon is defined as a vertical layer of soil with similar chemical and physical properties. If you make a vertical cut in the soil, there is usually a clear visual distinction between the horizons. This division should determine the number of horizons to be defined, their order and their depth.

DAISY will need the following information about the soil:

- The soil texture, i.e. the clay, silt and sand fractions of the soil. DAISY needs this information for all horizons in the profile, not just the top horizon.
- The humus content and C/N-ratio in each horizon. The last parameter is important for N-calculations, while the humus content also influences estimates of hydraulic parameters.
- The maximum root depth of the soil (soil parameter, not crop-dependent).
- The location of the groundwater and whether soil is drained. There are the following possibilities:

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- The soil is drained. Then we need to know the position of the drains (depth and distance between drains). In this case information about the drainage period or a time series of drain flow, preferably both, is useful. This will be used to calibrate the drainage information.
- The groundwater is located below 4 meter. If so, we don't need to know more.
- The groundwater is located above 4 meter. If so, we would like to know where it is located and better a whole time series of the groundwater table.

If this is all that is available, DAISY will calculate hydraulic functions based on a pedotransfer function (Cosby). If, in addition, the bulk density is known, the HYPRES pedotransfer-function is used. For many types of simulations, we have good experience with using HYPRES-generated data for the hydraulic functions.

Additional soil data

A key problem in modelling the soil/plant-system is the initialization of the organic pools in the soil. DAISY contains pools describing slow and fast turn-over of added organic matter, soil microbes and soil organic matter – or no turnover of organic matter at all. The size of the pools cannot be measured, so it necessary to estimate their size. The total carbon content and organic nitrogen is considered the total "pool size".

- Bulk density is a good improvement of predicted hydraulic properties and some of the sorption processes.
- An estimate for the average yearly carbon input to the soil in the decades before the simulation period. The yearly carbon input is rarely available; you can use numbers from a predefined table of input from various farm types if someone has created such a table for your area, or better yet run a simulation with a "typical" historical crop rotation to let DAISY calculate the input. This information is important in relation to initializing the organic pools in the soil.
- If possible, you should measure the nitrogen yield from a plot with a non-fertilized crop. This provides an indicator of the mineralization of the soil and can be used for model calibration
- You should measure the C/N ratio for the humus in at least the Ap horizon. The C/N-ratio influences the distribution between organic pools and thus the mineralization. Soils with a high C/N-value are likely to contain a fraction of organic C and N that should be characterized as "SOM3" which is inert.

You may improve your simulations by measuring the hydraulic properties of the soil. This can be done at different levels of detail:

- Measurement of (selected) points on a retention curve at different suction (field capacity, wilting point, perhaps other points and saturation based on the bulk density measurement),

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which may be used to calibrate parameters for the most common hydraulic functions (Brooks and Corey, Campbell, van Genuchten), or – if there are enough points, the values can be used directly.

- Measurement of saturated hydraulic conductivity,
- Measurement of unsaturated hydraulic conductivity at different suction, which again can be used for fitting common hydraulic functions (Burdine, Mualem), or can be used directly.

Additional information on carbon turn-over improves simulations considerably. If you have few measurements of hydraulic properties, the experience is that it may not yield better results than using a pedotransfer function. This is due to high spatial variability of these parameters. The purpose of the simulations is important here – if you are looking very detailed at effects of tillage on transport of solutes, these parameters have to be monitored closely.

In detailed studies, the above information can be supplemented with measurements of a) moisture content in the soil over time and in different depths; b) drain flow; c) nitrate content in soil moisture (soil samples, suction cups); d) nitrate concentration in drain flow.

Management

DAISY will need to know the date of the following management operations:

- Fertilizing: In addition to the date, we need to know the amount and type of the fertilizer used, and whether it was incorporated or not.
- Irrigation: We need also to know the amount of water applied, how it was applied (surface, overhead or subsoil), as well as the amount of mineral fertilizer in the water, if any.
- Tillage operations: We need to know the type of operation, e.g. plowing or seed bed preparation, and if possible, the depth if it is not “standard”.
- Sowing: We need to know the type of crop and the selected crop must exist in the Daisy crop library with the required level of parameterization.
- Harvesting: We need to know whether residuals are removed or left on the field.

Predictions

DAISY allows the manager to “be smart” about the state of the simulation, so instead of using fixed dates it can harvest when the crop is ripe and irrigate when the crop needs water. You can use these techniques to implement your management plan in the simulation. This is also useful when you don’t have information about exact dates. This is particular useful when you analyze large areas, where you do not has information from individual field. From statistical information about preferred crop types and knowledge about common praxis in the area, you can create representative crop rotations and run these under various climate conditions, and on the soil types found in the area.

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Additional management information

Initialisation: Carbon and nitrogen balance of the soil is influenced by what happened earlier on the same plot. We recommend that simulations start *with a "warm up" period of at least 5 years* before the period of interest. You don't need exact dates for management operations for the warm up period (although having them helps). If no weather data are available for this period, you may have to re-use the data you do have. This may not be correct, but it may still provide better starting conditions for your simulation that running without an initialization period.

Fertilizing: For fertilization, you should specify the amount of carbon, nitrogen and ammonium directly. You can examine the exact content of organic fertilizer, which tend to vary a lot between farms, and you can estimate the turnover rate with laboratory experiments.

