Assessment of water and nutrient use efficiencies and gaps in the network of production systems

WaterFARMING project
Report for deliverable 2.2.

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Disclaimer

This deliverable aims to **analyse and provide benchmarks for water and nutrient use** within the network of production systems within the WaterFARMING project. This is to be done using the field-level model approach described in D2.1 for all production systems and using farmer field data for a smaller number of production systems and depending on data availability. Below, we document what has been done so far for each of these activities and identify the next steps needed to improve the current results in the near future.

Crop Model. The field level approach described in D2.1 for the field-level assessment of crop yields and water- and nutrient-use efficiencies comprises two crop models: WOFOST and DAISY. The former is led by WUR (The Netherlands) while the latter by UCPH (Denmark). As described in this deliverable, WOFOST was used to simulate wheat yields (potential, water-limited and nitrogen-limited), water- and nitrogen-use efficiencies across the network of production systems of WaterFARMING. The model was evaluated in more detail in the Netherlands and Germany for which detailed data was readily available. For the other production systems, the simulations relied mostly on expert knowledge and literature. Overall, WOFOST was able to simulate the different production levels well but we identified some aspects that require model improvements in the future. An update of the activities conducted with DAISY are also described in this deliverable. The model was calibrated and validated for pea-barley intercrop, as well as a pea and a barley sole crop, in Denmark based on field trials conducted locally. In general, the model was able to reproduce aboveground biomass and yield relatively well. However, the current exercise will be improved further until the end of the project also incorporating data from a similar intercropping trial conducted in 2019.

Farm data. Initially, we planned to analyse water- and nutrient-use efficiencies using farmer field data for two contrasting production systems of the WaterFARMING project (Germany and Italy). However, we were not able to access to this date detailed information on crop yields and crop management for a relatively large number of farmer fields in those production systems. The reasons for this are various such as privacy reasons in case of Germany and budget limitations in case of Italy. To overcome these challenges, we considered another production as a case study for this analysis, namely arable crops in The Netherlands, for which the data requirements were met. A full description of the dataset, methodological approach and preliminary results, as well as some words about the usefulness and applicability of the methods used and knowledge gained in this analysis to the other production systems, are provided in this deliverable. The next steps to finalize this analyse are detailed in Section 7. We will work on such improvements within the remaining of the WaterFARMING project and plan to submit this work for peer-review in an international scientific journal.

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Simulation of wheat yield, water and nitrogen use efficiencies across Europe and North Africa

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1 Introduction

Current concerns about limited availability and pollution of water resources cal for an assessment of the potential to improve water (WUE) and nutrient use efficiency (NUE) in agriculture. Both concepts can be expressed by a number of different indicators (van Halsema & Vincent, 2012; Dobermann, 2005) such as water productivity (WP) and agronomic N use efficiency (AE-N). WP expresses the crop yield produced per unit of water available for crop growth during the growing season (van Halsema & Vincent, 2012). This helps understanding how water stress limits to crop growth and how these relates to the amount, distribution and source of water available. AE-N indicates the crop yield produced per unit of N applied (Dobermann, 2005). This is useful to assess nutrient losses to the environment (capture efficiency, defined as the amount of N uptake per unit N applied) and the ability of the crop convert N into yield (conversion efficiency, defined as the kg yield per unit N uptake).

An important tool to estimate WUE and NUE of cropping systems 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). Crop models are highly suitable to explore genotype x environment x management (G $\times$ E $\times$ M) interactions in a cost-effective way. Indeed, Asseng *et al.* (2001) proposed to use crop growth modelling to extrapolate experimentally-derived measurements of WUE and NUE across space and time across a Mediterranean climate in Australia. Grassini *et al.* (2009) and Lollato *et al.* (2017) used crop growth models to derive benchmarks of WP of maize and wheat in the U.S. mid-West, respectively. A similar approach was used for maize and wheat in Europe and North Africa (Edreira *et al.*, 2018), but NUE assessments at local level for these regions are lacking.

Insights into the magnitude and variation of WUE and NUE are useful to inform policies aiming to reduce the environmental impact of agriculture. These are especially pronounced in the EU Nitrates Directive (ND), Water Framework Directive (WFD) and Groundwater Directive (GD). The ND was launched in 1991 with the aim to reduce water pollution caused or induced by nitrate from agricultural sources. The WFD was adopted in 2000 to guarantee sufficient quantities of good quality water across the EU. This was complemented in 2006 with the GD, which introduced measures to limit inputs of pollutants into groundwater. Similar policies are implemented in North Africa with the aim to improve water quality and reduce water use in agriculture.

This report aims to set targets for water and nitrogen use efficiency in North Europe, South Europe and North Africa, using wheat as a test crop. First, the network of production systems is described. Second, the crop modelling approach is explained. This builds upon the crop model WOFOST to estimate potential, water-limited and nitrogen-limited yields. Finally, results of a field scale assessment are presented. These include a description of wheat yield variability and water limitations as well as benchmarks for water and nitrogen use efficiency in each production system.

2 Network of production systems

2.1 Site description and crop selection

A network of production systems representative of a) continuous arable systems (e.g., wheat/rapeseed rotation), b) mixed farming rotations of cereals with grass (e.g., wheat-alfalfa/clover leys/rye grass) and c) agroforestry systems with annual crops/grasses was identified in different socio-economic and environmental zones in Europe and North Africa (Figure 1). The production systems are embedded within catchments like Selke catchment in Germany, Nile valley in Egypt and Grombalia aquifer in Tunisia. The different production system capture a gradient of increasing water limitation and supply uncertainty on the field-farm-catchment scales from North Europe to North Africa. Each production system was described in terms of crop yields, water and nutrient management and socio-economic conditions as compiled in Deliverable 1.1.

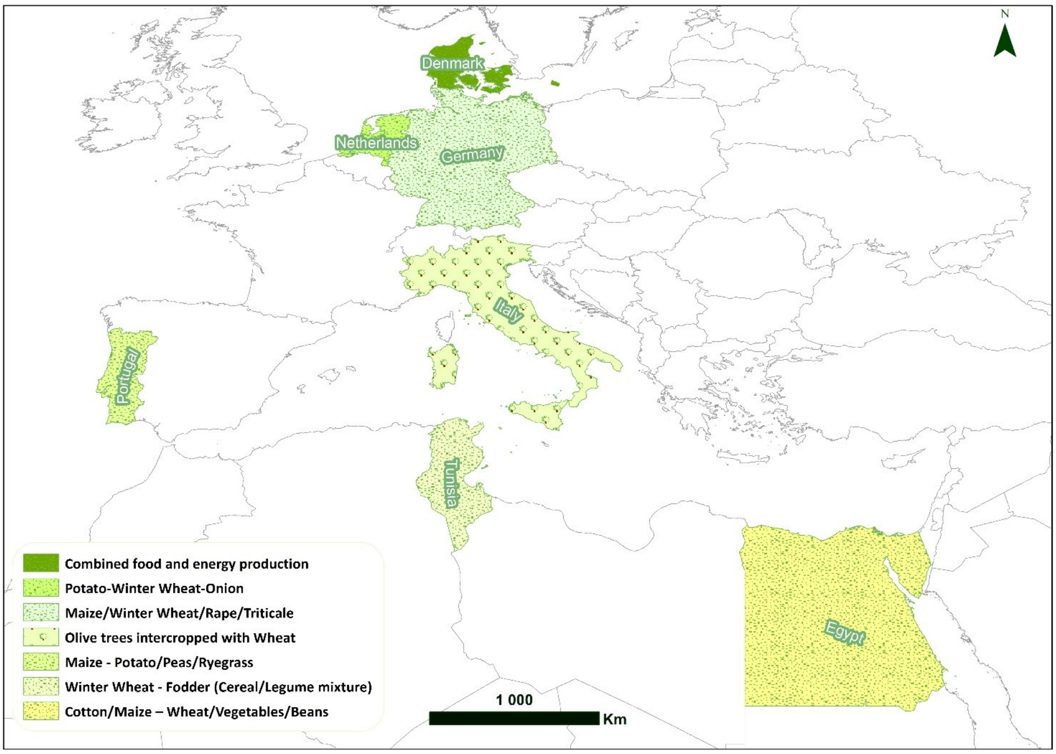

Figure 1. Production systems analysed in Europe and North Africa selected across a gradient of water scarcity. Details about the weather data of each production system are shown in Table 1.

The analysis of WUE and NUE presented here focuses on wheat only. Wheat is a major crop in Europe and North Africa and it is cultivated in all production systems. There are some striking differences in genotypes and crop management though. First, winter wheat varieties are cultivated in North Europe while spring wheat varieties are cultivated in South Europe and North Africa. The former require a period of vernalization during the winter, and are thus frost tolerant, while the latter do not have such requirements. In terms of crop management, considerably large amounts of nutrients are used in North Europe than in South Europe or North Africa, where the risk of crop failure due to rainfall variability is more pronounced. As a result, wheat yield gaps are smaller in North Europe than in South Europe and North Africa (Schils *et al.*, 2018).

2.2 Climatic conditions and weather data

The network of production systems covers three different macro-climates, according to the Köppen-Geiger climate classification (Table 1; Kottek *et al.*, 2006). The climate in North Europe is classified as 'warm temperate, fully humid with a warm summer' (Cfb) and in South Europe (and Northern Tunisia) as 'warm temperate, summer dry with a hot summer' (Csa). An 'arid, desert and hot arid' climate (BWh) is found in Egypt. The network of production systems also covers a gradient of water scarcity, which is best depicted by the aridity index (Table 1), defined as the ratio between annual total precipitation and annual total potential evapotranspiration (van Wart *et al.*, 2013). The aridity index increases with increasing latitude of each production system (Table 1) ranging from more than 10000 mm mm^{-1} in Denmark and The Netherlands to less than 4000 mm mm^{-1} in Tunisia and Egypt.

Table 1. Weather data compiled for each production system. Data from the Global Yield Gap Atlas (GYGA) are freely available at www.yieldgap.org, data from WUR are freely available at models.pps.wur.nl and data from UCPH and UFZ are available upon request.

Country	**Weather station**	**Lat.**	**Long.**	**Years**	**Köppen**	**Aridity**	**Source**
Denmark (DK)	Taastrup	55.65	12.30	1962 - 2016	Cfb	10199.2	UCPH
Netherlands (NL)	Wageningen	51.97	5.67	1954 - 2018	Cfb	11129.4	WUR
Germany (DE)	Magdeburg	51.80	11.32	1981 - 2014	Cfb	7173.5	UFZ
Italy (IT)	Viterbo	42.44	12.06	2001 - 2013	Csa	7092.2	GYGA
Portugal (PT)	Beja	38.02	-7.87	2001 - 2013	Csa	4544.2	GYGA
Tunisia (TN)	Carthague	36.83	10.23	2000 - 2014	Csa	3628.9	GYGA
Egypt (EG)	Cairo	30.12	31.40	1980 - 2010	BWh	140.8	GYGA

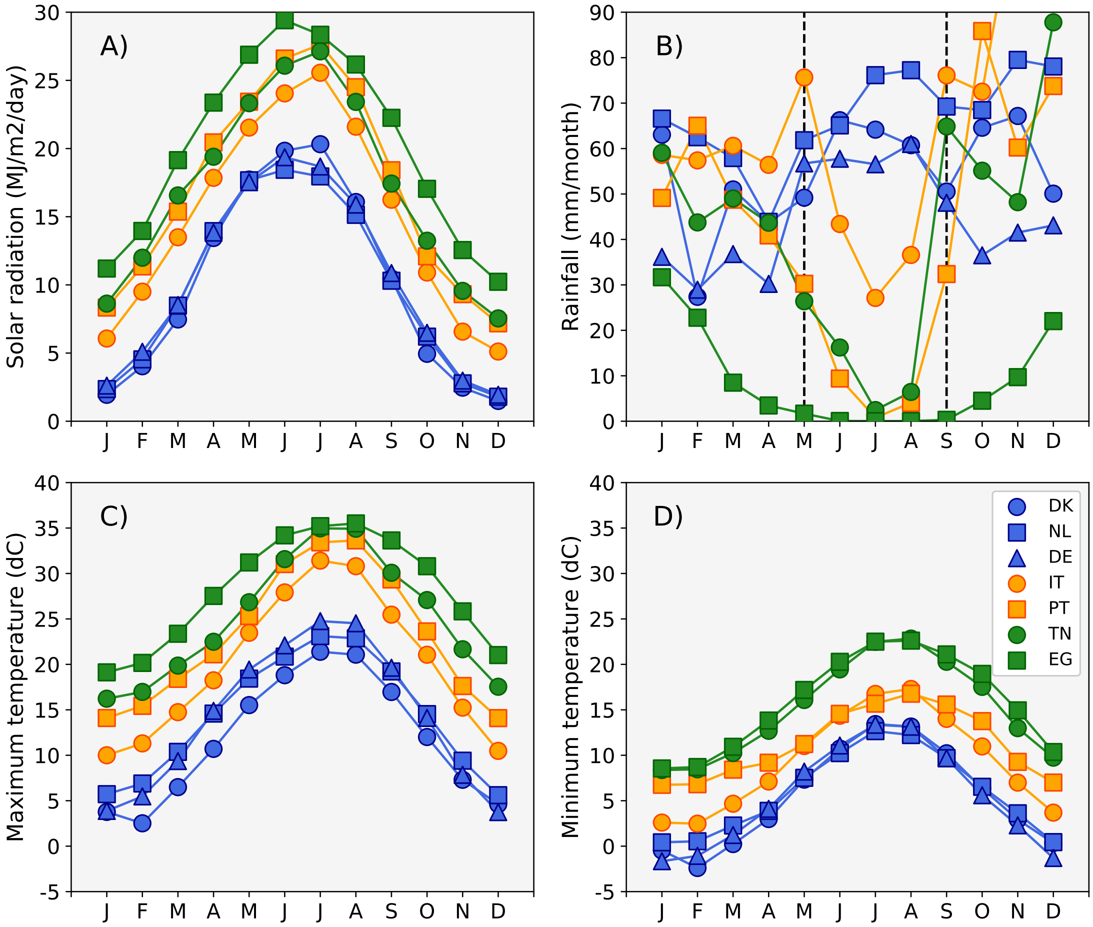

Figure 2. Monthly means of A) solar radiation, B) precipitation, C) maximum temperature and D) minimum temperature across the network of production systems over the period 1990 - 2010. Country codes: DK = Denmark, NL = The Netherlands, DE = Germany, IT = Italy, PT = Portugal, TN = Tunisia, EG = Egypt.

For each production system, a weather station with long-term daily weather data on solar radiation, minimum and maximum temperature and precipitation was selected (Table 1). For Denmark, weather data from Taastrup was available from the University of Copenhagen (UCPH) for the period 1962 - 2016. For The Netherlands, weather data from Wageningen was available from Wageningen University (WUR) for the period 1954 - 2018. For Germany, weather data from Magdeburg was available from the Helmoltz Centre for Environmental Research (UFZ) for the period 1981 - 2014. Weather data for Italy (Viterbo), Portugal (Beja), Tunisia (Carthague) and Egypt (Cairo) was available from the Global Yield Gap Atlas (GYGA). The period covered varied per station as indicated in Table 1.

The monthly mean solar radiation, precipitation and maximum and minimum temperature are shown for each weather station in Figure 2. Monthly mean solar radiation decreased with increasing latitude and had a maximum in June or July (ca. 20 MJ m^2 d^{-1} in North Europe and 25 - 30 MJ m^2 d^{-1} in South Europe and North Africa; Figure 2A). The variation of monthly mean maximum and minimum temperature across sites and months was similar to that of solar radiation (Figures 2C and 2D). The peaks of maximum (30 - 35°C in South Europe and North Africa and ca. 20°C in North Europe) and minimum temperatures (10°C in North Europe, 15°C in South Europe and 25°C in North Africa) occurred in the months of July or August. Negative minimum temperatures were observed only in North Europe (Figure 2D). Finally, there were also clear differences in precipitation across the network of production systems (Figure 2B): total annual precipitation declined with decreasing latitude and during the summer months ca. 60 - 70 mm $month^{-1}$ occured in North Europe and close to no precipitation was observed in South Europe and North Africa.

3 Crop modelling approach

The crop modelling approach used in this study builds upon the concepts of production ecology (van Ittersum & Rabbinge, 1997). These distinguish three different yield levels to capture the influence of growth-defining, -limiting and -reducing factors for crop growth. The *potential yield* assumes plant growth is defined by growth-defining factors only 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. The *water-* or *nutrient-limited yield* assumes plant growth 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. Finally, the *actual yield* reflects a further reduction of the water- or nutrient-limited yield by growth-reducing factors such as weeds, pests, diseases and/or other pollutants. This is the most common situation in farmers' fields across agricultural production systems worldwide.

Crop growth simulation models are often used to estimated potential, water-limited and nutrient-limited yields for a well-defined biophysical environment (van Ittersum *et al.*, 2013; Lobell *et al.*, 2009). In this study, a recent version of the crop growth model WOFOST (WOrld FOod STudies, de Wit *et al.*, 2019) was applied to estimate the different yield levels and associated water and nitrogen (N) use efficiencies. The former reflects the kg DM crop harvested per unit evapotranspiration and the latter per unit of N applied.

3.1 Model description

WOFOST is a semi-deterministic crop growth simulation model of physiological processes including crop phenology, light interception, photosynthesis (i.e., assimilation of carbohydrates), respiration, assimilate partitioning, leaf area dynamics, evapotranspiration, among others. The model is a member of the family of Wageningen crop models (van Ittersum *et al.*, 2003) and has been widely applied under temperate conditions (e.g., Schils *et al.*, 2018). Crop growth and development are simulated 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.

WOFOST simulates potential, water- and nutrient-limited production (de Wit *et al.*, 2019), although the latter is under testing phase. 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 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. This is determined through a soil water balance applying a tipping bucket approach in the root 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.

For *nutrient-limited conditions*, dynamic crop nutrient demand and uptake are simulated according to the methods described by Groot & de Willigen (1991) and Shibu *et al.* (2010). The approach is implemented for N, P and K using the concept of nutrient nutrition index i.e., the ratio of actual nutrient concentration and critical nutrient concentration in the crop. The former depends on the nutrients available in the soil through mineralization and applied fertilisers. The uptake of these depends on crop demand which is defined as the difference between maximum nutrient concentration in the crop and the actual nutrient concentration. Nutrient translocation to storage organs is accounted for but, similarly to nutrient uptake, it stops at a certain crop-specific development stage. Nutrient stress affects the assimilation rate, dry matter partitioning and leaf extension dynamics. In case of drought stress the strongest of these factors is selected as the overall stress factor.

3.2 Model parametrization

Simulations of potential, water-limited and nitrogen-limited production were done for the period 1990 - 2015, depending on the availability of weather data (Table 1). A detailed description of how the model was parametrized is provided below.

3.2.1 Potential production

Simulation of potential production in WOFOST requires daily weather data, a set of cultivar-specific crop parameters and management information on sowing and harvesting dates. Daily weather data for the entire simulation period, including the initialization period, includes solar radiation (MJ m^2 d^{-1}), minimum and maximum air temperature (°C), wind speed (m s^{-1}) and vapour pressure (kPa). Solar radiation, temperature and wind speed were directly available for each weather station (Table 1 and Figure 2), while vapour pressure was estimated based on the minimum temperature. An atmospheric CO_2 concentration of 360 ppm was assumed across sites and years.

Crop- and variety-specific parameters are available for different arable crops in WOFOST as a result of previous model parametrizations (Boons-Prins *et al.*, 1993). The simulations described here use the calibrated parameters for a generic winter wheat variety (#102) in North Europe and spring wheat variety (#106) in South Europe and North Africa. The main difference between both varieties is the length of the growing season (controlled by the parameters TSUM1 and TSUM2 i.e., the temperature sum between emergence and anthesis and between anthesis and maturity, respectively) and the vernalization requirements (defined by different parameters). The tabular parameter AMAXTB (maximum leaf CO_2 assimilation rate as function of development stage) was increased by 20% compared to the original value to capture yield progress and changes in atmospheric CO_2 concentration over time.

Regarding crop management, the day and month of sowing were randomized between day 1 and day 30 and between month 10 (October) and month 11 (November), respectively. This range corresponds to the common sowing window in each production system. The simulation was finalized on September 1st, a few weeks after the crop reached physiological maturity (data not shown). The potential yield (Yp, t DM ha^{-1}) derived from these simulations corresponds to the total weight of the storage organs at physiological maturity.

3.2.2 Water-limited production

The data and assumptions used to simulate potential production were also used to simulate water-limited production. The main difference between both was that the latter also considered daily precipitation (mm d^{-1}) and soil physical properties to assess the soil moisture and drought stress on a daily basis. Three contrasting soil types (clay, loam and sand) were considered in each production system. Clay soils were assumed to retain 0.104, 0.300 and 0.410 cm^3 water cm^{-3} soil at wilting point, field capacity and saturation, respectively. Loamy soils were assumed to retain 0.099, 0.272 and 0.390 cm^3 water cm^{-3} soil at wilting point, field capacity and saturation, respectively. Finally, sandy soils were assumed to retain 0.040, 0.110 and 0.390 cm^3 water cm^{-3} soil at wilting point, field capacity and saturation, respectively. These soil types were not meant to be representative within each production system but rather to explore water limitations across a wide range of weather × soil conditions.