Tillage operations: You can fit the tillage operations to the machinery used at the actual farm, and make sure e.g. the plowing depth is right. Tillage implements are defined by how far down the soil is mixed and the fraction of organic matter on the surface that is incorporated in the soil by this operation.

Harvesting: Measure or estimate for how large a fraction of the various crop parts are left on the field, rather than assume all or nothing.

Crop data

At the minimal level, the existing DAISY crop parameter files are used without calibration. The model will function with the information from the DAISY library. It is evident that such an uncalibrated simulation does not consider the local variety grown.

The crop parameterization can be adjusted to local conditions in various ways, depending on the purpose of the simulation.

- Yield information: For some simulations, statistical yield data may be useful, but they do not describe the conditions on a given field. Local information of yield may be useful when simulating leaching, because it includes the effects of other liming factors. In general, yield information can be used for either calibration or validation.
- Biomass development over time: A simple improvement of the simulation can be obtained by measuring the biomass development over time, and noting the most important growth stages. This can be used for calibration of the crop module (-or validation).
- LAI-values: can be used directly as input to DAISY, for calibration and for assimilation in DAISY. It can also be used for verification of the model calculations. Measurement of both biomass and LAI are particularly useful for calibration of (new) crops.
- Root depth of the plant: Potential root depth for the crop is given as parameter in the crop file. If better local knowledge is available, this can be included in the simulation.

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For more detailed calibration of the crop modules or creation of new crop modules, even more detailed information in the form of field experiments with various levels of irrigation and fertilization can be required. The measurements would typically be:

- Dry matter content of the individual crop parts: (leafs, stem, storage organ, and if you are ambitious, roots) at regular intervals throughout the growth season.
- N content of the individual crop parts: (leafs, stem, storage organ, and if you are ambitious, roots) at regular intervals throughout the growth season.
- LAI-values: at regular intervals throughout the growth season.
- Crop height is used in some process descriptions together with canopy cover. This could also be measured at regular intervals.

4. Database for crop modelling

An overview of the data compiled for crop modelling in the production systems of the WaterFARMING project is provided in Figure 4. So far, experimental data has been compiled in North Europe only, namely Germany (Static Fertilisation Experiment in Bad Lauchstädt; Merbach and Schulz, 2012), The Netherlands (Wheat Experiment in Wageningen; Wiertsema, 2015) and Denmark (Food and Energy Experiment in Taastrup; Ghaley and Porter, 2013). Details about these data are provided below.

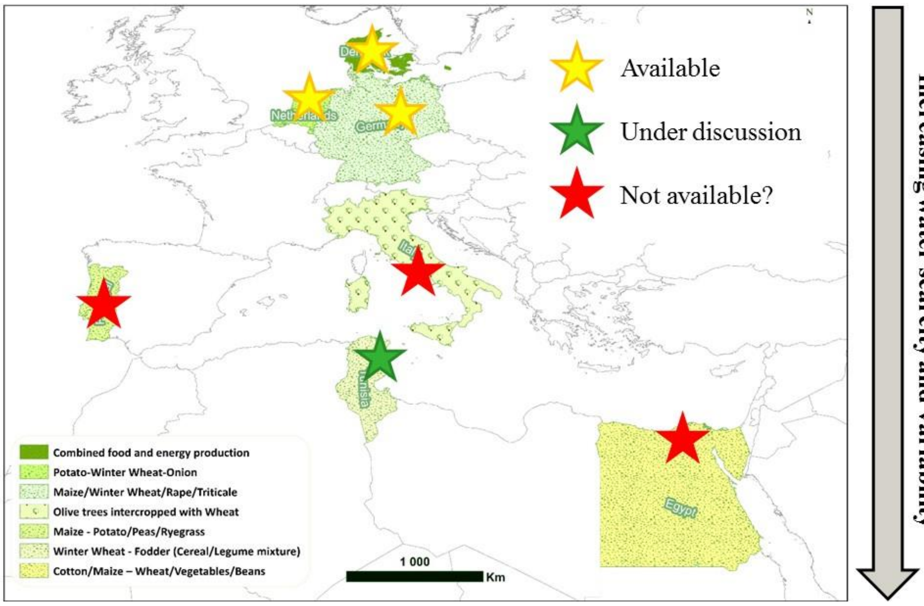

Figure 4. Data availability for crop modelling within the network of production systems of the WaterFARMING project. 'Available' means that data is ready to parametrize the crop models, 'under discussion' means the consortium is still seeking for promising datasets and 'not available' indicates that it remains unclear it will be possible to compile relevant data.

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The consortium is still looking for promising experimental data in Tunisia, and this will be discussed in the next annual project meeting to be held in Tunis (23rd – 25th April, 2018). Partners from Egypt, Portugal and Italy have difficulties compiling the experimental data requested and it is unclear whether the partners will be able to compile such information for these production systems.

4.1. Static Fertilization Experiment, Bad Lauchstädt, Germany

The Static Fertilization Experiment was established in 1902 in a Haplic Chernozem soil in Bad Lauchstädt, Central Germany. This long-term fertiliser experiment occupies an area of 4 ha and further information about describing the site/experimental conditions can be found in Merbach and Schulz (2013). This trial is relevant for WP2 as it allows the assessment of WUE and NUE in the production system of Germany using both empirical and crop modelling approaches.