The water-limited yield (Yw, t DM ha^{-1}) derived from these simulations corresponds to the total weight of the storage organs at physiological maturity. The difference between Yp and Yw indicates the yield gap due to drought stress during the growing season. Benchmarks for water productivity were further derived as the relationship between Yw and the simulated seasonal evapotranspiration (mm; Edreira *et al.*, 2018). The latter was computed as the cumulative soil evaporation and crop transpiration between sowing and physiological maturity.

3.2.3 Nitrogen-limited production

N limitations on crop growth were considered alongside water limitations for the same weather × soil units as described for water-limited production. Indigenous soil nutrient supply at the start of the season was assumed to be 50 kg N ha^{-1}, 250 kg P ha^{-1} and 250 kg K ha^{-1}, independently of the soil type.

A set of 300 different N management strategies were devised to compute wheat yield responses to N and to study agronomic N use efficiency (AE-N). These consisted of four split applications of N, with randomized N rate and N timing, and ample supply of P and K to avoid limitations of these nutrients. N rates included a control level (0 kg N ha^{-1} in all splits) and incremental levels of N applied per split (up to a maximum of 150 kg N ha^{-1} per split). The days of N timings were randomized between 1 and 30 and the first split occurred in February, the second in March, the third in April and the fourth in May. The total amount of N applied with the different management strategies ranged between 0 and 519 kg N ha^{-1} and was approximated by a normal distribution with mean 198 and standard deviation 10 kg N ha^{-1} (data not shown). The N-limited yield (Yn, t DM ha^{-1}) derived from these simulations corresponds to the total weight of the storage organs at physiological maturity.

4 Assessment at the field scale

4.1 Magnitude and variability of wheat yields

The potential yield (Yp) of wheat was greatest in North Europe, intermediate in South Europe and lowest in North Africa (Figure 3A). Differences between production systems were mostly explained by the duration of the growing season (longest in North Europe, intermediate in South Europe and shortest in North Africa; data not shown). Mean Yp of winter wheat in North Europe was 10.58 t DM ha^{-1} and there were no major differences between production systems. Mean Yp of spring wheat in Italy was greater than in Portugal, 9.60 and 8.58 t DM ha^{-1}, respectively. Mean Yp of spring wheat in Tunisia was 6.55 t DM ha^{-1}, while in Egypt it averaged 4.40 t DM ha^{-1}.

The water-limited yield (Yw) is by definition smaller than Yp and its magnitude was similar to Yp in North Europe but much lower than Yp in South Europe and North Africa (e.g., Figure 3B). For a loam soil, Yw was on average 10.32 t DM ha^{-1} for winter wheat in North Europe, 7.09 t DM ha^{-1} for spring wheat in South Europe and 1.32 t DM ha^{-1} for spring wheat in North Africa. In the latter case, it is worth noting that crop failure was observed in most of the years simulated in Egypt and, to a less extent, in Tunisia (see below). There were also clear differences in Yw across soil types with the greatest values reported in clay soils, intermediate in loam soils and lowest in sandy soils (Figure 4). This reflects differences in soil water holding capacity between soil types (see Section 3.2.2).

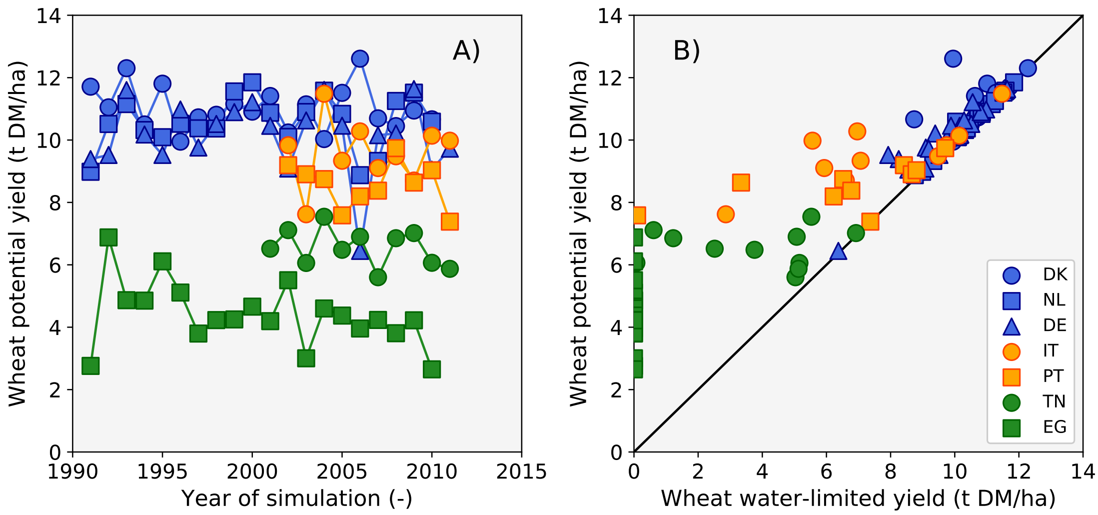

Figure 3. Simulated wheat potential (Yp) and water-limited yield (Yw) across the network of production systems: A) Yp variability over time and B) water limitations in a loamy soil per year per site. Country codes: DK = Denmark, NL = The Netherlands, DE = Germany, IT = Italy, PT = Portugal, TN = Tunisia, EG = Egypt.

The variability of Yp and Yw was greatest in North Africa, intermediate in South Europe and smallest in North Europe (Figure 3A and 3B, respectively). This reflects the gradient of water scarcity inherent to the network of production systems chosen (Table 1 and Figure 2B). The coefficient of variation of Yp for winter wheat in North Europe was 9.2%, while greater values were observed for spring wheat in South Europe (10.8%) and in North Africa (26.1%). The variability of Yw was much greater than that of Yp, especially in South Europe (47.3%) and North Africa (76.2%). In North Europe, Yw in loamy soils was similar to Yp in most of the years simulated reflecting few water shortages during the growing season (Figure 3B). In Italy and Portugal, Yw was similar to Yp in ca. 50% of the years. In Tunisia, Yp was more than double of Yw for most years while crop failure was recurrent in Egypt. The latter means that wheat cultivation in Egypt is unfeasible without supplementary irrigation and that Yp (not Yw) should be used as benchmark. These findings highlight that climatic risk is a major issue in South Europe and North Africa, but not in North Europe.

4.2 Benchmarks of water productivity (WP)

Crop evapotranspiration (ET) was greatest in South Europe, intermediate in North Africa and lowest in North Europe with a mean value of 379.8, 367.5 and 350.8 mm yr^{-1}, respectively (Figure 4A). There were some clear differences in ET across soil types: on average ET was smaller in sandy soils (304.8 mm yr^{-1}), while barely any differences in ET were observed for loamy (329.2 mm yr^{-1}) and clay soils (334.2 mm yr^{-1}; Figure 4B). ET for potential production (444.4 mm yr^{-1}) was greatest than ET for water-limited production, independently of the soil type, which was particularly true in North Africa. Figure 4B also shows that wheat yield variability under water-limited production was smallest in sandy soils, but comparable in loamy and clay soils.

Upper limits for the relationship between Yp, or Yw, and ET were linearly related over the range of ET in which wheat yields were responsive to increasing water availability (solid line in Figures 4A and 4B). The slope and x-intercept of this relationship are biophysical meaningful (French & Schultz, 1984). The former indicates the maximum yield that can be achieved per mm ET (potential WP) while the latter indicates unavoidable losses due to evaporation. The potential WP proposed by Edreira *et al.* (2018) for wheat, 34 kg mm^{-1} ha^{-1}, proved to be an appropriate benchmark for spring wheat, but not as much for winter wheat (Figures 4A and 4B). The same applies to the 60 mm ET considered as unavoidable soil losses (x-intercept). These preliminary results suggest that benchmarks of potential WP of winter wheat in North Europe need to be refined with additional model simulations. We also suggest to cross-validate the current benchmark for spring wheat in South Europe and North Africa with additional simulations of wheat yields under different irrigation strategies.

The WP was greatest in North Europe (on average 26.3 kg DM mm^{-1} ha^{-1}), intermediate in South Europe (16.2 kg DM mm^{-1} ha^{-1}) and smallest in North Africa (7.0 kg DM mm^{-1} ha^{-1}; Figure 4C), while there was a large variability in WP for each soil type (Figure 4D). The top 10th percentile WP in each region averaged 32.1, 25.3, 15.3 kg DM mm^{-1} ha^{-1}, respectively. Such differences between years and regions are due to differences in climatic conditions during the key periods growing season (Figure 2) but further research is needed to identify the exact drivers behind such variability in WP.

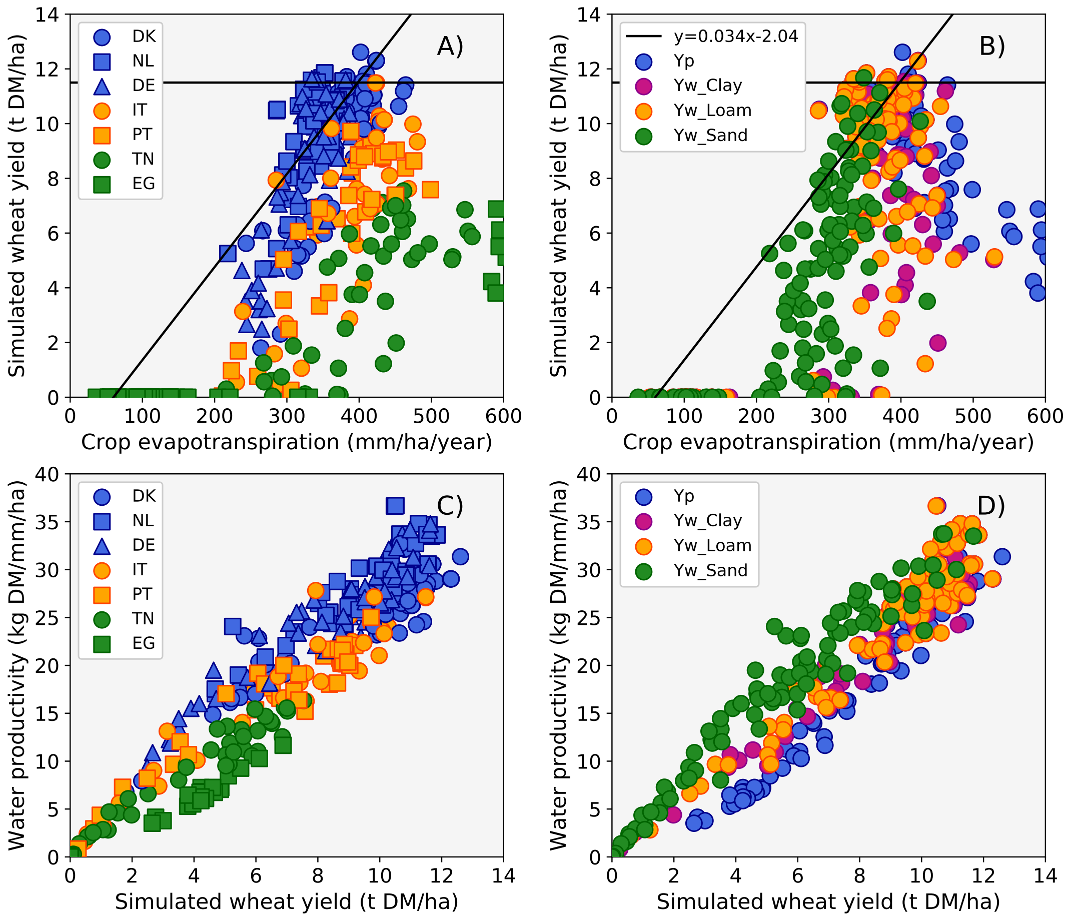

Figure 4. Water productivity, and underlying crop yield and evapotranspiration information, across the network of production systems: A), C) data shown per country and B), D) data shown per soil type. The solid line in A) and B) shows the frontier concept of French & Schultz (1984), with minimum soil evaporation set at 60 mm and water productivity set at 34 kg DM ha^{-1} mm^{-1} (Edreira *et al.*, 2018, and references therein). Country codes: DK = Denmark, NL = The Netherlands, DE = Germany, IT = Italy, PT = Portugal, TN = Tunisia, EG = Egypt.

4.3 Agronomic N use efficiency (AE-N)

Wheat yield response to N applied followed the law of diminishing returns (Figure 5). This was evident in all production systems but Egypt (Figure 5G), where water limitations masked possible N limitations. Wheat yield variability under nitrogen-limited conditions was much larger for a given amount of N applied in South Europe and Tunisia than in North Europe, which can be explained by greater inter-annual rainfall variability in the former (Figure 3B). This interaction between water and N limitations was also clear when comparing different soil types for each production system: yield responses to N were consistently smaller in sandy than in clay and loamy soils, where yield responses to N were rather similar.

The y-intercept, inflexion point and plateau of the yield response curves to N in Figure 5 are biophysically meaningful (e.g., Cassman, 1999). The y-intercept reflects the inherent soil productivity based on the indigenous supply of N from mineralization of soil organic matter or atmospheric deposition during the growing season. Although the simulations assumed a fixed amount of indigenous supply of N over time and across soil types, the inherent soil productivity was much lower in Tunisia and South Europe (0.5 - 3.5 t DM ha^{-1}) than in North Europe (3.5 - 7.5 t DM ha^{-1}; Figure 5). This difference can be explained by shorter growing seasons and greater water limitations in the former compared to the latter production systems. The inflection point of the response curve indicates the maximum agronomic N use efficiency (AE-N), after which the amount of grain produced per unit of N applied declines up to 0 in the plateau of the response curve. The maximum AE-N in loam and clay soils occurred at ca. 150 kg N applied ha^{-1} in North Europe and Tunisia and at ca. 200 kg N applied ha^{-1} in South Europe (Figure 5). This maximum AE-N was lower in sandy soils, independently of the production system (Figure 5). Finally, the plateau of the response curve reflects the yield level without N limitations. The plateau is expected to match with the potential (maximum yield for a given amount of N applied) or water-limited yields (average yield for a given amount of N applied) simulated in each production. This was only true for Portugal and Italy, meaning that improvements in model parametrization are needed.

The AE-N was greatest in North Europe (on average 53.1 kg DM kg^{-1} N applied), intermediate in South Europe (31.7 kg DM kg^{-1} N applied) and smallest in Tunisia (21.0 kg DM kg^{-1} N applied; data not shown). There were also differences in soil types, with lower AE-N observed in sandy (32.3 kg DM kg^{-1} N applied) than in loamy or clay soils (44.3 and 43.8 kg DM kg^{-1} N applied; data not shown). The top 10^{th} percentile AE-N was on average 169.0, 83.8 and 57.0 kg DM kg^{-1} N applied in North Europe, South Europe and Tunisia, respectively. The variation observed in AE-N across years, regions and soil types reflect water and/or N limitations during the growing season, which are a result of suboptimal amount and time of rainfall and/or N applied.

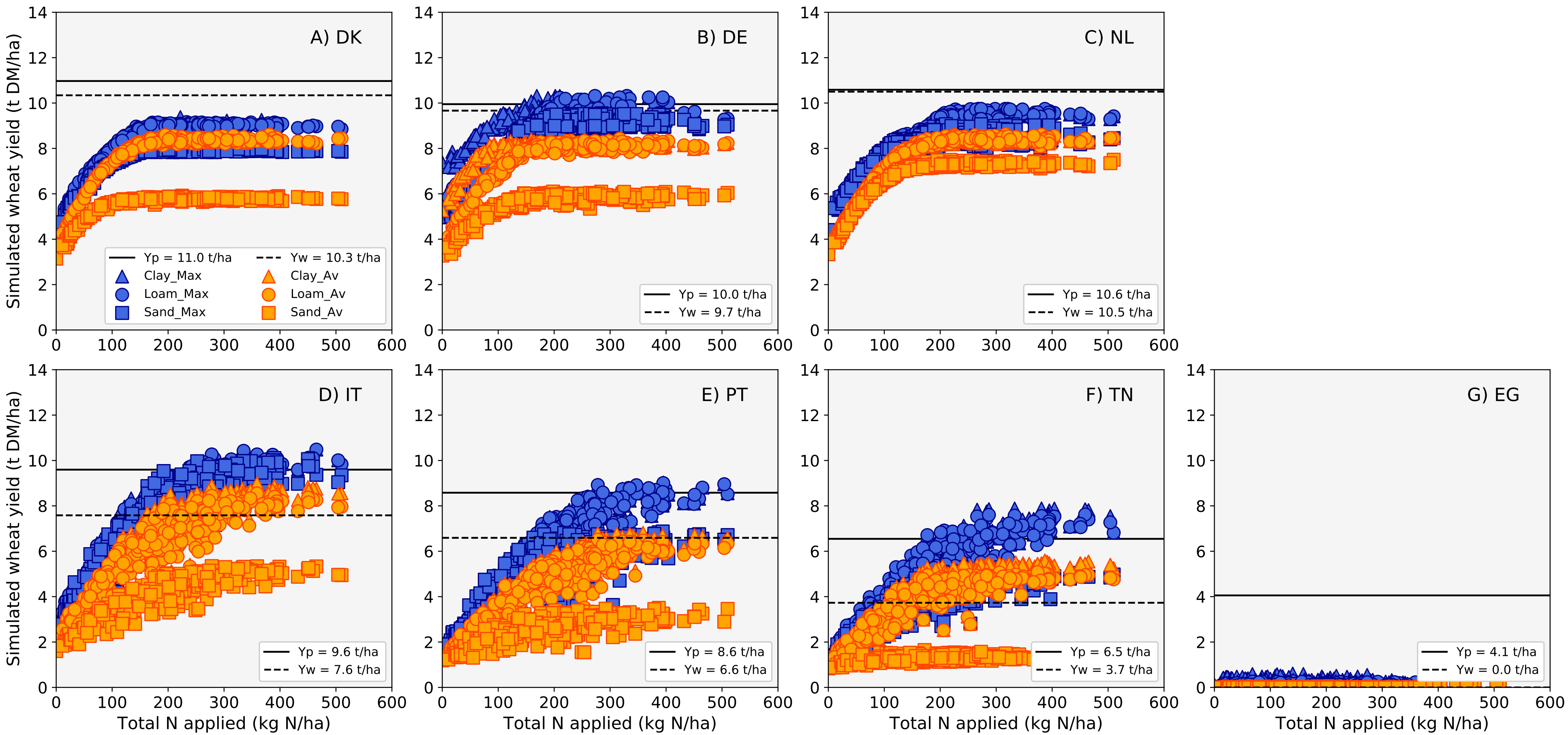

Figure 5. Wheat yield response to N for different soil types across the network of production systems. Observations in orange (blue) show the average (maximum) nitrogen-limited yields (Yn) simulated for a given amount of N applied across different years per soil type. The solid line refers to the average potential yield (Yp) and the dashed line to the average water-limited yield (Yw) in a loamy soil during the period 2001 - 2012. Country codes: DK = Denmark, NL = The Netherlands, DE = Germany, IT = Italy, PT = Portugal, TN = Tunisia, EG = Egypt.

5 Conclusions and way forward

Benchmarks for wheat yields and resource use efficiencies were simulated with the crop model WOFOST for different production systems across a gradient of water scarcity from North Europe to South Europe and North Africa. The potential yield (Yp) was greatest in North Europe, intermediate in South Europe and lowest in North Africa which is explained by longer growing seasons in North Europe, where winter wheat is cultivated, than in South Europe and North Africa, where spring wheat is cultivated. The water-limited yield (Yw) was similar to Yp in North Europe but much lower than Yp in South Europe and North Africa and the variability of Yp and Yw was greatest in North Africa, intermediate in South Europe and smallest in North Europe. These clearly indicate that water limitations on crop growth and climate risk are much more pronounced in South Europe and North Africa than in North Europe. The current WP benchmark of 34 kg DM mm^{-1} ha^{-1} seems to be adequate for spring wheat but not as much for winter wheat, for which greater values seem to be possible. There was a strong interaction between water availability and yield response to N, with AE-N averaging 53.1 kg DM kg^{-1} N applied in North Europe and 31.7 and 21.0 kg DM kg^{-1} N applied in South Europe and Tunisia, respectively. These benchmarks are preliminary and need further refinement alongside the following aspects:

- Exclude water limitations or include irrigation in the simulations for Egypt so that yield responses to N can be studied (Figure 5G);
- Simulations of Yn (Figure 5) require recalibration to ensure Yp and Yw are reached at high N application levels;
- Decompose AE-N into capture (kg N uptake per kg N applied) and conversion efficiencies (kg grain per kg N uptake) using the simulated data on N uptake;
- Identify the drivers of variability in WP and AE-N using a combination of weather data and simulated crop data for key periods during the growing season (e.g., water stress around anthesis);
- Link these field level results with insights at catchment scale and reflect on methods available to assess WUE and NUE and the implications for policy;
- Compare the current benchmarks with actual data so that we can assess the scope to improve WUE and NUE in each production system - literature on field-experiments or farm performance needed for this.

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Simulation of pea-barley intercrop with process-based DAISY model in Denmark

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Table of Contents

1. Introduction to the Daisy model in intercropping

Daisy model is a dynamic soil-plant-atmosphere system model for agro-ecosystems simulating plant growth and soil processes based on data on weather, soil, soil hydraulic parameters and field management. The Daisy model is used to simulate intercrops with details on partitioning of dry matter into leaf, stem, storage organ and roots (Abrahamsen & Hansen, 2000). In this study,pea-barley intercrop is used as a starting point to test the ability of the model to simulate intercropping system.

2. Model calibration and validation: data sets used and procedure

2.1 Field data used for calibration

The dataset for calibration was extracted from a field experiment in 2017 on spring barley sole crop (BSC) and pea sole crop (PSC) and pea- spring barley intercrop (IC). The field was under conventional management for the past four decades. In 2016, the experimental site was cultivated with malting barley and conventional management practice was followed (field trial record of the experimental farm). Prior to sowing in 2017, Biogrow (NPK 10-3-1), organic fertilizer was applied at the rate of 12 kg N ha^{-1}, to the field. Spring barley (cv. Salome) and pea (cv. Mythic) was sown as sole crops and as intercrops in 50:50 ratio in same rows. Both sole crop and intercrop plots were divided into two treatments; 1) 0 kg N/ hectare (N0) and 2) 100 kg N/ha (N100). N100 was applied in two doses of 50 kg N/ha each in the form of urea at 30 and 67 days after emergence (DAE). Just before sowing, the soil was sampled from 0-75 cm depth in four replicates and analyzed by a private company (OK, Laboratorium for Jordbrug). The N mineralization was 18 kg N ha^{-1} with 1.57 mg NO^{-} ^{3}N and 0.1 mg $NH^{-4}N$ kg^{-1} soil. The analyzed soil samples indicated sufficient phosphorous and potassium content for the target yields under Danish growth environment. Sampling of biomass for dry matter (DM) and N content analysis were carried out at 30, 67 and 102 DAE on 31st May, 7th July and 11th August 2017 for the N100 plots and grain yields, DM and N content were recorded for noth N100 and N0 plots at harvest at 102 DAE.

2.2 Field data used for validation

The data set for validation was an 11-year crop rotation with organic management without use of fertilizer, using nitrogen fixation by legumes as the sole nitrogen input source. The 11-year crop rotation and yields are provided in Table 1.

2.3 Soil and weather input data for the Daisy model simulations

For input to the model, calibrated soil parameters were taken from a former study carried out at the experimental farm and the weather data is from the local weather station at Taastrup Campus, located within the experimental farm approximately 130 m from the experimental field used for intercropping in 2017. Spring barley and pea crop input data parameterized for growing conditions and yield targets in Denmark were used.

3. Calibration procedure

The model was calibrated by 'trial and error' and was divided into several calibrations rounds in which each included several simulations and adjustments to achieve an acceptable fit before moving to the next calibration step; 1) calibration of the soil organic matter (SOM), 2) calibration of the pea height and nitrogen distribution in different crop organs of the pea crop during growth. Figure 1 illustrates the calibration and validation workflow.

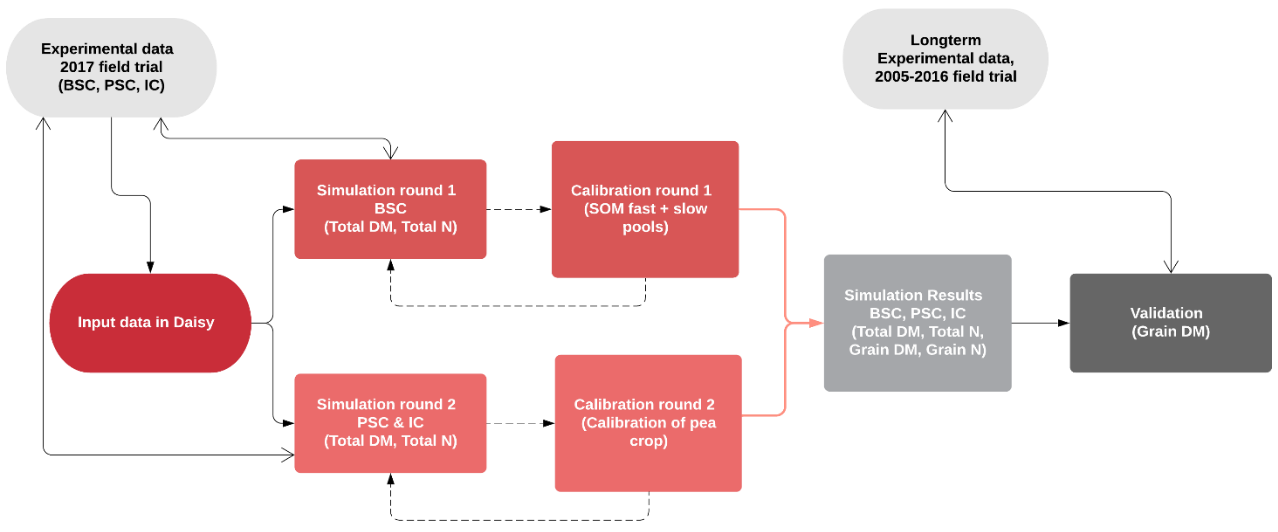

Figure 1. Overview of the model calibration and validation process

3.1 Calibration of soil organic matter

Daisy simulations are notably influenced by the initial distribution of SOM and changes in management and climate at the site before the onset of the simulated experiment (Bruun & Jensen, 2002). The experimental field had previously been subdivided into different parcels with various management and hence management information and values for initial SOM conditions for the whole field could not be obtained. The rate of N mineralization measured before the beginning of the trial at 18 kg N/ha is sensitive to time of year with respect to weather conditions and management. The initial SOM conditions in Daisy does not correspond to any measurable entities and hence the distribution of SOM cannot be initialized by a simple measurement (Bruun & Jensen, 2002). The most reliable way of calibrating was, therefore, to compare a model output (e.g. total crop N) with measured data of the same parameter and to use the initial conditions resulting in the best fit of simulated data to measurements. The model was initialized with two SOM fractions, a fast and a slow fraction. The percentage of each of the SOM fractions were altered until the simulated total crop N at harvest time corresponded to the measured data for both the N0 and N100 treatments. The same method has been used by Manevski et al., (2016).

3.2 Height of the pea

When initially simulating intercropping, the leaf area index (LAI) was very high for the pea and low for the barley compared to the LAI under Danish growth environments. This resulted in low yields of the barley in intercropping as the pea component out-competed the barley component in the simulation. Therefore, the pea height was adjusted in the model parameter controlling height at different crop development stages (DS). The pea height was changed to 50 cm at DS1 (flowering) and DS2 (ripe) from the default settings for sole crop pea at 100 cm. The 50 cm height corresponded well to the measured heights in Denmark of the Mythic pea variety used in this experiment with plant heights of 45-55 cm (Sortinfo, 2017).

3.3 Rate of nitrogen distribution in different plant parts of pea

The simulations for pea sole crop overestimated the nitrogen content and the final yields also after adjusting the plant height. The nitrogen content of the total aboveground biomass and the nitrogen content of the storage organs was therefore used for futher model calibration in accordance to recommendtions on Daisy model crop calibration (Styzcen et al., 2006). In the model, nitrogen content per dry matter, CrpN (g N/g DM), in different crop organs (stem, leaf, storage organ) were adjusted at certain development stages (DS) of the crop, with DS=0 being emergence to DS=1 at flowering to DS=2 at maturity, simulated with respective daily development rates (Manevski et al., 2016). The CrpN parameter was adjusted until the model output on storage organ nitrogen content and total aboveground nitrogen content resulted in a good fit with the measured values.

4. Calibration results

4.1 Barley sole crop

The simulations of total N (kg N/ha) in BSC fits well at 30 and 67 DAE for N100 and at 102 DAE for N0. There are overestimations of total N (kg N/ha) and total dry matter (Mg DM/ha) for N100 at 102 DAE, see Figure 2. The reason for the overestimations are most likely model simulations of N uptake in the barley late in the growing season which have most probably not taken place in the field, see further discussion of this in section 9. It is complicated to validate the total N status of the soil, which is critical to the simulation accuracy, due to lack of samples at 30 and 67 DAE for the non-fertilized plots but the good fit at 102 DAE for N0 total N and total DM indicates the estimates are useful.

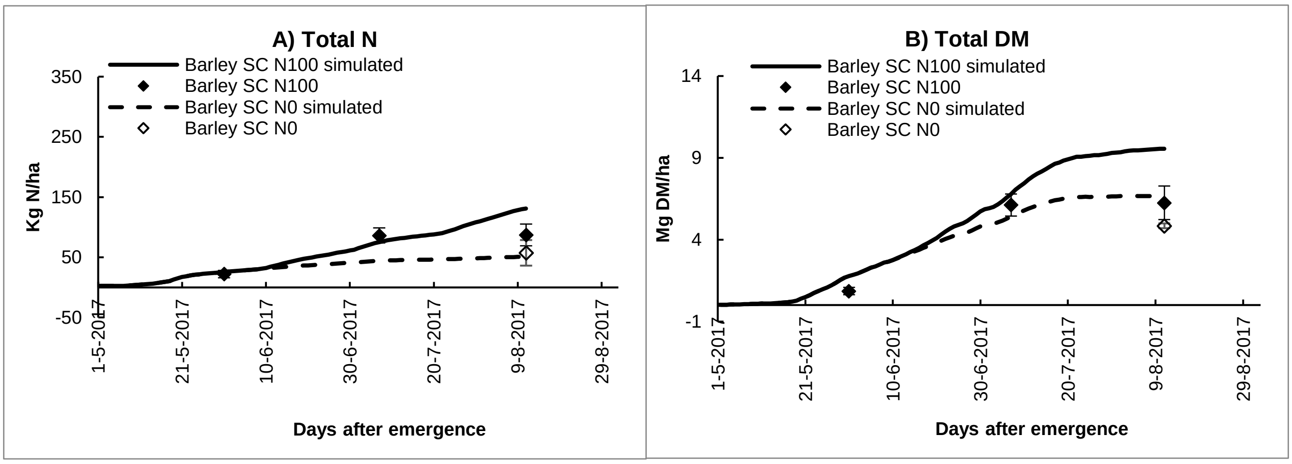

Figure 2 Barley sole crop, A = Total N (kg N/ha), B = Total dry matter (Mg DM/ha)

4.2 Pea sole crop

After performing calibrations for nitrogen distribution in the different plant parts, the total N content of pea sole crop fits quite well to the measured data (Figure 3). There is no difference between simulations of the pea at N0 and N100 treatments probably due to simulated compensating fixation of N on the N depleted plot. The large standard deviation for the measured data illustrates the uncertainty of simulating only one year of field data. When calibrating the N in different crop organs, it results in a good fit for total dry matter at harvest but considerable underestimations of the total dry matter during the growing season (Figure 3).

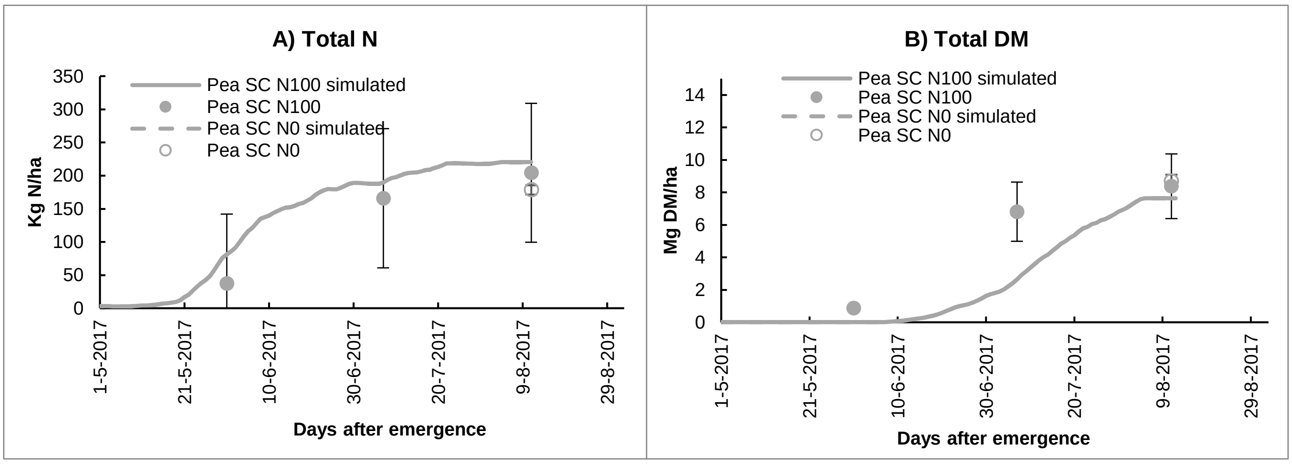

Figure 3. Pea sole crop, A = Total N (kg N/ha), B = Total dry matter (Mg DM/ha)

4.3 Intercropping

The intercrop simulations show good fit for the total N content for both barley, pea, and the total intercrop (Figure 4). The measured intercropped pea total N content was 145 kg N/ha (N0) and 128 kg N/ha (N100) at harvest 102 DAE. An increase in N fixation in intercrop has been recorded in other studies (Hauggard-Nielsen et al., 2009). In intercropping, barley most likely took up the bulk of the soil nitrogen and the pea was thus forced to meet its N requirement through fixation, with barley having greater competitive advantage in the fertilized plots. The measured data have substantial standard errors and general interpretations should be based on more years of data. With regard to total DM, the simulations resulted in overestimations for barley and pea alone, with larger overestimations for the total intercrop (Figure 5).

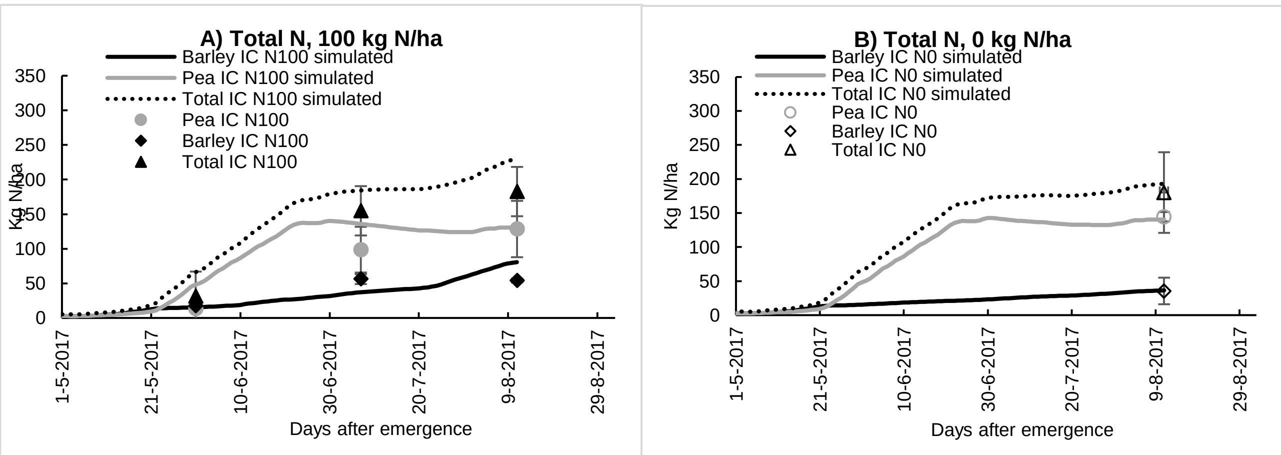

Figure 4. Intercropping, A = Total N (kg N/ha) for N100, B = Total N (kg N/ha) for N100

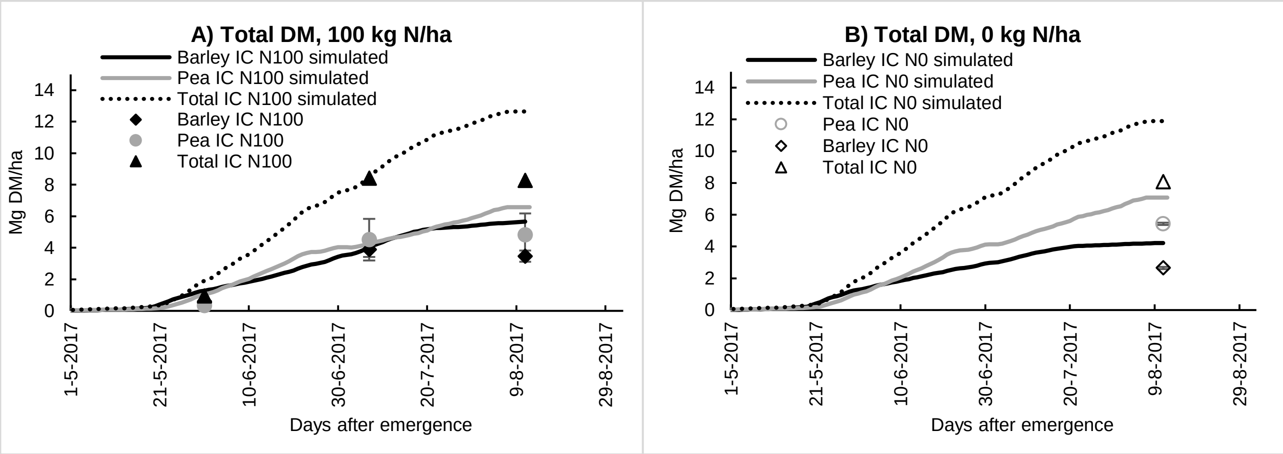

Figure 5. Intercropping, A = Total DM (Mg DM/ha) for N100, B = Total DM (Mg DM/ha) for N0

5. Model validation results

For the validation of the model simulation setup, we simulated an organic 11-year crop rotation (2005-2016) including spring barley, winter and spring wheat, clover, lucerne/alfalfa and oats. The model simulations were compared to measured grain yields (Table 1). In the model setup, the management was set to default management in accordance with Danish standard practices on organic farming without fertilizer. The 2005-2016 simulation results show that simulated yields for spring barley are similar to the measured values (Table 1) with a significant correlation between the measured and simulated values when including both barley and wheat values (Figure 6).

The simulations were started in 2003 with 2 years of clover simulations to create reliable initial conditions as clover is regularly grown on these fields, as per the crop rotation. For the spring wheat growth in 2006 and 2010, 50 kg N/ha was applied in the simulation to account for N2-fixation by cover crops grown between the main crops. Without these adjustments, the simulated wheat yields of 2005 were very low. This emphasizes the importance of using plausible assumptions to initialize the SOM and N content, and the robust method to initialize is a simulation of the pre-experimental period (Bruun & Jensen, 2002). The lucerne/alfalfa crop is not available in Daisy library and hence pea was used in the simulated crop rotation to account for N fixation. Oat is not available in Daisy crop library and hence spring barley was used in the crop rotation instead.

*Table 1. A*verage yields 11-year crop rotation from Højbakkegaard compared to simulated yields without fertilizer (Mg DM/ha). Numbers marked with grey should not be accounted for.

Year	Crop	Measured yields (Mg DM/ha)	Simulated yields (Mg DM/ha)
2005	Winter Wheat	3.9	3.3
2006	Spring Wheat	3.0	2.1
2007	Spring Barley	3.4	2.4
2008	Clover	6.5	-
2009	Clover	2.8	-
2010	Spring Wheat	4.5	3.8
2011	Spring Barley	3.0	3.8
2012	Lucerne (pea)	6.2	6.3
2013	Oat (Spring Barley)	4.1	4.9
2014	Spring wheat	3.4	2.3
2015	Spring Barley	3.4	2.6
2016	Lucerne (pea)	9.1	7.0

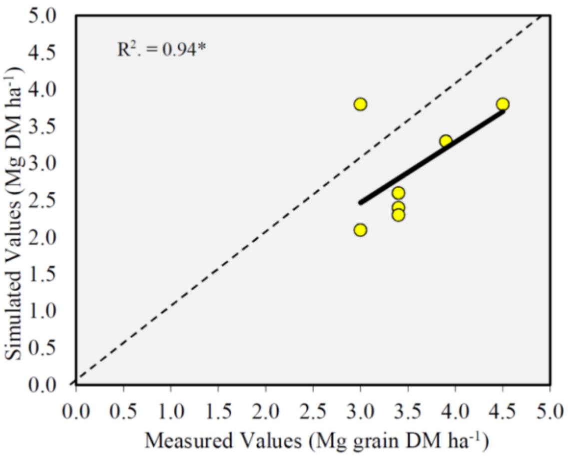

Figure 6. Correlation between measured yield data from 2005-2016 (long-term yield data and simulated BSC and PSC. Significant at P ≤ 0.05*

6. Results of model simulations on crop yield

To test the success of the model calibrations on crop nitrogen content which resulted in good fit, the yields were estimated from the models. The yields of peas were underestimated in the simulations for both N100 and N0 (Figure 7A and 7B) despite the good fit for the nitrogen content of the storage organ (Figure 7C and 7D). Overestimations for barley were expected for the storage organ N and grain dry matter due to the overestimations of the total N and total DM. Work will be done to improve this with new barley parameterisations to be developed in late 2019. It is promising that the simulated total intercrop storage organ N match the measured but investigations into reasons for the underestimations of the yield dry matter needs to be performed to improve the usage of Daisy for intercrop situations.