4.1.1. Experimental conditions

The experiment is divided in eight strips where all the crops of the crop rotation (namely sugar beet – spring barley – potatoes – winter wheat) are cultivated simultaneously every year. Each strip is divided into three main blocks consisting of three different treatments of organic fertiliser application: a) no farmyard manure applied, b) 20 t/ha of farmyard manure and c) 30 t/ha of farmyard manure applied every second year prior to the root crops. These manure treatments were orthogonally combined with six different mineral fertiliser treatments: a) no NPK applied, b) PK applied, c) N applied, d) NK applied, e) NP applied and f) NPK applied. The amount of NPK applied depends on the type of crop and on the amount organic fertiliser applied and was adjusted over time to match the characteristics of the cultivated varieties. In 1978, a new experiment ("Extended Static Fertilization Experiment") was initiated in two of the strips of the Static Fertilization Experiment. In this new experiment, the previous organic and mineral fertiliser treatments were orthogonally combined with five different N application levels so that crop yield responses to N could be assessed. Sugar beet leaves and straw of spring barley and winter wheat were removed from the plots after each harvest. The experiment was not irrigated and was kept free of pests, diseases and weeds as much as possible.

Detailed crop and soil data have been compiled over the years for these two experiments through crop and soil samples taken every year from each treatment. Crop data include crop development (BBCH code) within the growing season, crop yield at harvest time, crop biomass at harvest time, nutrient (N, P and K) uptake at harvest time and dry matter content of the harvested products. Soil data include soil organic carbon content, pH, Total N, Total P and Exchangeable K. Daily weather data is available from an automatic weather station located nearby the experiment.

4.1.2. Interactive data visualization dashboard

Crop and soil data from the Static Fertilization Experiment were organized into a database. An interactive data visualization dashboard was created to visually ascertain data quality and perform preliminary analysis on NUE for the different arable crops (Figure 5). This is described below vis-à-vis descriptive statistics on crop yields but detailed results are beyond the scope of this report.

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A general overview of the interactive data visualization dashboard developed for the data of the Static Fertilization Experiment is provided in Figure 5. The dashboard includes general information on crop development over the growing season (BBCH scale), sowing density (plants/m^2), harvesting index and yield progress for each crop as well as detailed information relevant to study NUE (e.g. crop yield, nutrient uptake and nutrient applied per source). These are presented in more detail below together with descriptive statistics of crop yield per treatment. Trends in Total N, Total P, Exchangeable K and soil organic carbon content over time are also described. The dashboard includes six filters allowing to subset the data for unique combinations of crop x variety x year x strip x fertiliser treatment.