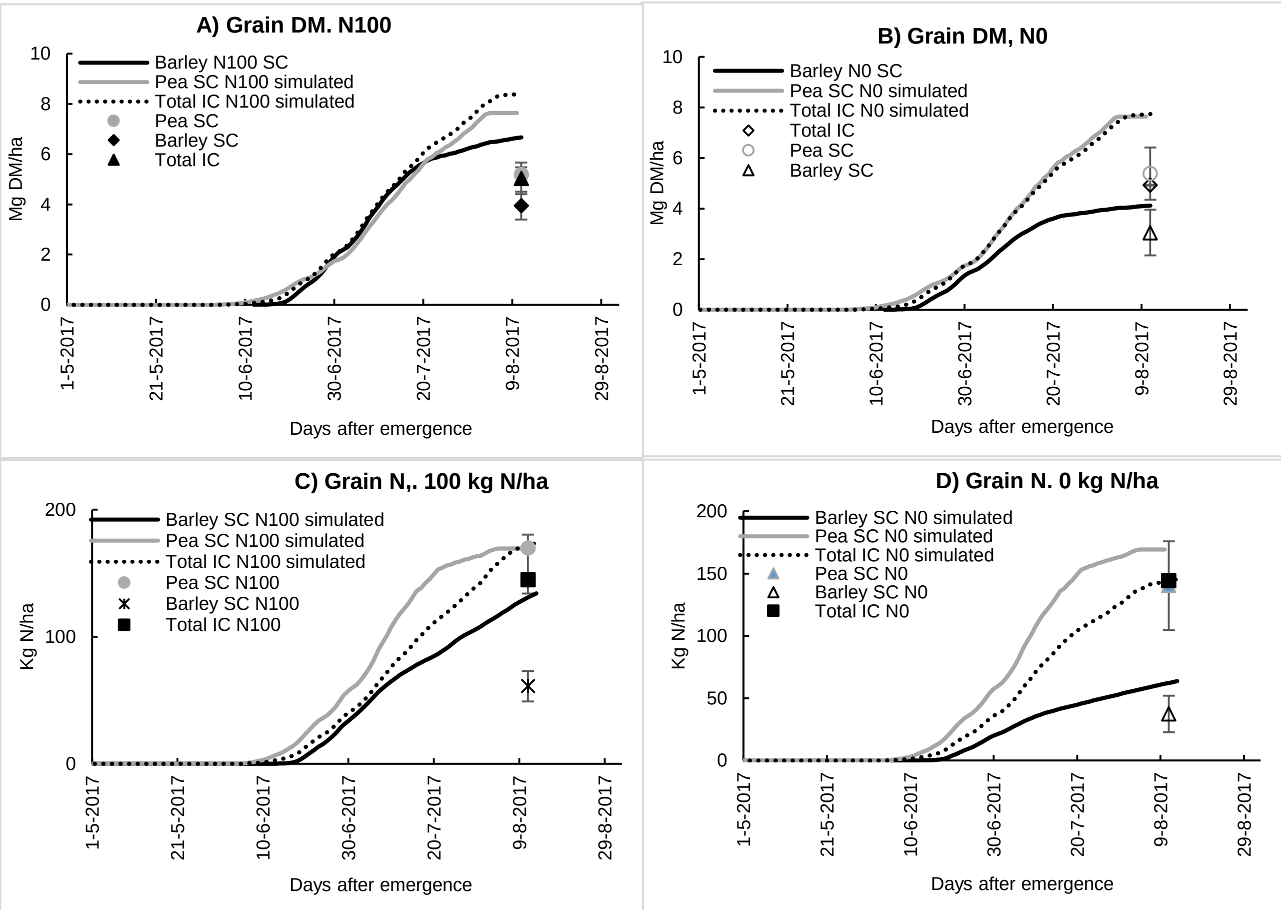

Figure 7. Intercrop yields and N content of the storage organ dry matter. A = Yield (Mg DM/ha) for N100, B = Yield (Mg DM/ha) for N0, C = Nitrogen content of storage organ (kg N/ha) for N100, D = Nitrogen content of storage organ (kg N/ha) for N0.

7. Water use efficiency estimations

The water use efficiency, as defined in D2.2 can be estimated as the grain yield divided by the total evapotranspiration in the period from emergence to maturity or harvest (kg ha^{-1} mm^{-1}). Calculations from the measured yield divided by calculated evapotranspiration for the 2017 intercrop experiment show lowest values for the unfertilized intercropped barley at 3.2 to 7.1 kg ha^{-1} mm^{-1} and highest WUE for pea sole crop at 13.4 to 21.6 kg ha^{-1} mm^{-1} (Figure 8). The Daisy simulation results overestimate WUE for all crops, except intercropped pea, and the overall pattern of WUE differences between the crops are similar to the measured data.

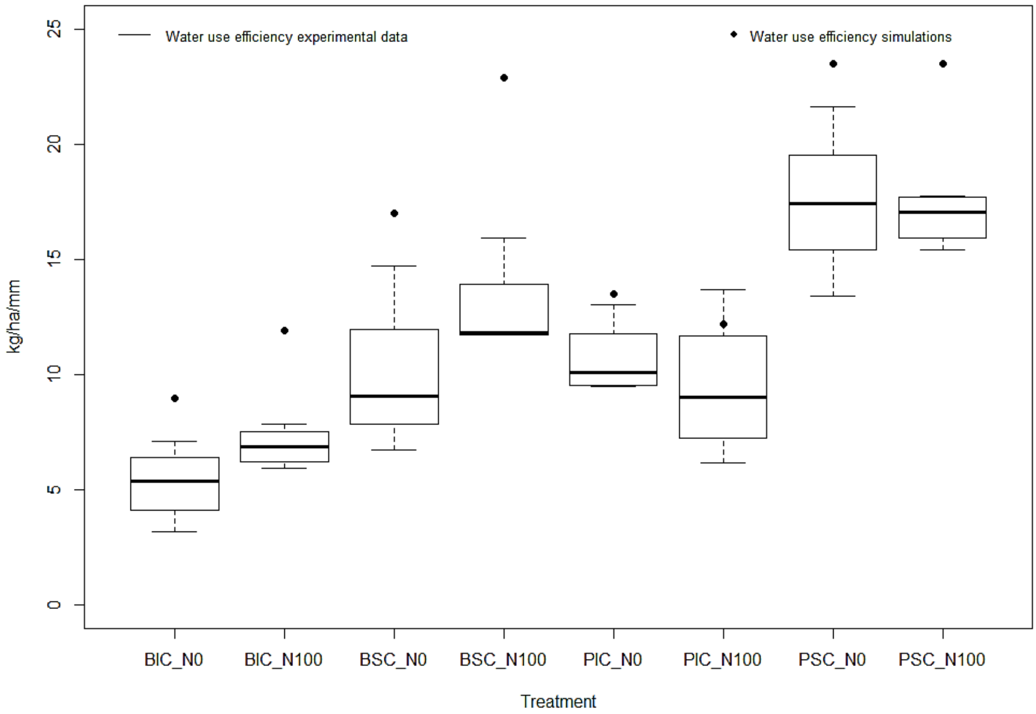

Figure 8. WUE calculations from measured yield data and from Daisy model output.

Ullah et al., (2019) have calculated WUE for water-stressed and well-watered barley plants sole cropped and found variations in barley between 16.2 kg ha^{-1} mm^{-1} for well-watered plants to 28.3 kg ha^{-1} mm^{-1} for water stressed plants when calculating WUE from grain yield divided by evapotranspiration. Our results with fertilized barley sole crop between 11.7 and 15.9 kg ha^{-1} mm^{-1} indicate the barley have been well-watered corresponding well to the quite wet growing season of 2017. Accordingly, no water stress was indicated for any of the crops in the Daisy simulations (data not shown). Values for field pea grown in mediteranean area between 6 and 15.9 kg ha^{-1} mm^{-1} have been identified similarly to the values from this study (Siddique et al., 2001) despite the different climates. The amount of experimental data used for this study does not yet include enough data to make any conclusions on the WUE as more years with different weather is needed to increase robustness of the results.

8. Nitrogen budgets during growing cycle

The nitrogen use efficiency (NUE) is dependent on the soil water content and hence WUE as nitrogen is readily available for plant uptake in liquid form in the soil water. The NUE could not be calculated due to lack of data, but estimates of different N pools have been identified from the Daisy model output. There is little difference in the modelled residual N between the sole pea crop and intercropping with slightly more in the sole crop pea (Figure 9) likely due to the doubled amount of pea plants in the sole crop compared to the intercrop fixing more N. The simulated N fixation is higher for the unfertilized plots for both intercrop and pea sole crop, with more distinct difference in the intercropping scenario between N100 and N0 treatments. The crop uptake of the barley reflects the amount of available N in the soil and is much higher at the fertilized plots. For the pea sole crop there is minimal difference between the fertilized and unfertilized plots and it is expected the difference in the intercrop is caused by the barley component. It is interesting to note that the model simulate the same amount of fixated N at both fertilization rates and needs further investigations in the pea crop module in the model.

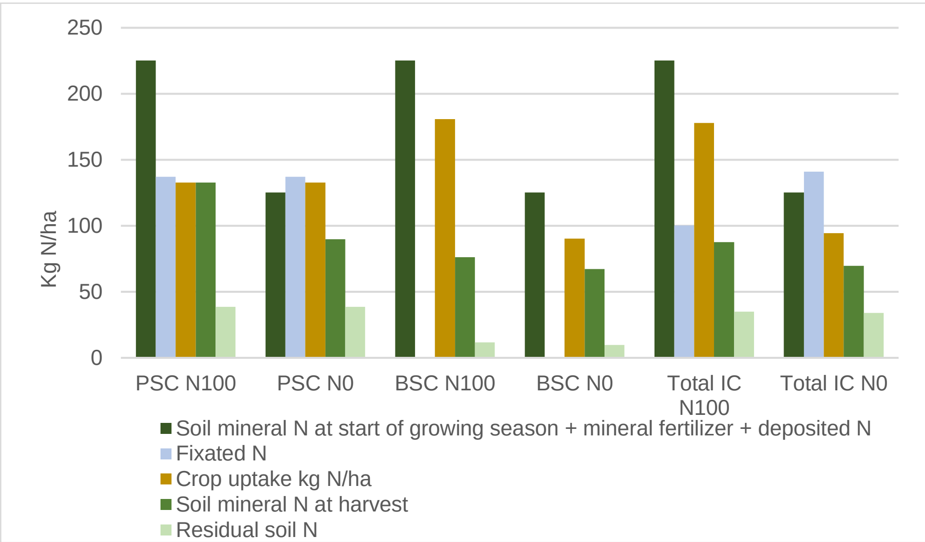

Figure 9. Daisy simulations of nitrogen input, output, crop uptake, nitrogen fixation and residual nitrogen in the soil.Simulations of 2017 intercrop barley and pea trial.

9. Discussion and perspectives

The Daisy model shows promising results for the simulation of intercropping. The model identified the differences between the nitrogen treatments reflected in the total N and dry matter of the crops but with overestimations of grain yield for the barley sole crop and intercrop. Kollas et al., (2015) have experienced similar systematic overestimations for barley yields for both multi-year modelling and single year modelling, when testing 15 different crop models including Daisy with only a few calibration factors included. The dynamics and competition between the crops need further investigations. The abovementioned overestimation is, however, is not necessarily solely a sign of bad fit for the model. The 2 x 50 kg N/ha was applied late in the season late compared to normal practice and hence the uptake and use of the applied N of the spring barley might have been smaller compared to the outcome of an early application. In 2017 it rained quite a lot in June and July and the applied N might have been partly lost through leaching if not utilized by the plants at the application timing. It is assumed that delayed N application after sowing could change the inter-specific dynamics in competitive ability of the cereal and the effects on N_2 fixation from N application at different stages. Naudin et al., (2010) tested the timing of N fertilization in wheat-pea intercropping on the percentage of each species and N_2-fixation and concluded that N fertilization independent of timing always increase the wheat growth and decrease pea growth.

The model does not show any significant differences in pea productivity in N0 and N100. Pea crops can be quite independent of N fertilizer due to the N_2 fixation and Naudin et al., (2010) found no effects of N fertilizer on the amount of N_2 fixed by intercropped peas compared to the unfertilized plots. It must be further investigated how to incorporate better response of the pea to fertilizer and intercropping.

Because of the high complexity of the simulated soil and crop processes, the model simulations should be compared to the trend in field data measurements (Manevski et al., 2016). Ideally, a warm up simulation period before the actual simulation period with inputs on previous known management, fertilizer and crop residues inputs, should be incorporated in the model to approximately estimate the annual net mineralization rate. Performing model validation on several independent datasets increases robustness and improve the simulation outputs (Manevski et al., 2016).

In order to further calibrate the Daisy model, a pea-barley intercrop field trial is implemented at Taastrup Campus during the current growing season of 2019. Barley and pea are sown as sole crops and intercropped at three seeding rates (sole crop barley, sole crop pea, intercropped barley:pea 50:50, 75:25 and 100:100) and at 4 nitrogen levels (see Table 2) resulting in 20 treatments with 3 replications. To both improve the model calibration and investigate differences between the treatments, soil moisture is measured weekly in one of each of the 20 treatments in 10, 20, 30, 40, 60 and 100 cm depth. Biomass is harvested approximately 30, 60 and 90 DAE and at final harvest, and the biomass samples will be analysed for nitrogen content.

Table 2. Nitrogen input for the 4 different nitrogen treatments. All numbers in kg N/ha. N topdress 1 is at tillering, N topdress 2 is at the development of the spike inside the stem.

N treatment	**N fertilizer scheme**			
	Base N	**1st Top-dress N**	**2nd Top-dress N**	**Total N**
N0	0	0	0	0
N50	50	0	0	50
N100	50	50	0	100
N150	50	50	50	150

10. Conclusion

The Daisy modelling exercise has demonstrated that the pea-spring barley intercrop can be simulated for comparison with sole pea and spring barley. At the start of the modelling exercise, simulated spríng barley yields were extremely low due to overshadowing by pea plants. With parameter changes made to the fast and slow fractions of SOM, reducing the pea height based on development stage and the N distribution to the different crop parts of the pea, DAISY was able to simulate acceptable intercrop yields of pea and spring barley. This provides a rational and well-justified basis for improving the model simulations by parameterization of soil carbon and nitrogen content, soil moisture content, LAI and biomass yields. Daisy modelling can identify increased N fixation in the unfertilized intercrop compared to fertilized and the larger crop N uptake on the fertilized plots and indicate the mechanisms for N competition are well described in the model. The 2019 intercrop trial will provide us the basis for further improvement of soil, plant and management variables during the growth period of the crops in order to fulfill the parameter requirements to improve the DAISY simulations in line with the measured field data.

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Using farmer field data and crop modelling to benchmark actual yield and resource use efficiency: A case study for arable cropping systems in the Netherlands

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Abstract

Arable farming systems in the Netherlands exhibit small yield gaps due to the use of up-to-date technologies and of substantial amounts of inputs. In this context, it is important to understand the scope to increase/maintain crop yields while improving resource use efficiency (and reducing environmental footprint) through reductions in input use. The objective of this report is to quantify the magnitude, and to identify the biophysical and management determinants, of on-farm radiation (RUE), water (WUE) and nitrogen use efficiencies (NUE) for the main arable crops in the Netherlands.

Individual field data from Dutch farms during the period 2015 - 2017 were used. The database was compiled through a commercial crop management software used by farmers. The sample used in this study was selected from a database of ca. 350.000 farm x field x crop x year combinations using as criteria the crop species (i.e., ware potato, seed potato, starch potato, sugar beet, spring onion, winter wheat and spring barley) and the completeness of the crop cycle, water and nutrient management information. A framework based on crop coefficients (kc) was used to estimate the potential yield (Yp), radiation intercepted and potential evapotranspiration (ETP) for each crop. Quantile regressions were used to identify 'best' performing fields and multiple regressions were used to identify the biophysical and management determinants of on-farm crop yields and resource use efficiencies.

Yield gaps ranged between 20% Yp for sugar beet and 55% for spring onion and were between 30 - 40% Yp for ware potato and cereal crops. The drivers of Ya were mostly related with water availability and sowing or harvest dates. The field-to-field variation observed in Ya and seasonal water available suggest there is scope to improve WUE, which can be best achieved through increases in Ya. The lack of yield responses to N indicate there is a large scope to further increase NUE and decrease N surplus, especially for ware potato and winter wheat crops. This is best achieved through decreases in N applied rather than through increases in Ya. Although these findings are only relevant to similar production systems in NW Europe, the underlying methods are generic and can be applied to similar datasets in other production systems.

1 Introduction

Yield gaps and resource use efficiencies are important indicators to benchmark agricultural systems (van Ittersum *et al.*, 2013). Traditionally, these have been assessed with crop growth models considering the variation in biophysical conditions and, to a lesser extent, crop management practices observed in farmers' fields. The advent of individual farm field data brought new opportunities to assess crop performance under farmers' conditions and to measure the on-farm impact of technological innovations over large geographic areas (e.g., Rattalino-Edreira *et al.*, 2018; Silva *et al.*, 2017b; Delmotte *et al.*, 2011), to the point that they '*can be considered equivalent to running hundreds of field experiments to capture both major management effects and M x E interactions*' (Rattalino-Edreira *et al.*, 2018).

Ecological and sustainable intensification provide the dominant paradigm to reconcile agricultural production on the one hand and environmental quality and resource scarcity on the other hand (Tilman *et al.*, 2011; Cassman, 1999). This can be achieved through increases in resource use efficiency as a result of yield gap closure and of reductions in the use, and need, for external inputs. Opportunities to achieve this are context-specific and depend on the relative importance of 'sustainability' and 'intensification' within the broader food security and environmental concerns at national level (Zhang *et al.*, 2015; Lassaletta *et al.*, 2014). An example for the European Union is provided by van Grinsven *et al.* (2019), where the Netherlands has the highest eco-efficiency but also the largest environmental impact.

Arable farming systems in the Netherlands exhibit relatively small yield gaps, with actual yields obtained by farmers reaching 70 - 80% of climatic potential yields. This is the case for cereals (Schils *et al.*, 2018) as well as for most tuber and root crops (Silva *et al.*, 2017a; Rijk *et al.*, 2013). These high yield levels are associated with the use of up-to-date technologies and intensive use of inputs as well as with water pollution and greenhouse gas emissions. Irrigation is not a default in the country, due to the humid climate and shallow depth of groundwater, but it is getting increasing attention as an adaptation strategy to dry summers (van Duinen *et al.*, 2015). This calls for a benchmarking analysis of crop yields vis-á-vis resource use efficiency in order to understand the interlinks between crop productivity, input use and environmental performance.

The objective of this report is to quantify the magnitude, and identify the determinants, of crops yields and resource use efficiency of arable cropping systems in the

Netherlands. The analysis draws upon a large database of individual farm field data during the period 2015 - 2017 and covers the production ecology of horticultural (ware, seed and starch potato, sugar beet and onion) and cereal crops (winter wheat and spring barley). The key factors determining the performance of these crops in farmers' fields, and the extent to which they can contribute to improve farm productivity and environmental performance, help setting targets for more sustainable arable cropping systems in the Netherlands and other similar regions of Western Europe.

2 Concepts and definitions

Four different yield levels are specified in agronomy to capture the importance of growth-defining, -limiting and -reducing factors for crop growth (van Ittersum & Rabbinge, 1997). The *potential yield* (Yp) is defined as the maximum yield of a crop cultivar when grown with water and nutrients non-limiting and biotic stresses effectively controlled (van Ittersum *et al.*, 2013). Yp assumes that plant growth is determined by growth-defining factors such as CO_2-concentration in the air, solar radiation and temperature, and intrinsic plant characteristics. The *water-limited yield* (Yw) and *nutrient-limited yield* (Yn) are defined similarly to Yp but for these yield levels crop growth is also limited by growth-limiting factors such as water and nutrients, respectively. Here, we focus on nitrogen (N) only as this is generally the most limiting macro-nutrient for crop growth in the Netherlands (Janssen, 2017) and due to its central role on environmental legislation, at national and regional levels, that farmers have to comply with. Finally, the *actual yield* (Ya) is mostly observed in farmers' fields and expresses a further reduction of Yw or Yn by growth-reducing factors such as weeds, pests and diseases.

The *yield gap* is defined as the difference between the Yp or Yw and Ya in case of irrigated or rainfed systems, respectively, and indicates how inefficiently land is used due to inefficient use of inputs and/or sub-optimal crop management. For the specific case of arable farming in The Netherlands, the relatively humid climate and presence of capillary rise across the country justify the use of Yp as benchmark (Silva *et al.*, 2017a), even if irrigation is not default for most arable crops.