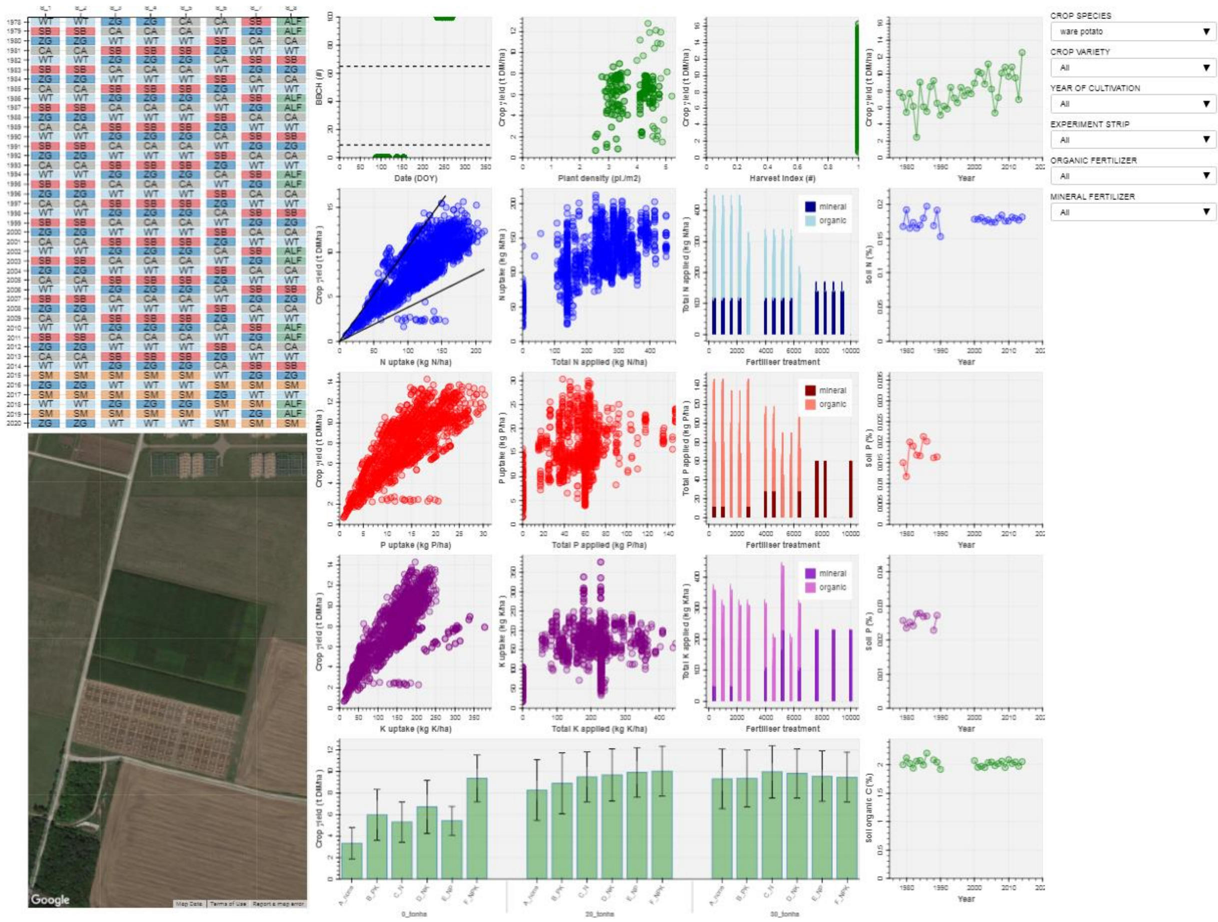

Figure 5. Overview of the interactive data visualization dashboard for the Static Fertilization Experiment, Bad Lauchstädt. The first column shows the crop cultivated in each strip in each year (top) and an aerial view of the experiment (below). The first row of scatterplots in green provides an overview of crop development, sowing density, harvest index and progress in actual yields. The second row of scatterplots in blue gives insights into crop yield, N uptake, N applied, form of N applied and Total N in the soil. Similar information is provided for phosphorus (third row in red) and potassium (fourth row in purple). Descriptive statistics of crop yield per treatment are provided in the barplot of the last row, in addition to trends in soil organic carbon. Six filters were included in order to subset the data by a) crop, b) variety, c) year, d) strip, e) mineral and/or f) organic fertiliser treatment.

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The relationship between crop yield and N uptake at harvest time is provided per crop in Figure 6 (data pooled between 1978 – 2016). The maximum yields observed in the experiment were approximately 22.0 t DM/ha for sugar beet, 5.5 t DM/ha for spring barley, 15.0 t DM/ha for ware potatoes and 10.0 t DM/ha for winter wheat. N uptake had a maximum of ca. 500 kg N/ha for sugar beet, ca. 200 kg N/ha for spring barley and ware potato and ca. 300 kg N/ha for winter wheat. For all crops, physiological efficiencies (in kg crop/kg N uptake) were properly benchmarked by the maximum N dilution values reported by Janssen (2017) for arable crops in the Netherlands. The large variability in physiological efficiencies observed can be explained by water and/or nutrient limitations during the growing season attributed to rainfall variability and fertilisers treatments imposed, but further research is needed to understand these. The effects of growth-reducing factors seem to be minor as most observations are above the value of maximum N accumulation value proposed by Janssen (2017).

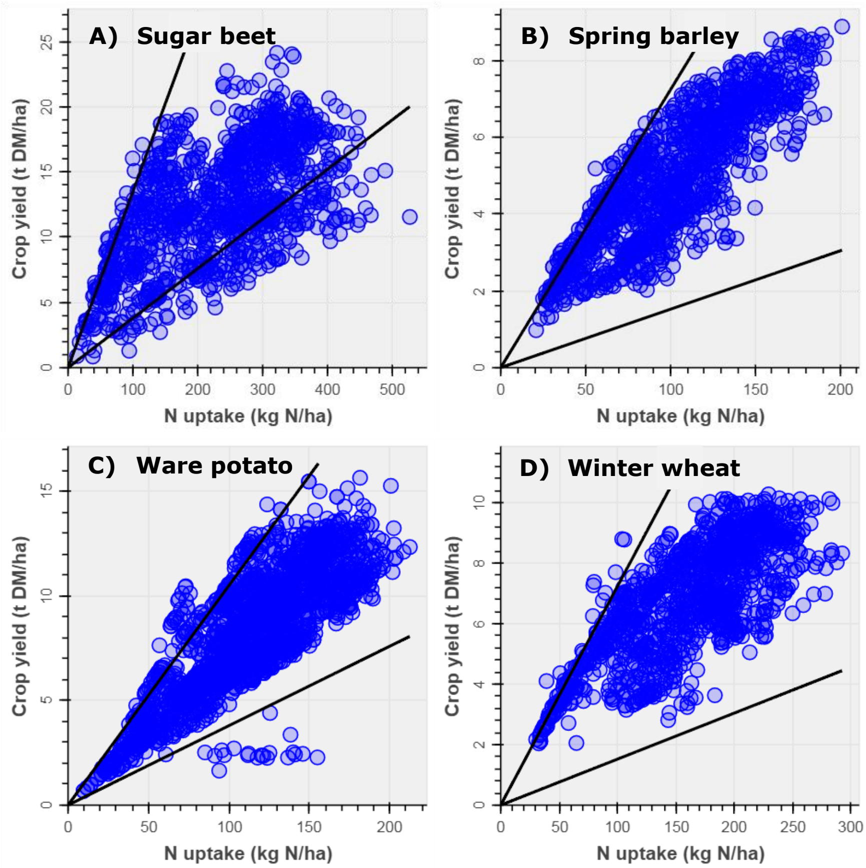

Figure 6. Relationship between crop dry matter yield and N uptake in the aboveground biomass (yield and biomass) at harvest time for A) sugar beet, B) spring barley, C) ware potato and D) winter wheat between 1978 – 2016. Data summarized from the Static Fertilization Experiment, Bad Lauchstädt (Central Germany). Solid lines show the maximum N dilution (top) and N accumulation (bottom) in each crop species according to Janssen (2017).