The aforementioned yield levels reflect differences in crop performance regarding radiation use efficiency (RUE), water use efficiency (WUE) and/or N use efficiency (NUE). For instance, Yp comprises the maximum RUE that is possible to achieve in a given biophysical environment for a specific sowing and harvest date. Similarly, Yw provides a benchmark for WUE and Yn for NUE as both yield levels reflect the maximum yield that can be achieved for a given amount of plant available water and N during the growing season, respectively. RUE (g DM MJ PAR^{-1}) is defined here as the amount of dry matter produced per unit MJ PAR (photosynthetically active radiation), WUE (kg DM ha^{-1} mm^{-1}) as the kg DM obtained per unit seasonal water available (Grassini *et al.*, 2011) and NUE as the kg N harvested per unit N input available (EUNEP, 2015). Further details about the quantification of these indicators are provided below.

3 Materials and Methods

3.1 Database of farm field data

3.1.1 Background and spatial distribution

The individual farm field data used in this study was provided by Agrovision B.V., a commercial company providing crop registration software and decision support systems to farmers in the Netherlands. The former is used by farmers to record for individual fields a set of biophysical characteristics and crop management operations including sowing and harvest dates, water and nutrient management, pest and disease management and final crop yield. All data is self-reported by the farmer in one of the four different software platforms provided by the company.

The relational database with the raw data contains one table per management operation, which can be linked through a unique farm × field identifier. The management operations recorded are land preparation (date and method), crop establishment (sowing date, density, method and variety), irrigation (dosage, date, source and method), fertilisation (*idem*), pesticide use (*idem*) and harvest (crop yield, date and method). Two additional tables include farm- and field-specific information, including location (postal code and GPS coordinates), commercial software used, crop year (2015 - 2017), cultivated crop, field area (ha) and soil type (based on the Dutch soil classification; cf. Hartemink & Sonneveld, 2013). Soil physical (e.g., texture) and chemical properties (e.g., organic matter, pH and available NPK) from soil samples were also available for a smaller number of fields (ca. 20% of all fields).

The fields included in the database were located across the main agricultural regions of the Netherlands (data not shown due to privacy reasons). Cultivation of potato was spread across the country but clear spatial differences in production systems could be identified. Ware potato was mostly produced in the polders and Southern regions, seed potato was mostly found in the Northeast and North coastal regions and starch potato was mostly confined to the Northeastern region. Sugar beet cultivation was spread throughout the country, while spring onion was mostly produced in the Southwestern, polders and North coastal regions. Winter wheat was cultivated in similar regions as spring onion, while spring barley was mostly found in the Northeastern region.

3.1.2 Data management and secondary sources

Different queries were designed with the Python module *pyodbc* to retrieve from the database all the data related to each management operation, with the exception of the pesticide data which is beyond the scope of this study. These queries were screened for basic data problems, such as duplicated records and non-standard units, and used to construct the variables of interest (e.g., total input applied and input dose, date, method and product per split). Actual crop yield (Ya, t FM ha^{-1}) was standardized to ton fresh matter (t FM) per ha and directly retrieved from the database.

A few intermediate steps were taken to derive the plant available nutrients applied in each field. These included the standardization of the amounts of N, P and K of each mineral and organic fertiliser applied (Figure A1) and the correction of these amounts with fertiliser replacement values for each organic fertiliser recorded (van Dijk *et al.*, 2004). Plant available nutrient applied (PANA, kg ha^{-1}) was thus estimated as:

$$\text{PANA}_i \text{ (kg ha}^{-1}\text{)} = \sum_{j=1}^{type} \sum_{s=1}^{season} \text{Napplied}_{ijs} \times \text{Ncont}_{ij} \times \text{ReplValue}_{ijs} \quad (1)$$

where Napplied (kg ha^{-1}) refers to the amount of mineral and organic macro-nutrient *i* applied with fertiliser type *j* in season *s* (Autumn or Spring), Ncont (%) to the macronutrient content of each fertiliser type and ReplValue (%) to the fertiliser replacement value of each fertiliser type (obtained from van Dijk *et al.*, 2004).

Daily weather data were obtained from the Royal Dutch Meteorological Agency (KNMI, in Dutch) for 25 weather stations spread across the Netherlands. These contained complete records of global solar radiation (MJ m^{-2}), minimum and maximum temperature (°C), precipitation (mm), vapour pressure (hPa) and wind speed (m s^{-2}) during the period of interest (2015 - 2017). Reference evapotranspiration (ET0, mm) was estimated for each weather station using the FAO-Penman-Monteith equation (Allen *et al.*, 1998). The nearest weather station to each farm was identified based on the postal code of the farm as GPS coordinates were not available for all fields.

This report focuses on the seven major arable crops in the Netherlands: ware potato, seed potato, starch potato, sugar beet, spring onion, winter wheat and spring barley. Ya lower or equal to 1 and $PANA_N$ lower or equal to 5 were excluded as these unrealistically low values point to incomplete records. Potato and winter wheat fields with no organic N applied were excluded for the same reason. Finally, observations of Ya, $PANA_N$, $PANA_P$, $PANA_K$, sowing date and harvest date above (below) the third (first) quartile plus (minus) 1.5 times the interquartile range were excluded from further analyses.

3.2 Crop modelling approach

A framework based on crop coefficients (kc) was used to estimate Yp, radiation intercepted and potential evapotranspiration of (ware, seed and starch) potato, sugar beet, spring onion, winter wheat and spring barley. This static approach was preferred over a dynamic crop growth model due to the large number of crops analysed and the lack of up-to-date parameters to run crop models for arable crops in the Netherlands. Conversely, soil water losses and seasonal water available were estimated for two contrasting soil types (fine and coarse textures) using a water balance based on a 'tipping bucket' approach with a daily time-step. A detailed description of the equations, and parameters used, and of the assumptions made is provided below.

3.2.1 Estimation of Yp based on crop coefficients

The methodological approach used to estimate Yp of each crop is summarized in Equations 4 − 7 (Sadras *et al.*, 2017). This approach defines Yp as a function of solar radiation and crop characteristics and builds upon daily records of global radiation (RAD_{GLOBAL}, MJ m^{-2} day^{-1}) and a number of crop-specific parameters (Table 1). The latter include harvest index (kg kg^{-1}), dry matter (DM%), protein (P%) and fat (F%) contents (g protein or fat g DM^{-1}) as well as tabulated crop coefficients (kc_ini, kc_mid and kc_fin, mm mm^{-1}) and crop growth periods (A, B, C and D days).

The crop coefficient (kc) is defined as the ratio between the actual evapotranspiration of a given crop (ETc, mm) and ET0. The value of kc during the growing season was estimated according to Doorenbos & Pruitt (1977), which represents the kc curve as a set of straight lines. This curve can be defined based on the duration of phases A, B, C and D, which in total define the length of the growing season ($length_{A+B+C+D}$), and the value of kc at three points in time (kc_ini, kc_mid and kc_fin). The value of kc was assumed to be constant during phases A and C and equal to kc_ini and kc_mid, respectively. During

Table 1. Crop-specific parameters used to calculate potential yields, radiation intercepted, crop water requirements and N yield in this study. Parameters for seed and starch potato were equal to the ones used for ware potato, with exception of N_{SEED} for which it is equal to 16.8 and 8.8 kg N ha^{-1} respectively. The sources of these values are provided in the main text.

		Ware potato	**Sugar beet**	**Spring onion**	**Winter wheat**	**Spring barley**
HI	Harvest index (kg kg^{-1})	0.80	0.80	0.85	0.50	0.46
DM%	Dry matter content (%)	21.0	17.0	15.0	86.5	86.5
P%	Protein content (g protein g DM^{-1})	0.108	0.078	0.092	0.126	0.140
F%	Fat content (g fat g DM^{-1})	0.005	0.005	0.009	0.017	0.030
LUE	Light use efficiency (g DM MJ PAR^{-1})	3.08	3.10	3.07	3.08	3.06
LUEc	Reference LUE (g DM MJ PAR^{-1})	3.20	3.20	3.20	3.20	3.20
kc_ini	Initial crop coefficient (mm mm^{-1})	0.15	0.50	0.70	0.10	0.30
kc_mid	Maximum crop coefficient (mm mm^{-1})	1.15	1.20	1.00	1.15	1.15
kc_fin	Final crop coefficient (mm mm^{-1})	0.70	0.70	0.75	0.35	0.30
A	Duration of period A (# days)	25	50	15	120	20
B	Duration of period B (# days)	40	40	25	75	25
C	Duration of period C (# days)	60	50	70	70	60
D	Duration of period D (# days)	30	40	40	25	30
A_corr	Correction factor in period A (-)	0.300	0.140	0.080	0.872	0.285
B_corr	Correction factor in period B (-)	0.080	0.257	0.166	0.096	0.071
C_corr	Correction factor in period C (-)	0.460	0.285	0.666	0.032	0.357
D_corr	Correction factor in period D (-)	0.150	0.314	0.080	0.000	0.285
N_{YIELD}	N content in storage organ (g N kg DM^{-1})	1.70	0.95	1.95	2.15	2.70
N_{SEED}	N in seed (kg N ha^{-1})	10.6	0.0	0.2	3.5	2.5

phases B and D, the value of kc was estimated through linear interpolation between kc_ini and kc_mid and between kc_mid and kc_fin, respectively.

The approach described above assumes an average growing season, which is inadequate to describe the variation in growing seasons observed in farmer field data. To overcome this limitation, a set of correction factors for each phase (Table 1) were used to increase or decrease the average duration of each phase (AvLength), depending on the length of the growing season across fields in the database ($Length_{FIELD}$). These correction factors were calculated as the difference between the maximum and the minimum duration for each phase, as reported by Villalobos & Fereres (2017), divided by the difference between the maximum and minimum length of the growing season (i.e., the sum of A, B, C and D). The actual length of each phase, *i*, was calculated as follows:

$$\text{Length}_\text{i}\ \text{(days)} = \text{AvLength}_\text{i} + \text{CorrFact}_\text{i} \times (\text{Length}_\text{FIELD} - \text{Lenght}_\text{A+B+C+D}) \quad (2)$$

Total aboveground biomass production (TAGP, g DM m^{-2}, also including below-ground storage organs in case of horticultural crops) under potential conditions was defined as a linear function of the PAR intercepted during growing season (PAR_{INT}, MJ PAR m^{-2}), considering a crop-specific light use efficiency coefficient (LUE, g DM MJ PAR m^{-1}; Equation 3; Sadras *et al.*, 2017; Steduto *et al.*, 2009; Monteith *et al.*, 1977). PAR_{INT} was calculated following Equation 4 as the sum from sowing to harvest of the daily RAD_{GLOBAL} and the fraction of intercepted PAR in a given day (f_PAR). The latter depends on crop development stage as it is expressed as a function of kc (Equation 5; Allen *et al.*, 1998; Doorenbos & Pruitt, 1977). Incident PAR was assumed to be 0.45 of RAD_{GLOBAL} (Sinclair & Muchow, 1999). Crop-specific LUE for dry matter production was defined in relation to the reference value LUEc (assumed as 3.2 g DM MJ PAR^{-1} for C3 crops; Sadras *et al.*, 2017) considering crop-specific HI, P% and F% contents (Equation 6). For each crop, HI was compiled from existing literature, P% and F% were obtained from Sadras *et al.* (2017).

$$\text{TAGP (g DM m}^{-2}\text{)} = \text{PAR}_\text{INT} \times \text{LUE} \quad (3)$$

$$\text{PAR}_\text{INT}\ \text{(MJ PAR m}^{-2}\text{)} = \sum_{i=sowing}^{harvest} 0.45 \times \text{RAD}_{\text{GLOBAL}i} \times \text{f\_PAR}_i \quad (4)$$

$$\text{f\_PAR} = \begin{cases} 0.1, & \text{kc} \leq \text{kc\_ini} \\ \text{kc} - 0.3, & \text{kc} \geq \text{kc\_ini} \end{cases} \quad (5)$$

$$\text{LUE (g DM MJ PAR}^{-1}\text{)} = \frac{\text{LUEc}}{(1 - \text{HI}) + \text{HI} \times (1 + 0.4 \times \text{P\%} + 1.5 \times \text{F\%})} \quad (6)$$

$$\text{Yp (t FM ha}^{-1}\text{)} = \frac{\text{TAGP} \times \text{HI}}{100} \times \frac{1}{\text{DM}} \quad (7)$$

$$\text{RUE (g DM MJ PAR}^{-1}\text{)} = \frac{\text{Ya} \times \text{DM\%}}{\text{PAR}_\text{INT}} \times 100 \quad (8)$$

Yp (t FM ha^{-1}) was calculated based on TAGP, HI and DM% (Equation 7) and the yield gap closure was calculated as the ratio between the reported Ya and the estimated Yp. RUE was further estimated as the ratio between Ya and PAR_{INT} (Equation 8). These calculations were done for each unique combination of farm × field × year × crop in the database, using the farmer reported sowing and harvest dates and the measured global radiation data from the nearest KNMI weather station.

3.2.2 Estimation of Yw and water use efficiency

Crop water requirements Crop water requirements during the growing season were estimated following the methodology described by Steduto *et al.* (2009). It was assumed that crop water requirements for potential conditions are equal to the cumulative potential crop evapotranspiration (PCETP, mm) during the growing season, which was calculated based on the daily kc and daily ET0 (Equation 9). By definition, PCETP is equal to the sum of potential crop transpiration (TRP, mm) and total evaporation from soil and canopy (SEV, mm). The former was calculated with Equation 10 and depends on crop development (expressed by kc), weather conditions (expressed by ET0) and intercepted radiation (expressed by f_PAR), while the latter was computed as the difference between PCETP and TRP (Equation 11).

$$\text{PCETP (mm)} = \sum_{i=sowing}^{harvest} \text{kc}_i \times \text{ET0}_i = \sum_{i=sowing}^{harvest} (\text{TRP}_i + \text{SEV}_i) \tag{9}$$

$$\text{TRP (mm)} = \sum_{i=sowing}^{harvest} \text{kc}_i \times \text{ET0}_i \times \text{f\_PAR}_i \tag{10}$$

$$\text{SEV (mm)} = \sum_{i=sowing}^{harvest} \text{kc}_i \times \text{ET0}_i \times (1 - \text{f\_PAR}_i) \tag{11}$$

PCETP comprises the amount of water needed to achieve Yp previously estimated for each unique combination of farm × field × year × crop. As explained below, Yp and PCETP can be used to derive a benchmark for the water use efficiency, and for Ya and seasonal water available, in each field.

Soil water losses and crop transpiration Soil water losses refer to the outflows of water from the soil profile through crop transpiration, crop and soil evaporation, deep percolation and surface run-off. These losses are independent of crop management and occur in the beginning of the growing season, when SEV and TRP do not counterbalance rainfall inputs leading to significant deep percolation losses. The estimation of soil water losses was done for two contrasting soil types, namely clay (FC = 0.27, wilting point as WP = 0.12 and saturation as SAT = 0.37, all in mm mm^{-1}) and sandy soil (FC = 0.21, WP = 0.10 and SAT = 0.31), with a daily soil water balance:

$$\theta_i \text{ (mm day}^{-1}) = \theta_{i-1} - \text{Outflow}_i + \text{Inflow}_i \quad (12)$$

$$\text{Outflow}_i \text{ (mm day}^{-1}) = \text{SR}_i + \text{DP}_i + \text{SEV}_i + \text{TRP}_i \quad (13)$$

$$\text{Inflow}_i \text{ (mm day}^{-1}) = \text{RAIN}_i + \text{CapR}_i \quad (14)$$

where θ_i is the soil water available in day *i* (assumed as equal to field capacity at sowing), SR_i and DP_i are daily water losses due to surface run-off and deep percolation, SEV_i and TRP_i are the daily soil and canopy evaporation and crop transpiration (Equations 11 and 10), $RAIN_i$ is the amount of rainfall measured in day *i* in the nearest weather station and $CapR_i$ is the inflow of water through capillary rise in day *i*. The latter was estimated per soil type, as explained below. Irrigation was not considered in the calculation of soil water losses as these are independent of crop management.

The outflows defined in Equation 13 were divided into soil water losses and crop transpiration. The latter was included in the water balance but not considered as an unavoidable loss due to its linear relationship with crop yield (Rattalino-Edreira *et al.*, 2018; Grassini *et al.*, 2011; Sadras & Angus, 2006; French & Schultz, 1984). Water losses due to surface run-off were assumed to be negligible due to flat topography in The Netherlands and water losses due to SEV were estimated with Equations 9 - 11. Capillary rise in the Netherlands was assumed to be on average 0.39 mm day^{-1} in clay soils (Knotters & van Walsum, 1997). It was also assumed that capillary rise from groundwater tables in sandy soils was 25% lower than in clay soils. Daily water losses due to DP were calculated for a each soil type using a 'tipping bucket' approach:

$$\text{DP}_i \text{ (mm day}^{-1}) = \begin{cases} 0, & \theta_{i-1} \leq \theta\text{FC} \\ \text{SWCON} \times \text{Z} \times (\theta_i - \theta\text{FC}), & \theta_{i-1} > \theta\text{FC} \end{cases} \quad (15)$$

where θ_i (mm) is the daily soil water content, SWCON represents the fraction of water excess (when $\theta_i > \theta$FC) that is lost through deep percolation, Z (m) is the rooting depth of the crop (i.e., 0.5m for horticultural crops and 1.2m for cereals) and θFC (mm) is the amount of water in the soil at field capacity. SWCON was assumed to be 0.53 and 0.80 for clay and sandy soils, respectively (Villalobos & Fereres, 2017). Finally, the cumulative deep percolation during the growing season was calculated as the sum of daily deep percolation between sowing and harvest.

Seasonal water available The total seasonal water available for crop growth (TSWA, mm), and water use efficiency (WUE, kg DM ha^{-1} mm^{-1}), were computed for each unique farm × field × year × crop combination as follows:

$$\text{TSWA (mm)} = \theta_{\text{sowing}} + \text{RAIN} + \text{IRRIG} + \text{CapR} \tag{16}$$

$$\text{WUE (kg DM/ha mm}^{-1}) = \frac{\text{Ya} \times \text{DM\%}}{\text{TSWA}} \times 1000 \tag{17}$$

where θ_{sowing} (mm) is the soil water available at sowing, RAIN (mm) is the total growing season rainfall from the nearest weather station, IRRIG (mm) is the total irrigation water supplied and CapR (mm) is the amount of water available through capillary rise. θ_{sowing} was determined for clay and sandy soils as the difference between field capacity and permanent wilting point times the rooting depth of the crop (Z), assuming soils were at field capacity at sowing. Capillary rise during the growing season was estimated as the cumulative daily capillary rise between sowing and harvest. The contribution of each water source to TSWA is provided in Figure A2.

3.3 Benchmarks for N use efficiency at crop level

The NUE indicator proposed by the EU N Expert Panel (EUNEP, 2015) was used to quantify NUE and N surplus for arable crops in the Netherlands, considering the field as the spatial system boundary. This indicator is based on the mass balance principle and uses field-specific N input and N output data for its calculation:

$$\text{N output (kg N ha}^{-1}) = \text{Ya} \times \text{DM\%} \times \text{N}_{\text{YIELD}} \tag{18}$$

$$\text{N input (kg N ha}^{-1}) = \text{PANA}_{\text{N}} + \text{N}_{\text{SEED}} + \text{N}_{\text{DEPO}} + \text{N}_{\text{SOIL}} \tag{19}$$

$$\text{NUE (kg N kg N}^{-1}) = \frac{\text{N output}}{\text{N input}} \tag{20}$$

$$\text{N surplus (kg N ha}^{-1}) = \text{N input} - \text{N output} \tag{21}$$

where Ya, DM% and $PANA_N$ are as previously defined, N_{YIELD} (%) is the N concentration in the storage organ (Table 1; Nijhof, 1987), N_{SEED} (kg N ha^{-1}) is the amount of N in planting material (www.agrimatie.nl; Table 1) and N_{DEPO} (kg N ha^{-1}) is the atmospheric N deposition (ca. 25 kg N ha^{-1}; MNC, 2014). The contribution of these N sources to N input is provided in Figure A3. N_{SOIL} (kg N ha^{-1}) refers to the amount soil mineral N available for plant growth during the growing season due to mineralization of soil organic matter, organic manures applied and crop residues incorporated in previous years. This is not considered in the original NUE indicator but was included here so that its impact on NUE and N surplus could be explicitly assessed.

The value of N_{SOIL} is uncertain as it depends on the past history of a field. For this reason, the contribution of N_{SOIL} to NUE and N surplus was assessed through sensitivity analysis. This means that NUE and N surplus were estimated for N_{SOIL} values ranging between 0 and 350 kg N ha^{-1}, in steps of 10 kg N ha^{-1}.

The reference values for NUE (0.5 and 0.9 kg N kg N^{-1}) and N surplus (80 kg N ha^{-1}) proposed by EUNEP (2015) were adopted in this study. Based on these thresholds, it was possible to differentiate a zone with high NUE ($>$ 0.9 kg N kg N^{-1}) characterized by mining of soil N in the long-run, a zone with desired NUE ($0.5 \leq \text{NUE} \leq 0.9$ kg N kg N^{-1}) and, a zone with low NUE (NUE $<$ 0.5 kg N kg N^{-1}) due to inefficient N use and high N losses. A target of 80 kg N ha^{-1} was adopted for N surplus, as values above this incur potential N losses to the environment (e.g., N-leaching).