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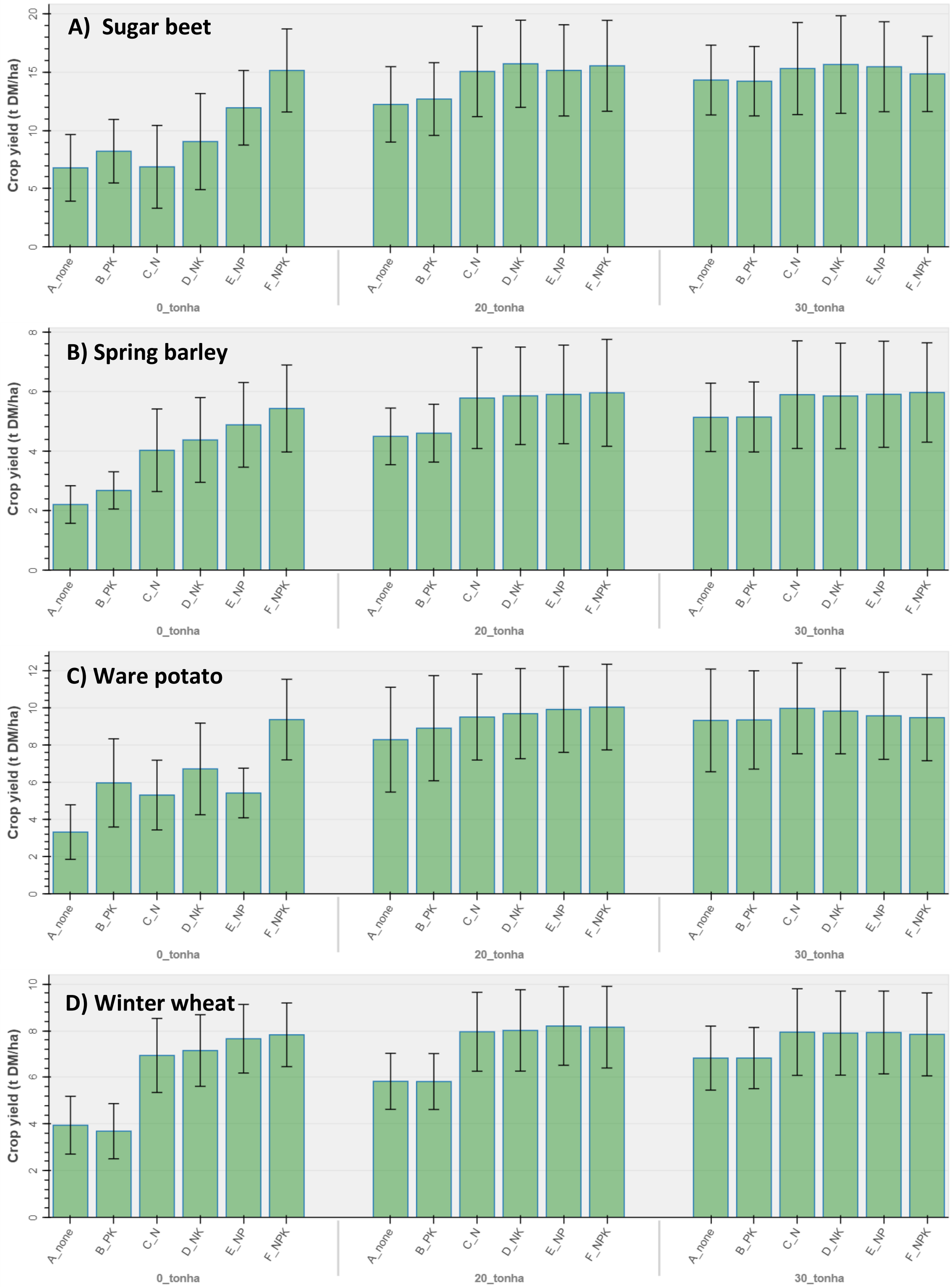

Figure 7. Descriptive statistics of crop dry matter yield per fertiliser treatment for A) sugar beet, B) spring barley, C) ware potato and D) winter wheat across the years 1978 – 2016. Data summarized from the Static Fertilization Experiment, Bad Lauchstädt (Germany). Error bars show the standard deviation of the mean.

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Descriptive statistics of crop yield per treatment are provided in Figure 7 for the period 1978 – 2016. Overall, crop yields were less affected by the omission of specific macro-nutrients in the treatments which received organic fertiliser, which points to a build-up of soil fertility (i.e., soil N, P and K) over time when farmyard manure is regularly applied to crops. Moreover, N seems to be the limiting factor when farmyard manure is applied as indicated by a) similar crop yield in the treatment with no mineral fertiliser and the treatment with only PK applied, b) similar crop yield between the N, NK, NP and NPK treatments and c) high crop yield in the treatments described in b) compared to the treatments described in a). Conversely, omitting specific macro-nutrients resulted in relatively large yield differences between the mineral fertilizer treatments when no farmyard manure was applied. In this case, there are some clear differences between crops: a) sugar beet yields are particularly high only in the NP and NPK treatments, c) ware potato yields are particularly high in the NK and NPK treatments c) spring barley and winter wheat yields are especially limited by N rather than by P and K. Further research will be conducted to gain further insights in NUE empirically using these data, to assess statistically significant yield differences between treatments and to calibrate and validate WOFOST for the production system in Germany.