3.4 Statistical analyses

3.4.1 Quantile regression

Maximum boundary functions were estimated using quantile regressions in which the 95th percentile Yp and/or Ya for a given *x*-level was regressed against different biophysical and management factors (Grassini *et al.*, 2009). All quantile regressions were estimated for unique crop $\times$ year combinations using the *statsmodels* module in Python. Different functional forms were specified for different independent variables:

$$\text{Yp, Ya (t FM ha}^{-1}) = \text{a}\, x^2 + \text{b}\, x + \text{c}, \qquad x = \text{harvest\_DOY},\ \text{PAR}_{\text{INT}} \tag{22}$$

$$\text{Yp, Ya (t FM ha}^{-1}) = \text{a}\, x + \text{b}, \qquad x = \text{sowing\_DOY},\ \text{PCETP} \tag{23}$$

$$\text{Ya (t FM ha}^{-1}) = \text{a}\, 0.99^x + \text{b}\, x + \text{c}, \qquad x = \text{PANA}_{\text{NPK}} \tag{24}$$

A quadratic functional form was chosen for the relationship between crop yield and harvest date (expressed in day-of-the-year, DOY) or PAR_{INT} to explore if there is a maximum yield across the range of harvest dates and radiation intercepted across fields (Equation 22). As previously stated, a linear functional form was chosen for the relationship between Yp and PCETP (Equation 23), with the slope of this regression representing the maximum WUE of a given crop (Rattalino-Edreira *et al.*, 2018) and the x-intercept representing the minimum unavoidable soil water losses (French & Schultz, 1984). A linear functional form was also used for the relationship between sowing date and crop yield because quadratic effects were not statistically significant. Finally, a logistic functional form was chosen for the relationship between Ya and $PANA_{NPK}$ in order to capture possible yield declines when high amounts of nutrients are applied.

3.4.2 Multiple regression

Multiple regression analysis was used to assess the relationship between a set of biophysical and management factors and Ya, RAD_{INT}, TSWA and N surplus. The biophysical and management determinants used as independent variables included year and soil type dummies, on the one hand, and sowing date, harvest date and the amount, time, space and form of the inputs applied, on the other hand. Descriptive statistics of these variables are provided in Table A1. Collinearity between the different independent variables was assessed using correlation matrix (Figures A7 - A13) and analysis of variable inflation factors (VIF). Variables included in the estimated models had a VIF vaue smaller than 10. The intercept and coefficients of the regression models were estimated for the pooled sample of each crop using ordinary least squares (OLS, lm function in R) with all continuous variables mean-scaled. The relationship between the fitted values and the residuals were checked for normality and homoscedasticity and no patterns were observed in the residuals of the different models.

4 Results

4.1 Yield gaps and resource use efficiencies

Yield gaps were smallest for sugar beet (20 - 30% Yp), intermediate for ware potato and cereal crops (30 - 40% Yp) and largest for spring onion, seed potato and starch potato (40 - 60% Yp; Figures 1A - 1C). For sugar beet, Ya and Yp were on average 86.2 and 103.8 t FM ha^{-1} over the period 2015 - 2017. Consistent differences in Ya and Yp were observed for potato production systems: yields were greatest for ware potato (Ya = 52.6 and Yp = 82.6 t FM ha^{-1}), intermediate for starch potato (Ya = 44.8 and Yp = 79.8 t FM ha^{-1}) and lowest for seed potato (Ya = 35.6 and Yp = 74.4 t FM ha^{-1}). For cereals, Ya and Yp were on average 9.6 and 14.9 t FM ha^{-1} for winter wheat and 6.7 and 9.7 t FM ha^{-1} for spring barley, respectively. The large yield gaps for spring onion were a result of low Ya (57.2) compared to Yp (128.5 t FM ha^{-1}).

The radiation, water and N use efficiencies associated with these yield gaps are provided in Figures 1D - 1F. RUE was greatest for sugar beet (2.07), followed by ware potato (1.57), starch potato (1.39), seed potato (1.17), winter wheat (1.00) and spring barley (0.96 g DM MJ PAR^{-1}). WUE of the horticultural crops ranged between 22.98 for sugar beet and 15.18 kg DM ha^{-1} mm^{-1} for spring onion, with potato fields exhibiting an average WUE of 18.52 kg DM ha^{-1} mm^{-1} independently of the production system. The differences in RUE and WUE for the horticultural crops reflect well the differences observed in yield gap closure for these crops (Figure 1C). NUE was relatively high (> 0.9 kg N kg N^{-1}) for all crops and all years, which could indicate soil N mining in the long-term. On average, NUE ranged between 1.38 for spring barley and 0.96 kg N kg N^{-1} for winter wheat. This high NUE is explained by the correction of N in organic manures with replacement values and by the assumption that N_{SOIL} equals to zero.

4.2 Determinants of actual yields

4.2.1 Biophysical conditions

Significant differences in Ya were observed across years and soil types for all crops, except spring onion (Table 2). The lowest average Ya of ware potato, starch potato and winter wheat was recorded in 2016. Conversely, the average Ya was highest for horticultural crops, and lowest for cereals, in 2017. Ya of seed potato and sugar beet was, on average, ca. 5 t FM ha^{-1} lower in sandy soils than in clay soils while for winter

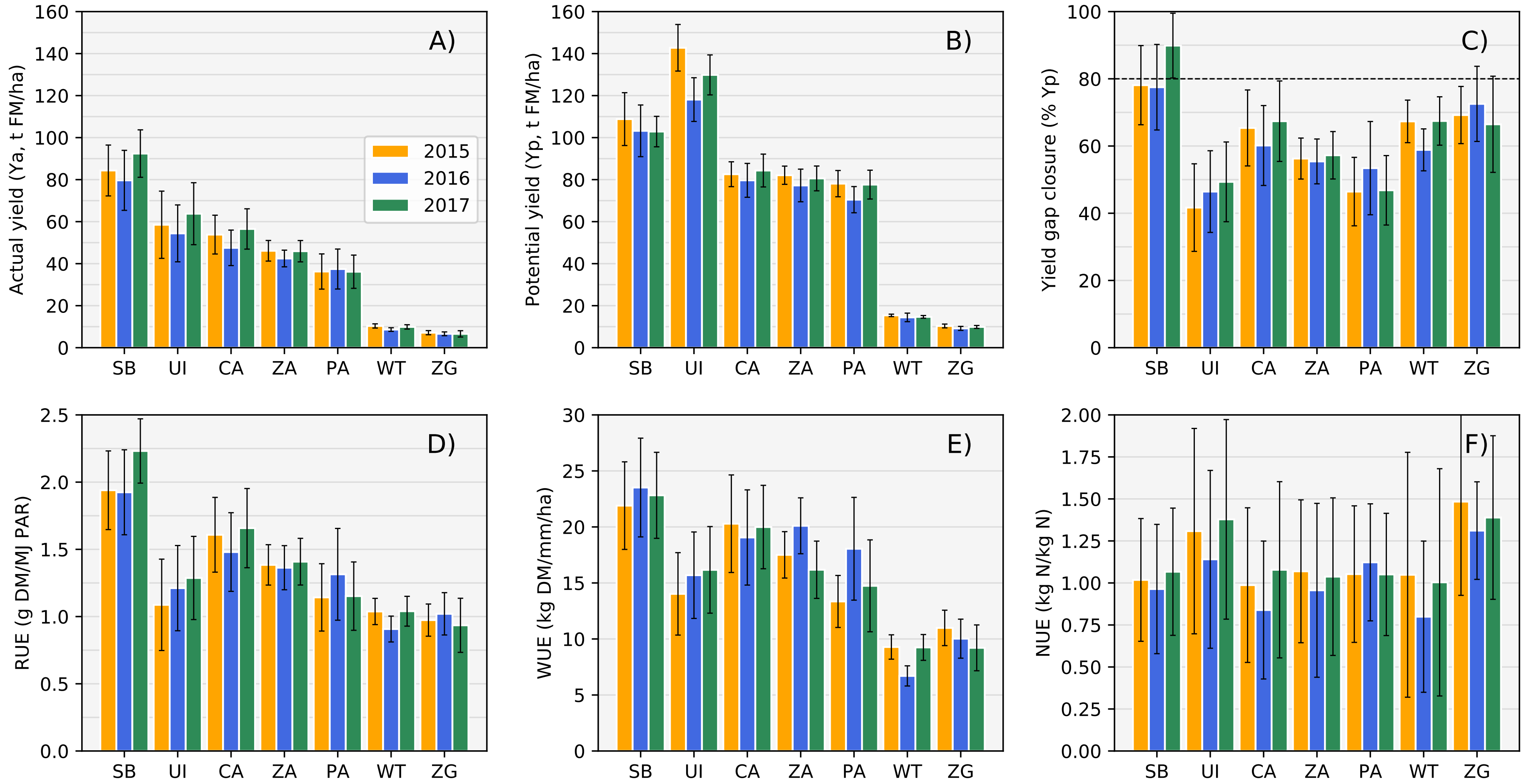

Figure 1. Descriptive statistics of A) actual yield, B) potential yield, C) relative yield gap closure, D) radiation use efficiency, E) water use efficiency and F) N use efficiency for the main arable crops in the Netherlands during the period 2015 - 2017. The NUE values presented here do not consider N_{SOIL} as input. Error bars show the standard deviation of the mean. Codes: CA = ware potato, PA = seed potato, ZA = starch potato, SB = sugar beet, UI = spring onion, WT = winter wheat, ZG = spring barley.

wheat this difference was about 0.4 t FM ha^{-1}. There were no significant differences in Ya across soil types for the other crops.

Intercepted PAR was associated with greater Ya of seed potato, sugar beet and winter wheat and with lower Ya of ware potato and spring onion (Table 2). This negative effect can be attributed to collinearity between intercepted PAR and sowing date (Figures A7 and A11). For most crops, there was a positive effect of summer rainfall, and no clear effects of spring rainfall, on Ya (Table 2). This indicates that water availability towards the end of the growing season is important for Ya of arable crops in the Netherlands.

4.2.2 Sowing and harvest dates

Later sowing was associated with lower Ya for most crops (Table 2), but there were slight differences between years (Figures 2, A15 and A16). In what follows, data and coefficients estimated with quantile regression are described for 2017 only (Figures 2). The sowing window for potato ranged from mid-March to mid-May and there was a negative effect of sowing date on Ya for ware (-106.3) and seed potato (-440.1 kg FM ha^{-1} day^{-1}), respectively. Sugar beet was planted between mid-March and end of April and later sowing had a negative effect on Ya (-858.9 kg FM ha^{-1} day^{-1}). The sowing window of spring onion was narrowest from all crops and no significant effects of sowing date on Ya were observed for this crop. For winter wheat, the sowing window was considerably long (mid-September to mid-December) and there was a negative effect of sowing date on Ya (-11.1 kg FM ha^{-1} day^{-1}). For spring barley, the sowing window ranged from early March to early April and Ya decline with later sowing date by 106.8 kg FM ha^{-1} day^{-1}. Finally, the sowing date of horticultural crops was not associated with the length of the growing season of these crops, while for cereals there was a significant negative relationship between both (Figure A14).

The harvest window of horticultural crops was longer compared to cereals (Figure 3) and the effects of harvest date on Ya and Yp were consistent across years (Figures 2, A15 and A16). Ware potato was harvested between end of July and mid-December. Seed potato and starch potato were harvested from August to October and from mid-August to end of November, respectively. Later harvest had a positive effect on Ya for ware potato and a negative effect on Ya for seed potato. No significant effect was observed for starch potato. For sugar beet, the harvest window ranged between early September and late December, and there was a positive effect of harvest date on Ya. The harvest window for spring onion was similar to seed potato and no significant effect was observed between onion yield and harvest date. Wheat and barley were harvested

Table 2. Biophysical and crop management determinants of actual yields (Ya) of the main arable crops in the Netherlands. The reference level of the categorical variables is as follows: Year = '2015'; Soil = 'Clay'. The amount of $PANA_N$ with mineral fertiliser and before sowing were not included in the model to avoid alias between variables. Significance codes: '***' 0.1% '**' 1% '*' 5% '#' 10%.

	Ware potato	**Seed potato**	**Starch potato**	**Sugar beet**	**Spring onion**	**Winter wheat**	**Spring barley**
Intercept	52.98***	33.66***	45.38***	82.11***	61.51***	10.17***	7.11***
Year_2016	−4.02***	9.14***	−2.60***	3.48#	−5.24	−1.31***	−0.19
Year_2017	3.32***	3.73**	0.36	11.64***	0.09	−0.33***	−0.44***
Soil_Sand	0.54	−5.34***	0.31	−5.33***	−1.83	−0.76***	−0.24#
Sowing (DOY)	−0.22***	0.39***	−0.03	−0.03	−0.41	−0.01***	−0.01
$Sowing^2$	0.00	−0.01**	0.00	−0.01*	0.00	0.00	0.00#
Harvest (DOY)	0.10***	−0.23***	0.03*	0.09***	0.20	−0.02*	0.01
$Harvest^2$	0.00***	0.00	0.00	0.00	−0.01*	0.00	0.00
Intercepted PAR (MJ m^{-2})	−0.03**	0.10***	0.00	0.06***	−0.11**	0.00**	0.00
Spring rainfall (mm)	0.00	0.00	0.00	−0.03***	0.06#	0.00	0.00#
Summer rainfall (mm)	0.00	0.07***	0.01	0.02#	0.10***	0.00*	0.00
Spring irrigation (mm)	0.04**						
Summer irrigation (mm)	0.10***						
Cattle manure (kg N ha^{-1})	0.03*	0.07*	−0.01	0.03		−0.01***	0.00
Cattle slurry (kg N ha^{-1})	0.03***	0.06*	−0.02**	−0.02	0.06	0.00	0.00
Pig manure (kg N ha^{-1})	0.01	0.08**	−0.02*	0.04	−0.08	0.00	0.00
Pig slurry (kg N ha^{-1})	0.03***	0.07***	0.00	0.00		0.00#	0.00#
Mixed manure (kg N ha^{-1})	0.00	0.07	0.00	0.02		−0.01***	0.00
Other organic (kg N ha^{-1})	0.00	0.00	−0.01#	0.00	0.02	0.00	0.01**
0-6 weeks (kg N ha^{-1})	0.00	0.01	−0.01#	−0.01	−0.02		0.00
6-12 weeks (kg N ha^{-1})	0.01	−0.06	−0.01	0.02	−0.03	0.00	0.01#
+12 weeks (kg N ha^{-1})	0.02	0.00	−0.02	−0.01	−0.14#	0.00*	0.00
Total P applied (kg P ha^{-1})	−0.04#	0.00	−0.01	−0.07#	0.03	0.00#	−0.01
Total K applied (kg K ha^{-1})	0.01	0.01#	0.01*	−0.02**	−0.01	0.00	0.00**
Number of splits (#)	0.20	−0.40	0.14	0.59	0.98	−0.03	0.10
Field size (ha)	0.22***	−0.13	0.11***	0.26**	0.26	0.01#	0.07***
Ajusted-R^2	0.31	0.39	0.19	0.44	0.16	0.41	0.23
Sample size (n)	1293	294	1034	783	196	1080	531

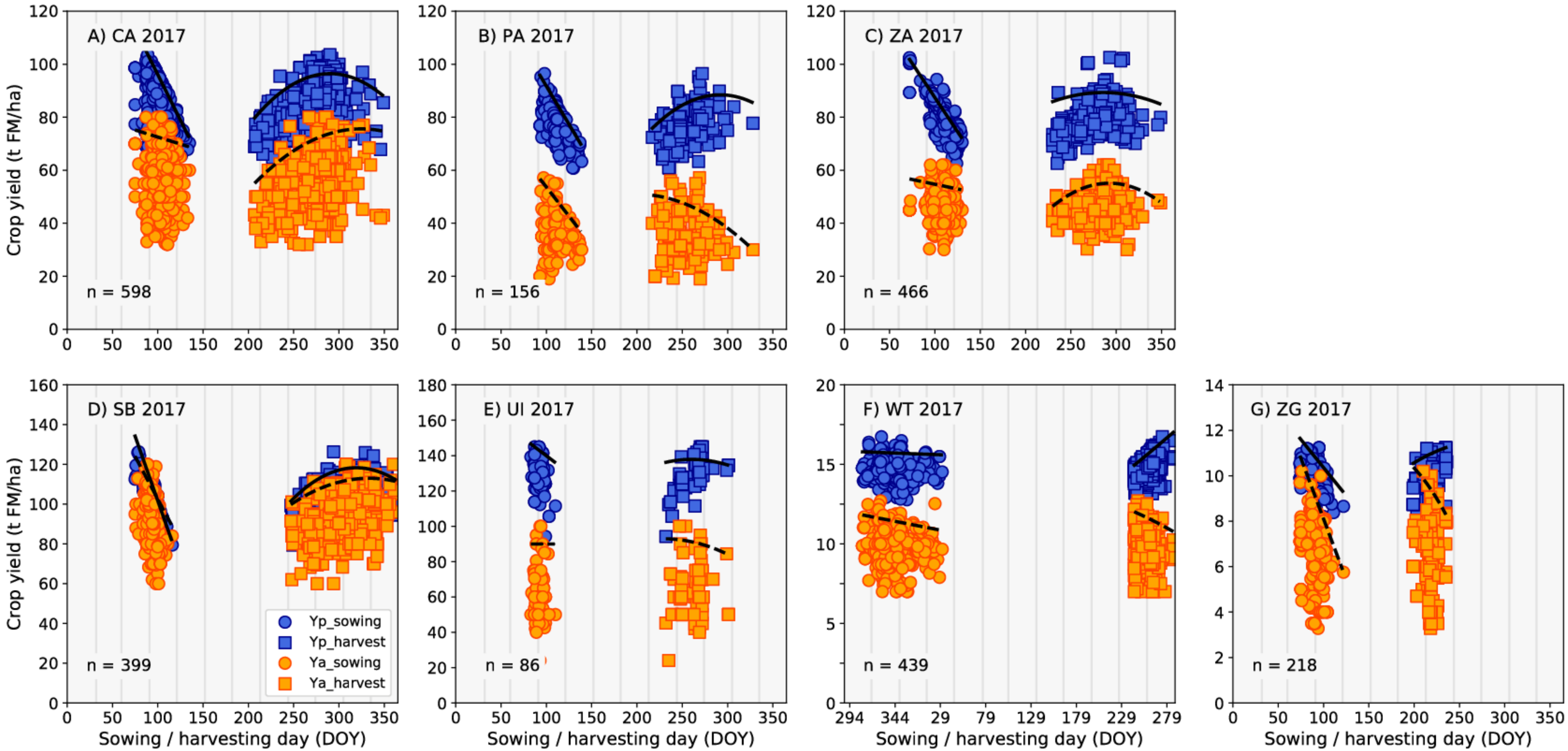

Figure 2. Relationship between sowing or harvest date (day of the year, DOY) and actual and potential yields (t FM ha^{-1}) in the year 2017 for arable crops in the Netherlands: A) ware potato, B) seed potato, C) starch potato, D) sugar beet, E) spring onion, F) winter wheat and G) spring barley. Solid and dashed lines are quantile regressions fitted to the 95th percentile of the potential and actual yields, respectively. The number of fields per crop (n) is shown for each crop and vertical grey lines indicate the different months. The duration of the growing in relation to the sowing date is provided in Figure A14 and data for the years 2015 and 2016 can be found in Figures A15 and A16.

between mid-July and end of August and there was a negative effect of harvest date on Ya for wheat. There was no significant effect of harvest date on Ya for barley.

4.2.3 Water management

Irrigation water in the Netherlands was supplied to ware potato, hence its effects on Ya were not assessed for the other crops (Table 2). The amount of water supplied as irrigation during spring and summer had a positive effect on Ya of ware potato, while the amount of spring and summer rainfall had no significant effect on Ya. This suggests that rainfall distribution, not its total amount, may be limiting potato yields during spring and summer periods and that supplementary irrigation to ware potato in key periods of the growing season is justified to achieve high yields.

4.2.4 Nutrient management

The effects of $PANA_N$ rate, timing and form on Ya were small, and not consistent, across crops (Table 2 and Figure A4). The amount of $PANA_N$ as cattle manure, cattle slurry and pig slurry was positively associated with Ya of ware potato. However, this effect was rather marginal for all N sources (30 kg FM kg N applied^{-1}). For seed potato, Ya was positively associated with the amount of $PANA_N$ as cattle manure, cattle slurry, pig manure and pig slurry but again the effect was only ca. 70 kg FM kg N^{-1} applied. A similar positive effect, but of smaller magnitude, was observed between the amount of $PANA_N$ provided by 'other manures' and Ya of spring barley. The amount of $PANA_N$ as cattle slurry and pig manure was negatively associated with Ya of starch potato. A similar negative effect was observed for winter wheat, but with the amount of $PANA_N$ as cattle manure and mixed manure.

The effects of $PANA_P$ and $PANA_K$ on crop yields were also small, and only marginally significant for most crops (Table 2 and Figures A5 and A6). $PANA_P$ was negatively associated with Ya of ware potato and sugar beet, but this effect was only marginally significant and most likely confounded by the available P in the soil. $PANA_K$ was positively associated with Ya of seed potato, starch potato and spring barley and negatively associated with Ya of sugar beet.

4.2.5 Field size

Field size was positively associated with Ya for most crops (Table 2). Increasing field size by 1 ha resulted on average increases in Ya of ca. 250 kg FM ha^{-1} for ware potato and sugar beet and ca. 90 kg FM ha^{-1} for starch potato and spring barley. Marginal effects of field size on Ya were observed for winter wheat and no significant effects were observed for seed potato and spring onion.

4.3 Radiation intercepted and radiation use efficiency

There was a large variation in RAD_{INT} across fields for all crops (Figures 3A, 3B and 3C). RAD_{INT} ranged between 500 and 900 MJ PAR m^{-2} for horticultural crops, between 700 and 950 MJ PAR m^{-2} for winter wheat and between 500 and 700 MJ PAR m^{-2} for spring barley. There were significant differences in RAD_{INT} across years, which were crop-specific, and later sowing was associated with lower RAD_{INT} for all crops (Table A2). Later harvest was associated with a greater RAD_{INT} for cereals and a quadratic relationship with a maximum was observed for horticultural crops (Table A2). Similar effects were observed between harvest date and RAD_{INT}, and Yp, as Yp was modelled as a linear function of RAD_{INT} (Figure 3 and Table A2).

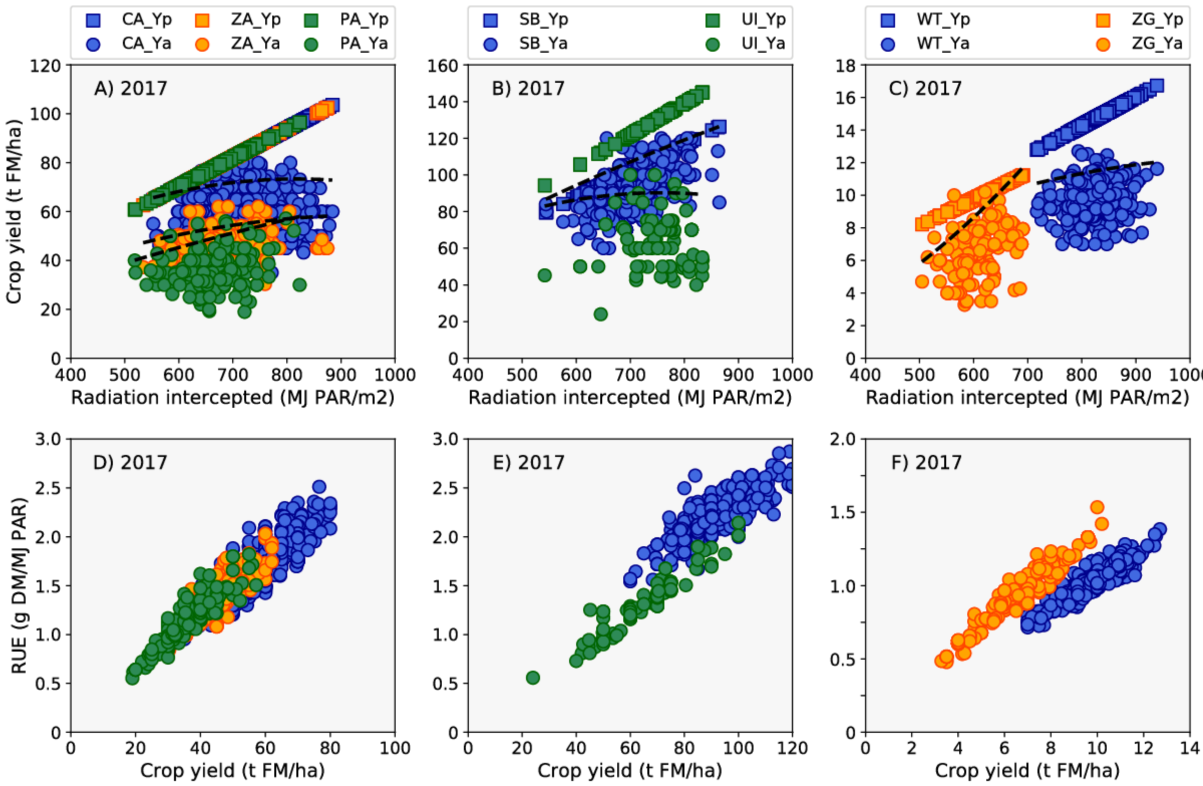

Figure 3. Radiation intercepted, crop yields and radiation use efficiency in the year 2017 for arable crops in The Netherlands. Dashed lines in A), B) and C) are quantile regressions fitted to the 95th percentile of Ya. Codes: CA = ware potato, PA = seed potato, ZA = starch potato, SB = sugar beet, UI = spring onion, WT = winter wheat, ZG = spring barley.

RUE was positively associated with Ya for all crops, meaning that narrowing yield gaps is key to improve RUE (Figures 3D, 3E and 3F). For potato, RUE varied between 0.5 and 2.5 g DM MJ PAR^{-1} with lowest RUE observed for seed potato, intermediate RUE for starch potato and highest RUE for ware potato. RUE for sugar beet ranged between 1.5 and 3.0 g DM MJ PAR^{-1} and for spring onion between 0.5 and 2.0 g DM MJ PAR^{-1}. Cereals had much lower (maximum) RUE than horticultural crops, as RUE was at most 1.40 g DM MJ PAR^{-1} in highest yielding wheat and barley fields.

4.4 Total seasonal water available and water use efficiency

TSWA ranged between 350 and 900 mm for potato, between 400 and 1000 mm for sugar beet, between 450 and 800 mm for spring onion and spring barley and, between 800 up to more than 1400 mm for winter wheat (Figure 4). For a considerable amount of fields, TSWA was lower than the PCETP, which indicates that an additional source of water input is missing in our water balance. We believe this corresponds to capillary rise (Kroes *et al.*, 2018). It is worth noting that ca. 70% of TWSA refers to growing season rainfall (Figure A2) and that soil water available at sowing was much smaller in sandy soils than in clay soils (Table A2). For horticultural crops, TSWA was mostly associated with later harvest date rather than with sowing date. The opposite was true in case of cereals: earlier sowing of winter wheat was positively associated with TSWA while for spring barley a quadratic relationship with a maximum was observed between TWSA and the sowing and harvest dates.

The slope and x-intercept of the boundary functions derived between Yp and PCETP for each crop (Figure 4) are biophysically meaningful. The former is a measure of WUE (i.e., kg yield per unit transpiration) while the latter indicates the unavoidable soil water losses due to evaporation and deep percolation. The maximum slope of the boundary lines ranged between 17.9 kg DM ha^{-1} mm^{-1} for spring barley, 26.7 kg DM ha^{-1} mm^{-1} for winter wheat, 28.0 kg DM ha^{-1} mm^{-1} for sugar beet, ca. 31 kg DM ha^{-1} mm^{-1} for potato and 33.3 kg DM ha^{-1} mm^{-1} for spring onion. The x-intercept of the boundary lines was smallest (ca. 200 mm) for potato, sugar beet and spring barley, intermediate for spring onion (ca. 300 mm) and largest for winter wheat (ca. 400 mm). The interception of the estimated boundary lines with the maximum Yp (defined here as the mean Yp above the 90^{th} percentile Yp) indicates the minimum amount of water needed to avoid water limitations during the growing season. As such, no further yield increases were observed for TSWA $\geq$ 700 mm for spring barley, $\geq$ 800 mm for potato, $\geq$ 900 mm for winter wheat and $\geq$ 1000 mm for sugar beet and spring onion.

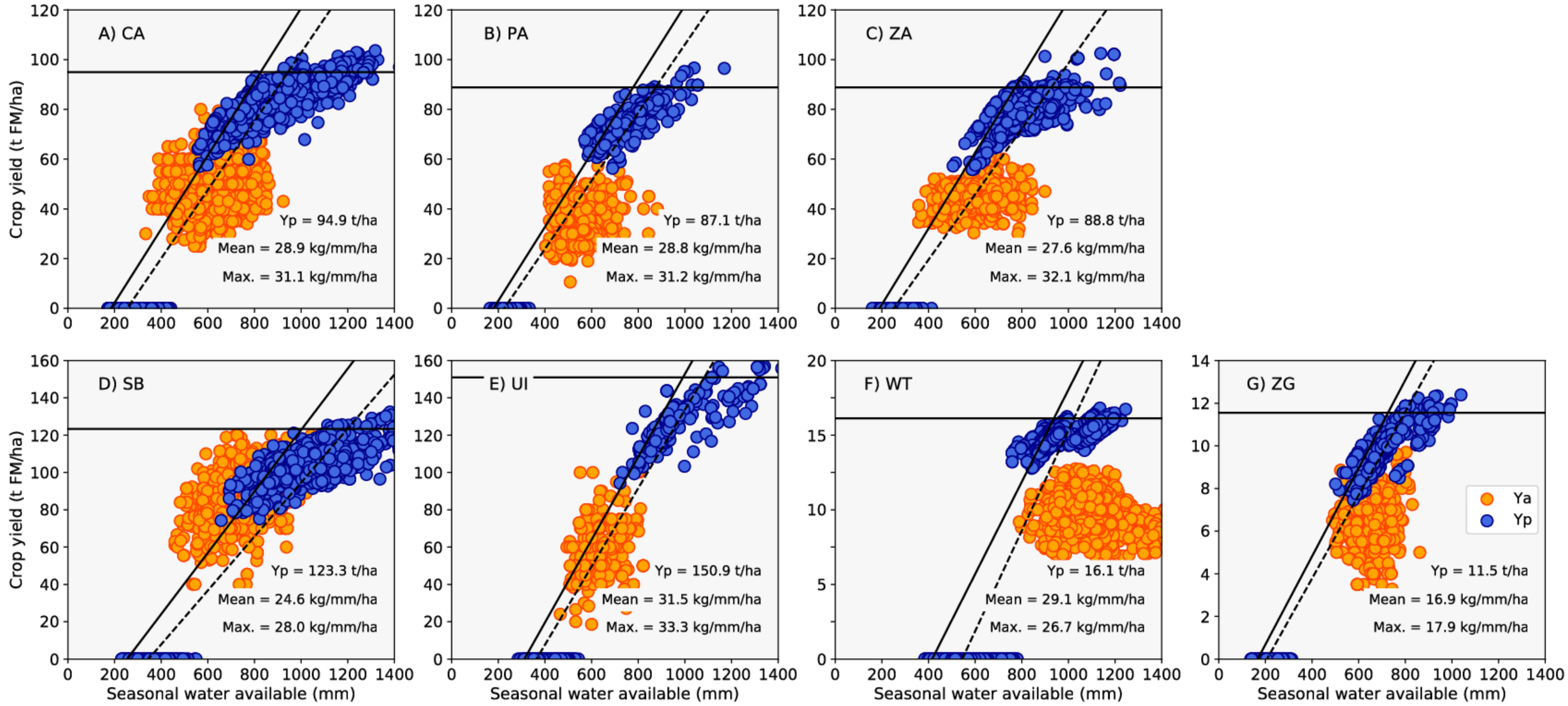

Figure 4. Relationship between Ya and total seasonal water available (TWSA) for arable crops in the Netherlands during the period 2015 - 2017. Note that data from the 3 individual years are presented. Solid and dashed lines show the maximum and mean WUE (values of the slopes are presented on a DM basis) and were fitted between Yp and potential crop evapotranspiration with quantile regressions to the 95th and 50th percentiles, respectively. Codes: CA = ware potato, PA = seed potato, ZA = starch potato, SB = sugar beet, UI = spring onion, WT = winter wheat, ZG = spring barley.

The benchmarks described above provide a reasonable upper limit for the WUE estimated with the farmer field data (based on Ya and TSWA) for seed potato, starch potato, spring onion, winter wheat and spring barley (Figure 4). The mismatch observed between the boundary line and upper limit of the farmer field data for ware potato and sugar beet are due to the underestimation of the water supplied to the crop as capillary rise, which is a major source of water for crop growth in the Netherlands (Kroes *et al.*, 2018). Moreover, the data indicates that current levels of TWSA for all crops, except winter wheat, were not high enough to avoid water limitations during part of the growing season. Further research will focus on improving the estimates of water available for crop growth from capillary rise using the data of Kroes *et al.* (2018).

4.5 N use efficiency and N surplus

A large variation in N input and N output was observed for all crops (Figure 5). This was particularly true for ware potato and winter wheat. For both crops N input ranged between 25 and 450 kg N ha^{-1}, and N output ranged between 100 and 300 kg N ha^{-1} for the former and between 100 and 225 kg N ha^{-1} for the latter (Figures 5A and 5F). For starch potato, maximum N input and N output was ca. 300 and 200 kg N ha^{-1} (Figure 5C), respectively. The variation in N output was smallest for sugar beet (ca. 70 - 140 kg N ha^{-1}, Figure 5D), while the variation in N input was smallest for spring barley (ca. 50 - 150 kg N ha^{-1}, Figure 5G). Relatively similar amounts of N input and N output were observed for seed potato and spring onion (Figures 5B and 5E). The relationship between N output and N input was generally weak, which confirm the lack of yield responses to N (Figure A4).

NUE was greater than 0.9 kg N kg N^{-1} for most fields, independently of the crop (Figure 5). These high NUE values indicate soil N mining in the long-term, which is misleading given the annual inputs of crop residues and addition of organic manures (for which replacement values were used to correct N inputs). In 2017, this was true for 88.9% of the spring barley fields, 77.9% of the spring onion fields, ca. 60% of the sugar beet fields and seed potato fields, ca 50% of the ware and starch potato fields and for only 32.1% of winter wheat fields. In contrast, less than 5% of the fields analysed exhibited NUE lower than 0.5 kg N kg N^{-1}. This means that intermediate NUE levels were observed in 63.3% of the winter wheat fields, 40 - 45% of the potato and sugar beet fields and less than 20% of the spring onion and spring barley fields. The drivers of NUE were similar in magnitude and significance to the drivers of N surplus described below (Table 3), but of opposite sign (Table A3).

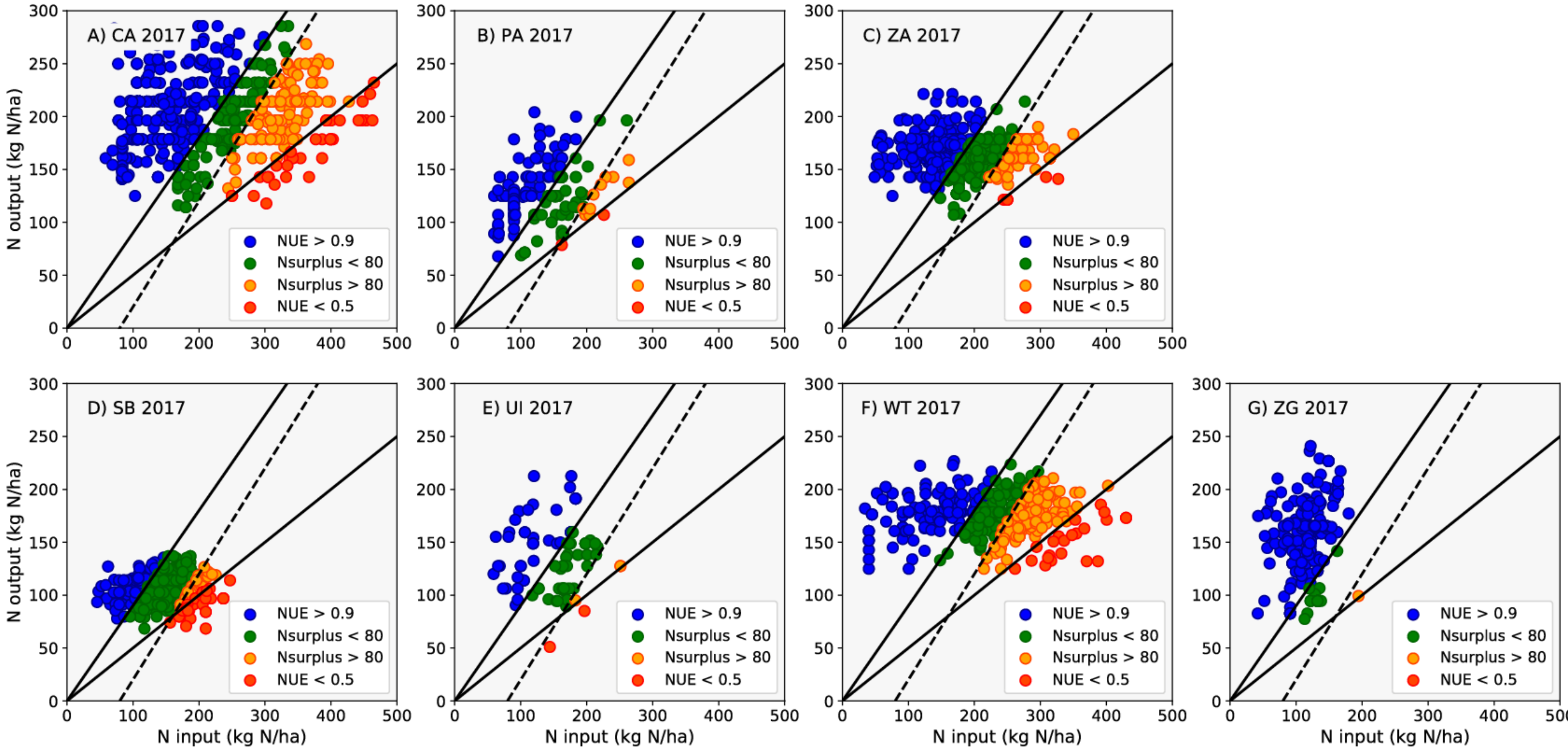

Figure 5. N use efficiency indicator of the EUNEP (2015) applied for arable crops in the Netherlands, without accounting for N_{SOIL} (input) and N in crop residues (output). Data refer to 2017 only. Solid lines indicate NUE equal to 0.5 and 0.9 kg N kg N^{-1} and the dashed line indicates N surplus equal to 80 kg N ha^{-1}. Codes: CA = ware potato, PA = seed potato, ZA = starch potato, SB = sugar beet, UI = spring onion, WT = winter wheat, ZG = spring barley.

Table 3. Biophysical and crop management determinants of N surplus (kg N ha^{-1}) of the main arable crops in the Netherlands. The reference level of the categorical variables is as follows: Year = '2015'; Soil = 'Clay'. The amount of $PANA_N$ with mineral fertiliser and before sowing were not included in the model to avoid alias between variables. Significance codes: '***' 0.1% '**' 1% '*' 5% '#' 10%.

	Ware potato	**Seed potato**	**Starch potato**	**Sugar beet**	**Spring onion**	**Winter wheat**	**Spring barley**
Intercept	44.25***	3.41	22.73***	18.01***	−21.68#	42.01***	−38.02***
Year_2016	13.04*	−30.24***	27.98***	−5.12	9.25	24.27***	4.87
Year_2017	−18.77***	−10.23#	7.48#	−11.20**	−2.14	6.20***	9.16*
Soil_Sand	−13.12***	18.27***	−19.31***	−10.06***	−1.62	14.19***	−8.01#
Sowing (DOY)	0.70*	−1.34*	0.51	1.11***	1.33	0.14***	0.01
$Sowing^2$	0.00	0.03*	−0.01#	0.01	−0.01	0.00	0.01#
Harvest (DOY)	−0.28**	0.65**	−0.25**	−0.29***	−0.42	0.34*	0.15
$Harvest^2$	0.01***	0.00	0.00	0.00	0.02	0.00	−0.01
Intercepted PAR (MJ m^{-2})	0.02	−0.30***	0.08	0.10#	0.35**	−0.06**	−0.16#
Spring rainfall (mm)	0.03	−0.08	−0.02	0.07*	−0.14	0.01	0.07#
Summer rainfall (mm)	0.08#	−0.10	0.18***	0.05	−0.44***	−0.04*	0.09#
Spring irrigation (mm)	−0.10						
Summer irrigation (mm)	−0.55***						
Cattle manure (kg N/ha)	0.62***	0.93***	0.88***	0.07		0.25***	−0.03
Cattle slurry (kg N/ha)	0.82***	0.78***	0.97***	0.41***	0.26	0.00	−0.17
Pig manure (kg N/ha)	0.84***	0.72***	1.00***	0.30***	0.35	0.03	0.05
Pig slurry (kg N/ha)	0.82***	0.75***	0.92***	0.43***		0.03#	0.41***
Mixed manure (kg N /ha)	0.94***	0.62**	0.93***	0.43***		0.11***	0.15
Other organic (kg N/ha)	0.88***	1.16***	0.96***	0.56***	−1.14	0.01	0.06
0-6 weeks (kg N/ha)	0.57***	0.33***	0.47***	0.28***	0.64***		0.12**
6-12 weeks (kg N/ha)	0.71***	1.32***	0.48***	0.24***	0.79***	0.99***	0.09
+12 weeks (kg N/ha)	0.34*	0.73*	0.20	0.25**	0.89***	0.97***	0.79***
Total P applied (kg P/ha)	−0.07	−0.26	−0.31***	0.08	0.23	−0.08#	−0.12
Total K applied (kg K/ha)	0.05*	−0.06#	−0.02	0.04	0.12**	0.01	−0.03
Number of splits (#)	9.49***	15.06***	17.84***	6.86***	0.52	0.47	4.57**
Field size (ha)	0.43	0.78	−0.99***	−0.80**	−0.83	−0.18#	−1.64***
Ajusted-R^2	0.75	0.53	0.69	0.38	0.54	0.96	0.28
Sample size (n)	1293	294	1034	783	196	1080	531

N surplus was lower than 80 kg N ha^{-1} for most fields analysed (Figure 5). As an example, more than 85% of the seed potato, starch potato, sugar beet, spring onion and spring barley fields had an amount of N surplus lower than 80 kg N ha^{-1}. For ware potato and winter wheat fields that proportion was 70 and 60%, respectively. As expected, there was a consistent positive of effect of the amount $PANA_N$ on N surplus for all crops (Table 3). This can be seen in the positive significant effect of N splits (highly correlated with $PANA_N$) on N surplus for most crops and on the positive effect of $PANA_N$ from different sources and at different moments. However, there were slight differences between crops regarding the latter. For potato and sugar beet crops, both $PANA_N$ from different sources, and on different timings, contributed to greater N surplus. For spring onion, only $PANA_N$ in different dates increased N surplus while for cereals mixed results were observed. N surplus was significantly smaller in sandy soils than in clay soils in case of ware potato, starch potato, sugar beet and spring barley, while the opposite was true for seed potato and winter wheat. The effects of other biophysical (e.g., rainfall) and management (e.g., $PANA_P$ and $PANA_K$) variables on N surplus were inconsistent across crops, which makes it difficult to generalize the findings.