4.2. Wheat Experiment, Wageningen, The Netherlands

A detailed experiment was carried out near the Haarweg (Wageningen, The Netherlands) by the Plant Production Systems Group, Wageningen UR, in the years 2014 and 2015. The objective of this experiment was to collect detailed data on biomass accumulation and leaf area dynamics of winter wheat to be used for crop modelling purposes. In this site, the dominant soil type is silty clay loam. Further details about this experiment can be found in Wiertsema (2015). This experiment is highly suitable for crop modelling purposes and will allow for detailed parameterization of crop models prior to WUE and NUE assessments for winter wheat within WP2.

4.2.1. Experimental conditions

A full factorial split-plot design (with four replicates/blocks) was used in this experiment with the different N application levels allocated to the whole plots and the varieties to the split-plots. The mineral N treatments consisted of 180, 240 and 300 kg N/ha applied during the growing season. These rates were chosen to assess the optimal amount of N required to achieve the potential yield, given that the current technical recommendation for winter wheat in the Netherlands is 240 kg N/ha. Three different varieties were cultivated at each N application level namely Julius, Tabasco and Ritmo. Julius and Tabasco are two recently released varieties (2009 and 2008, respectively) which are still widely cultivated by farmers in the Netherlands. Conversely, Ritmo is an old variety released in 1992, which is hardly cultivated by farmers nowadays, but it was included in the experiment to assess how crop characteristics may have changed over the last two decades. The experiment was irrigated twice with a boom irrigator (based on monitoring of soil water availability with seven monitoring wells and tensiometers placed at 35 and 65 cm depth in seven replications) and was kept free of pests, diseases and weeds as much as possible.

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Crop growth and development was closely monitored during the growing season. Nine destructive samplings were conducted to assess the dry matter weight of different plant organs as well as leaf area index and specific-leaf area over time. Light interception measurements were also conducted with a LiCOR-2000 above, within and below the canopy to describe changes in radiation use efficiency throughout the growing season and crop development was assessed using the Fekkes scale. Long-term daily weather data is available from an automatic weather station located nearby the experiment.

4.2.2. Interactive data visualization dashboard

An overview of the interactive data visualization dashboard developed using the data of the wheat experiment conducted in Wageningen is provided in Figure 8. This dataset contains detailed information on crop development, leaf area dynamics and biomass accumulation over time, which makes it ideal for crop modelling purposes. More precisely, this dataset is suitable for detailed calibration and evaluation of crop models and for testing potential model improvements in the routines describing WUE and NUE.

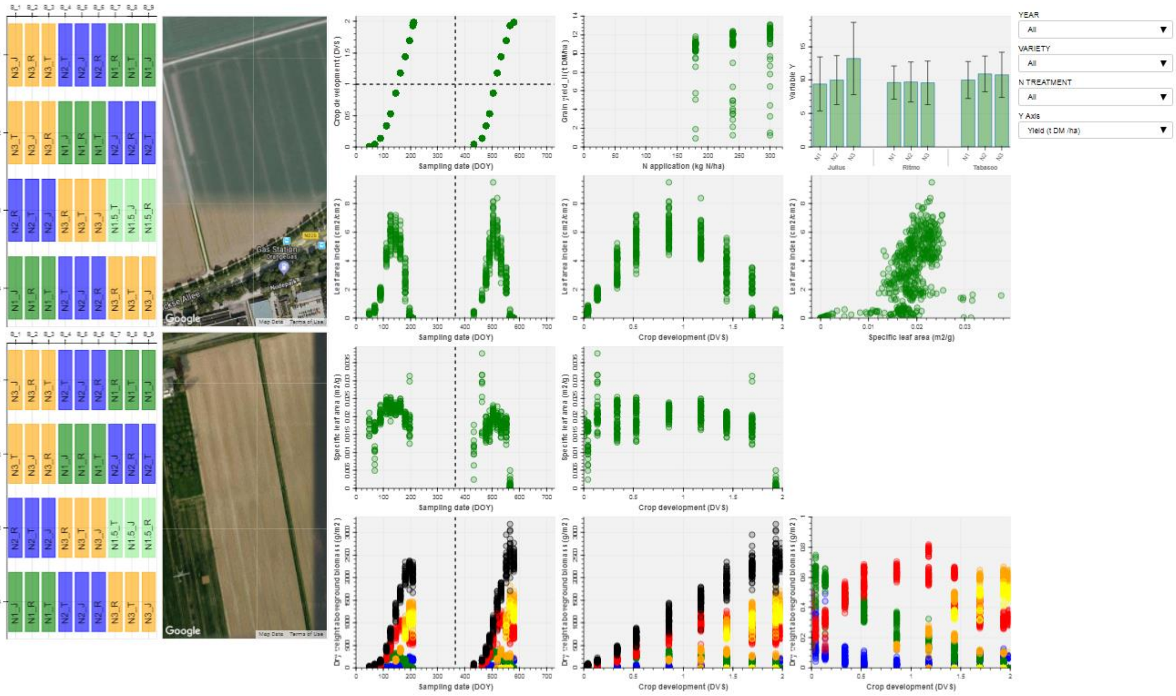

Figure 8. Overview of the interactive data visualization dashboard for the wheat experiment conducted by the Plant Production Systems group in Wageningen, The Netherlands (2014 – 2015). The first column shows the layout out of the experiment (left) and an aerial view of the field (right). The first rows provides information on crop development over time and on yield response to N applied, while descriptive statistics of crop yield are presented in the barplot. The second and third rows summarize leaf area index and specific leaf area over time. The last row shows biomass accumulation per organ and the partition of biomass for the different crop organs over time. Three data filters were included to subset the data by a) year, b) variety and/or c) N treatment.

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Yields of winter wheat were above 10 t/ha for all treatments in the year 2014 and yield variability in each treatment was small (Figure 9A). Yield responses to N applied were observed for each variety meaning the highest wheat yield was observed when 300 kg N/ha were applied. The temporal dynamics of leaf area index followed the expected pattern (Figure 9B): a sharp increase was observed in the first half of the growing season, up to a value of ca. 7 cm^2/cm^2 slightly before anthesis (DVS=1), after which it gradually decreased until physiological maturity (DVS=2). The variability observed in leaf area index for each sampling time reflects differences in varieties and N application levels. Trends in biomass accumulation (total and per organ) are presented in Figure 9C. Total biomass accumulation increase linearly over time up to ca. DVS=1.5 after which it remained constant at a maximum of ca. 1400 g/cm^2. In terms of biomass partition in the crop, there was a decline in leaf biomass and an increase in ear and grain biomass over time. Stem biomass increased until anthesis after which it slightly declined. The temporal trends observed in biomass partition can be explained by the translocation of assimilates from vegetative to reproductive organs.

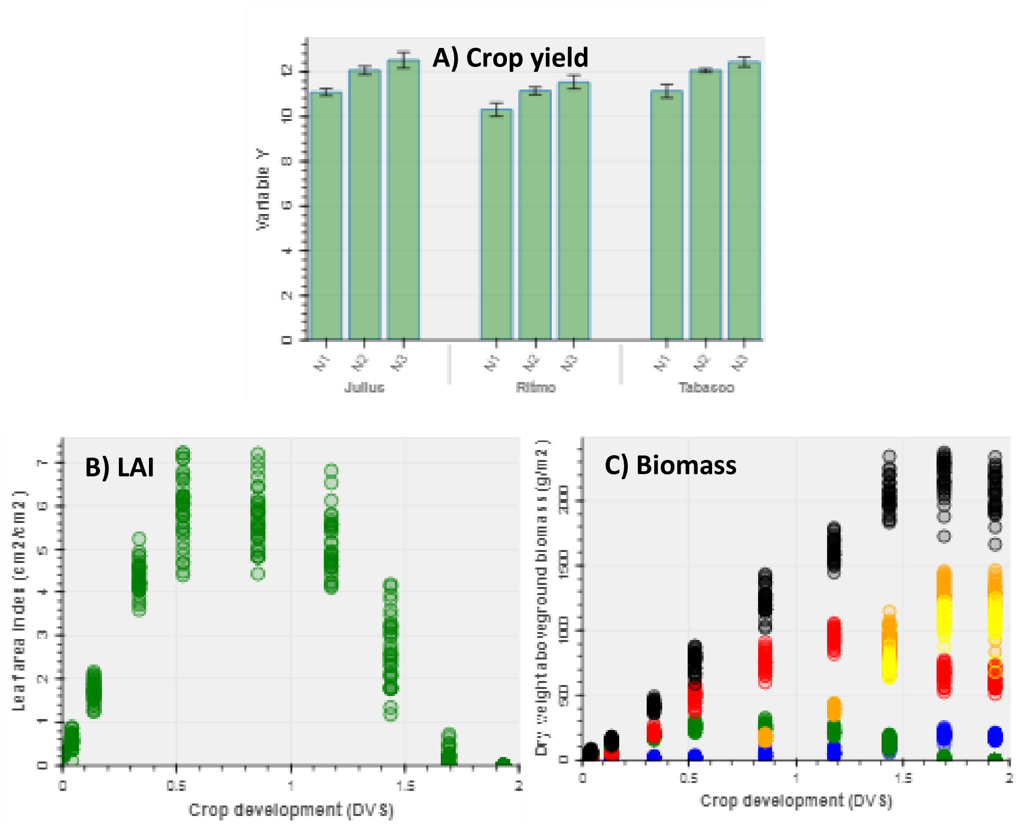

Figure 9. Summary results of the wheat experiment conducted by the Plant Production Systems group in Wageningen, The Netherlands (2014): A) descriptive statistics of crop yield for three different varieties cultivated with three different N application levels, B) dynamics of leaf area index (LAI) over time and C) biomass accumulation over time.

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4.3. Food-Energy System, Taastrup, Denmark

The Danish CFE system is a Combined Food and Energy system, integrating food and fodder crops with mixed stands of willow, alder and hazelnut. It was established at the former Royal Agricultural and Veterinary University's experimental farm, Taastrup (55°40'N, 12°18'E), about 20 km west of the city of Copenhagen in the Spring of 1995 (Porter et al., 2009). Since the beginning of 2007, the site has been an experimental farm under the Faculty of Life Sciences of the University of Copenhagen (Porter et al., 2009). The farm is located at 130 m above sea level, with sandy clay loam (clay 15%, silt 18%, sand 65%) and soil depth is 1-2 m (Ghaley et al., 2014).

4.3.1. Experimental conditions

The CFE system consists of 10.1 ha of food components like spring barley, winter wheat, oat and lucerne/ryegrass as fodder components and 0.75 ha of biofuels (biomass belts) consisting of five belts of short rotation woody crops (Ghaley and Porter, 2013). Each biomass belt is 10.7 m wide and consists of 5 double rows of SRC; within the five double rows, three in the middle consist of three willow clones (one double row each) of *Salix viminalis* (L.) "Jor", *Salix dasycladus Wimmer* and *Salix triandra cinerea* (L.) bordered by one double row of common hazel *Corylus avellana* (L.) on one side and one double row of alder (*Alnus glutinosa (L.) Gaertner*) on the other side (Figure 10; Ghaley and Porter, 2013).

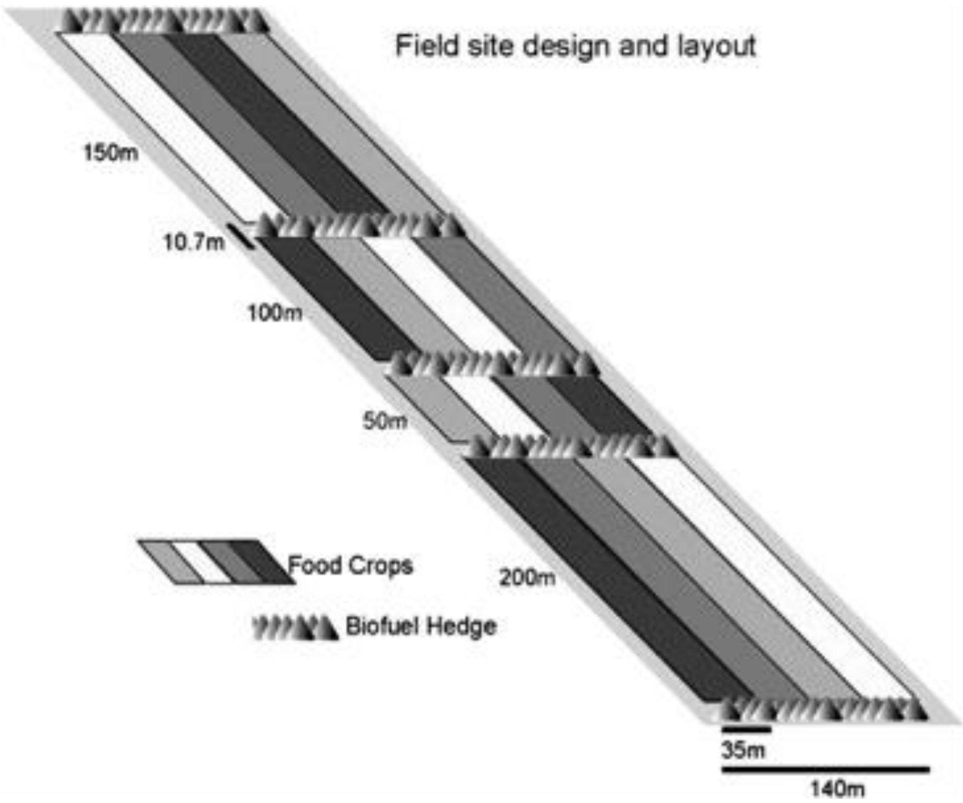

Figure 10. Field layout of the CFE experimental farm in Taastrup, Denmark.

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The trees are planted at within-row spacing of 0.5 m and between-row distance of 0.7 m. Each double row is 1.3 m apart, with a planting density of 18,600 trees/ha. Along the long edges of the SRC belts, 4 meter-wide "turning headlands" were created by fallowing a grass-ley, this area was only for machinery turning without any crop production. The biomass belts are established at varying distances of 50, 100, 150 and 200 m to assess the spatial effects of distance (Figure 10). The biomass belts are harvested and chipped every 4 years and the wood chips taken to a nearby heat and power station for the production of heat and electricity; while the food and fodder crops grown between the biomass belts are harvested annually (Porter et al., 2009). An external company was hired to harvest and chip the tree component of the system. The woodchips are then taken to a nearby heat and power station for the production of heat and electricity.

The initial four-year crop rotation was in the following order: 1) winter wheat 2) spring barley 3) clover grass 4) clover grass. The CFE system had been in such rotations from 2003 till 2012. Since 2013, the CFE system has been followed by another rotation: 1) oat 2) winter wheat + ryegrass 3) barley under-sown with lucerne and ryegrass 4) lucerne and ryegrass. The CFE system is managed organically, without the use of any fertilizers, herbicides or pesticides and with the nutrient sources mainly derived from biological nitrogen fixation (Ghaley et al., 2014).

5. Next steps

5.1. Expanding the database

So far only experimental data from the production systems in North Europe has been compiled, as described in this report. As the agroecological conditions, and varieties used, differ considerably between these production systems and the production systems in South Europe and North Africa, further efforts will be placed to compile experimental data in collaboration with partners from at least one production system in South Europe and one production system in North Africa. This will be discussed in the next annual meeting to be held in April 2018 in Tunis, Tunisia. This database will be the core of the crop modelling work conducted within the WaterFARMING project.

5.2. Estimation of NUE and WUE

The database of field experiments compiled in this report will be used to parameterize crop models and evaluate their accuracy in predicting crop yield, WUE and NUE. Once model parametrization is done, the model will be used to simulate WUE and NUE for the main crops and crop rotations in each production system. This information will be used to benchmark WUE and NUE observed in farmers' fields in a later stage of the WaterFARMING project. The crop model will also be used to simulate different management scenarios over as many years as possible and covering spatial variability at catchment scale as possible so that model outputs can be used in the up-scaling exercise planned for a later stage in the WaterFARMING project. Overall, we hope to have crop models parametrized so that they can be re-used in future studies conducted in these production systems.

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