Finally, we need to note that the present study largely overestimates NUE and underestimates N surplus because the amount of organic N applied and N_{SOIL} were not included in the calculation of N input. As shown in Figure 6, increasing amounts of N_{SOIL} reduced NUE exponentially and increased N surplus linearly. This is to be expected from Equations 20 and 21. For instance, average NUE decreased to 0.75 kg N kg N^{-1} with additional N_{SOIL} of 50 and 125 kg N ha^{-1} depending on the crop (Figure

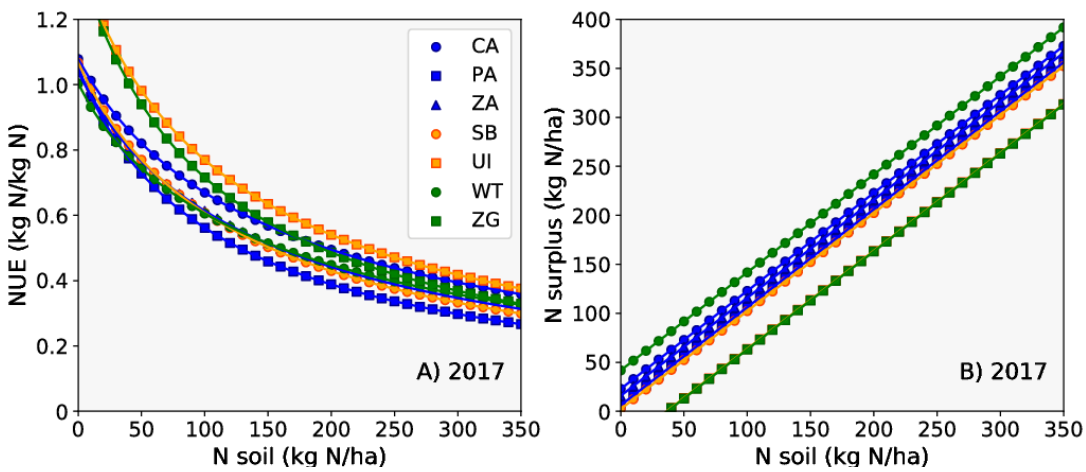

Figure 6. Sensitivity analysis of A) N use efficiency and B) N surplus to N_{SOIL} for arable crops in the Netherlands in the year 2017. Codes: CA = ware potato, PA = seed potato, ZA = starch potato, SB = sugar beet, UI = spring onion, WT = winter wheat, ZG = spring barley.

6A). Average N surplus of 80 kg N ha_{-1} were observed with additional N_{SOIL} of ca. 50 kg N ha for most crops (Figure 6B). These results clearly show that the NUE indicator proposed by EUNEP (2015) is highly sensitive to the the amount of N_{SOIL} considered, at least for arable cropping systems in The Netherlands. This means that this source of N needs to be explicitly considered in future NUE assessments and that further research is needed to understand its actual contribution to the N balance under farmer field conditions.

5 Discussion

This report builds upon a large number of farmer field data and a pragmatic crop modelling approach to benchmark crop yields and resource use efficiencies of arable crops in The Netherlands. This helps to set targets for future sustainability assessments in this production system and provides a blueprint for similar assessments in other production systems. These two issues are discussed below.

5.1 Benchmarks for Dutch arable farming

Yield gaps estimated in this study (Figure 1C) were slightly larger than those reported by Silva *et al.* (2017a) for the same crops and in the same region. This is explained by a larger Yp estimated in this study (Figure 1B) rather than differences in Ya between the two studies (Figure 1A). The Yp used by Silva *et al.* (2017a) were obtained from variety trials (Rijk *et al.*, 2013) and from crop model simulations using parameters calibrated in 1980s (Reidsma *et al.*, 2015b). The Yp estimated in this study set more realistic benchmarks for Ya, at least compared to the values of Reidsma *et al.* (2015b) for ware potato and winter wheat which are smaller than Ya for many of the fields analysed (Figure 3). This means that yield gaps reported by Silva *et al.* (2017a) were underestimated and that crop models need to be re-calibrated if they are to produce reasonable benchmarks for farmer field data in The Netherlands.

This is the first study providing benchmarks of WUE (and NUE) for the most important arable crops in Western agriculture based on farmer field data (Figure 4). The maximum WUE estimated here were slightly different to those provided in earlier studies (Rattalino-Edreira *et al.*, 2018; Lollato *et al.*, 2017; Wang *et al.*, 2018) due to differences in methods used and uncertainties related to capillary rise and recirculation of water in the soil profile (Kroes *et al.*, 2018). It is likely that actual WUE is largely overestimated in the current study for horticultural crops due to those uncertainties, as can be seen in

Figure 4 for situations where seasonal water supply is smaller than the potential crop evapotranspiration, but in any case our results show a large scope for increasing crop yields given current amounts of seasonal water available.

No yield responses to $PANA_N$ were observed for any crop (Figures 5 and A4), which is in line with the findings of Silva *et al.* (2017a). This may be explained by the fact that farmers adapt their N management to the amount of N in the soil, which makes it possible to achieve high yields at low input levels. As a result, more site-specific nutrient management is needed in detriment of current blanket recommendations based on environmental regulations. These results also suggest there is a large scope to further improve NUE and reduce N surplus in The Netherlands. This can be best achieved through reductions in the amount of $PANA_N$ (Tables 3 and A3) rather than through increases in Ya (Table 2).

Actual yields observed in farmers' fields were mostly associated with sowing date, harvest date and water availability during the growing season (Table 2 and Figure 3). The latter explains the differences in Ya for fields with similar amounts of seasonal water available (Figure 4) while the former link to crop types and machinery constraints at farm level (Reidsma *et al.*, 2015a). The length of the growing season of cereals declined with delayed sowing, which was not the case for the horticultural crops (Figure A14). This is a result of a well-defined physiological maturity for cereals but not for horticultural crops and has important implications for farm management. More precisely, it allows adjusting the harvest date of horticultural crops to the availability of machinery, hence reducing labour competition between these crops.

The database used in this report contains uncertainties as it builds upon the willingness of farmers to record crop management operations in detail. That is why potato and winter wheat fields without organic N applied were excluded from the analysis. This limitation should be overcome in future studies by focusing on monitoring a smaller sample of farmers in different agricultural regions. Further research is also needed to better understand the actual contribution of capillary rise and water recirculation within the soil profile to seasonal water supply and WUE and, of the amount of N in the soil to NUE and N surplus. Other aspect that deserve attention in the future is the impact of previous crop, and frequency of cultivation, on actual yields.

5.2 Lessons learnt for other production systems

This report focused on Dutch arable farming systems only due to lack of similar datasets available for the other production systems within the WaterFARMING consortium. We trust that the findings presented here are useful for other production systems in North-west Europe. This is justified by the similar biophysical conditions, types of crops cultivated and level of input use in this region compared to The Netherlands. However, the same is not true for production systems in South Europe and North Africa as these regions are far more affected by water scarcity and include the cultivation of perennial crops alongside arable crops. Although our findings are not directly applicable to Mediterranean regions, we explain below how this methodology could be generalized given that a minimum set of data is available in those regions.

A database containing farmer field data and data on local weather and soil properties can be used to determine resource use efficiency gaps for any given production system. Such database should contain at the very least the actual yield harvested, the GPS coordinates of the field, the sowing and harvest date, information on the water regime (irrigated vs. rainfed) and daily weather data on solar radiation, temperature and rainfall. For WUE assessments, further information on the amount, timing and quality of the irrigation water supplied and the depth of the groundwater tables is required. For NUE and N surplus assessments, detailed information on the amount, form and timing of the N applied is also necessary.

Data availability determines the indicators that can be calculated, and their uncertainty, as well as the assumptions needed for that. The pragmatic methodological approaches used in this report to quantify Yp and the components of the water balance provide a good starting point for these type of analysis, not least to identify the bottlenecks and sources of uncertainty of current benchmarks. This was preferred over a dynamic crop model due to a lack of experimental data to calibrated the latter under current conditions. This clearly shows how data availability constraints the methods that can be used and provides a blueprint of the types of decisions and secondary data sources that need to be undertaken when data are scant.

6 Conclusion

A large database of farmer field data was combined with crop modelling techniques to derive benchmarks for crop yields and resource use efficiency of arable crops in The Netherlands. Yield gaps ranged between 20% Yp for sugar beet and 55% for spring onion and were between 30 - 40% Yp for ware potato and cereal crops. The biophysical and management drivers of Ya differed per crop but were mostly related with water availability during the growing season and sowing or harvest dates. Yet, the multiple regressions explained only 16 to 44% of the variation observed in Ya. The maximum WUE observed was between 28 and 33 kg DM ha^{-1} mm^{-1} for horticultural crops, 26.7 kg DM ha^{-1} mm^{-1} for winter wheat and 17.9 kg DM ha^{-1} mm^{-1} for spring barley. The field-to-field variation observed in Ya and seasonal water available suggest there is scope to improve WUE. This should come especially through increases in Ya, as arable farming in The Netherlands is mostly rainfed. The lack of yield responses to N indicate a large scope to increase NUE and decrease N surplus further, particularly for ware potato and winter wheat. Differently from WUE, the latter are best achieved through decreases in N applied rather than through increases in Ya. However, we reckon a number of uncertainties regarding these indicators (e.g., N in soil and non-consideration of N applied in organic form) and recommend to interpret such conclusion cautiously.

Further research should focus on defining sustainability targets for Dutch arable farming based on comparisons between highest-, average- and lowest-yielding fields. The working hypotheses to be tested are that better performance at rotation level is associated with better performance at individual crop level and that highest-yielding fields are most efficient in using radiation, water and N independently of the crop studied. Finally, the methods used in this report are generic and can be applied to a set of similar data in other production systems.

7 Next steps

This report includes preliminary results only and improvements are needed in the quantification of the current indicators. The envisaged modifications in next versions of this work include:

- Estimates of Yp for seed potato need to be excluded as this crop is harvested for quality rather quantity purposes;
- The assumed dry matter content of sugar beet is rather low and needs to be increased to levels between 20 - 25%;
- Calculations of capillary rise need to be revised and implemented based on the data of Kroes *et al.* (2018);
- NUE indicator needs to be calculated with total N applied rather than $PANA_N$ only, as this is in line with EUNEP (2015);

- The maximum value of N_{SOIL} in farmers' fields will be calculated based on N yield and N biomass assuming a HI_N. The latter will be estimated based on the y-intercept of a yield response curve to N fitted with quantile regression to the highest-yielding fields for a given level of $PANA_N$ (cf. Figure A4). The latter will be derived based on N harvest index for each;
- Interactions between biophysical and crop management factors will be tested in addition to the single effects currently evaluated (Table 2) and the amount of N applied from different sources, and on different timings, will be expressed as proportions of total N applied rather than in amounts of N applied.

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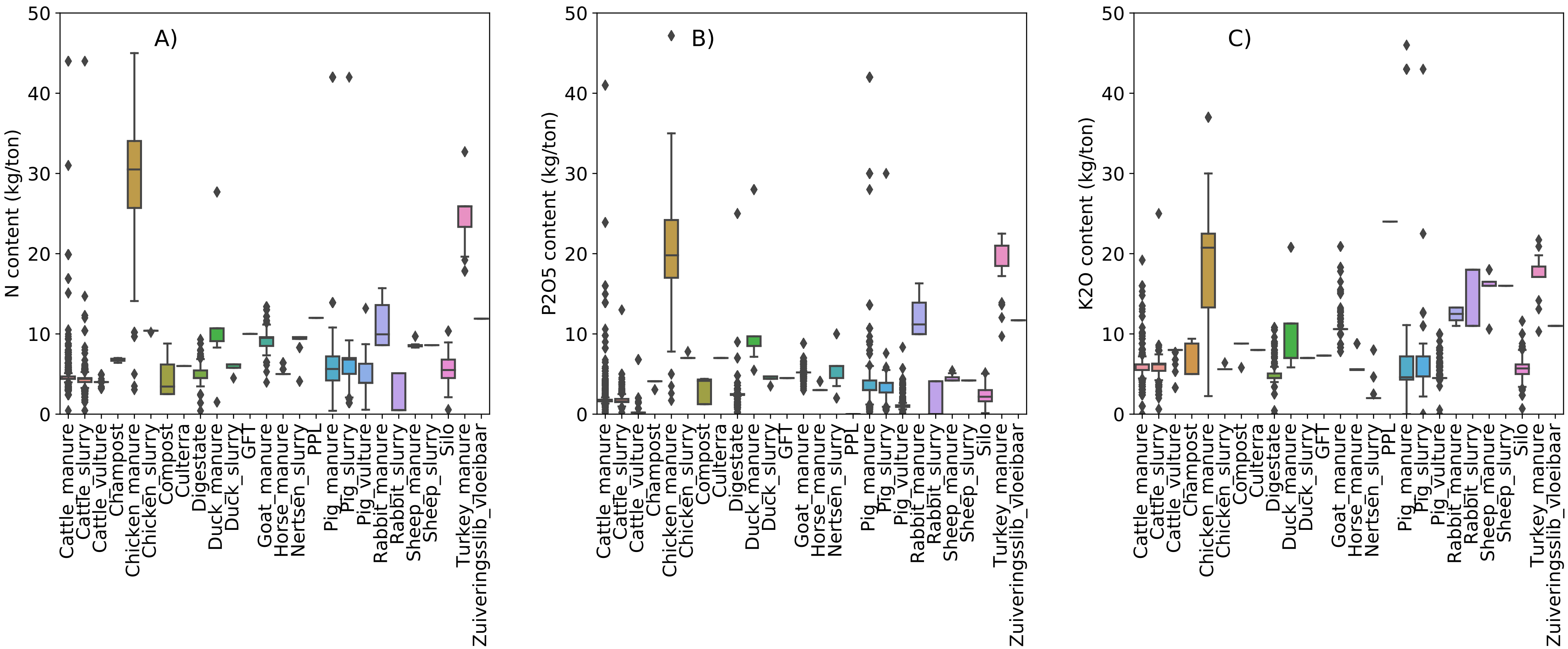

Figure A1. Variation in the content (kg ton^{-1}) of A) N, B) P_2O_5 and C) K_2O of different types of organic manures used in arable cropping systems in the Netherlands.

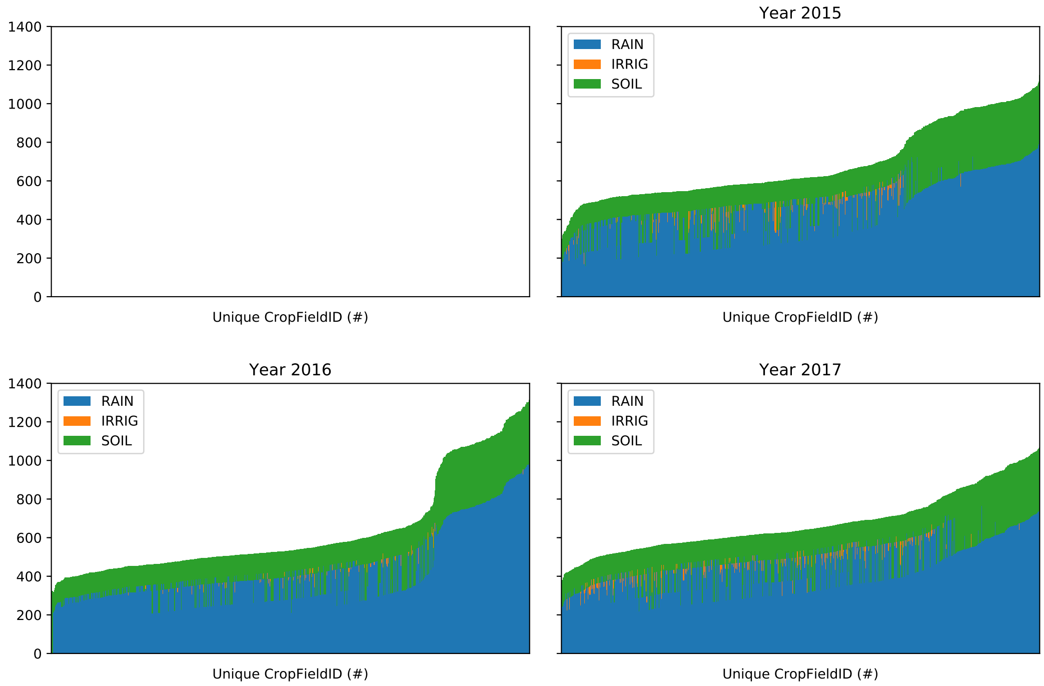

Figure A2. Contribution of rainfall, irrigation water and soil available water at sowing to total seasonal water available for the year 2015, 2016 and 2017. Each panel presents pooled data for all crops and the x-axis shows all fields per year ordered from low to high seasonal water available.

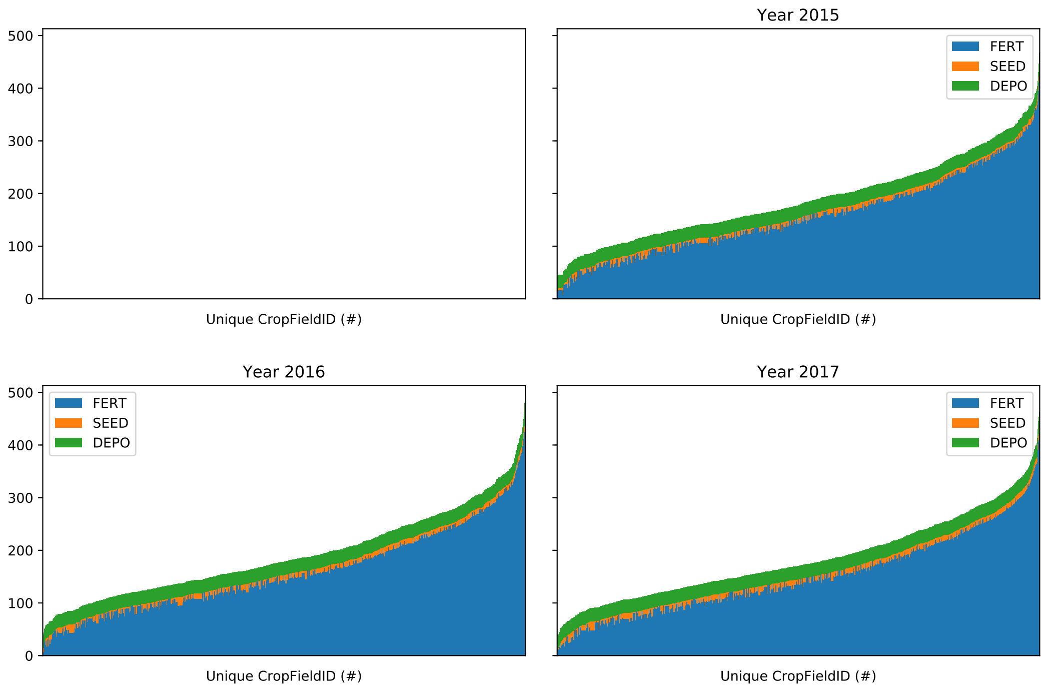

Figure A3. Contribution of plant available N applied, N seed and atmospheric N deposition to N input for the year 2015, 2016 and 2017. Each panel presents pooled data for all crops and the x-axis shows all fields per year ordered from low to high plant available N applied.

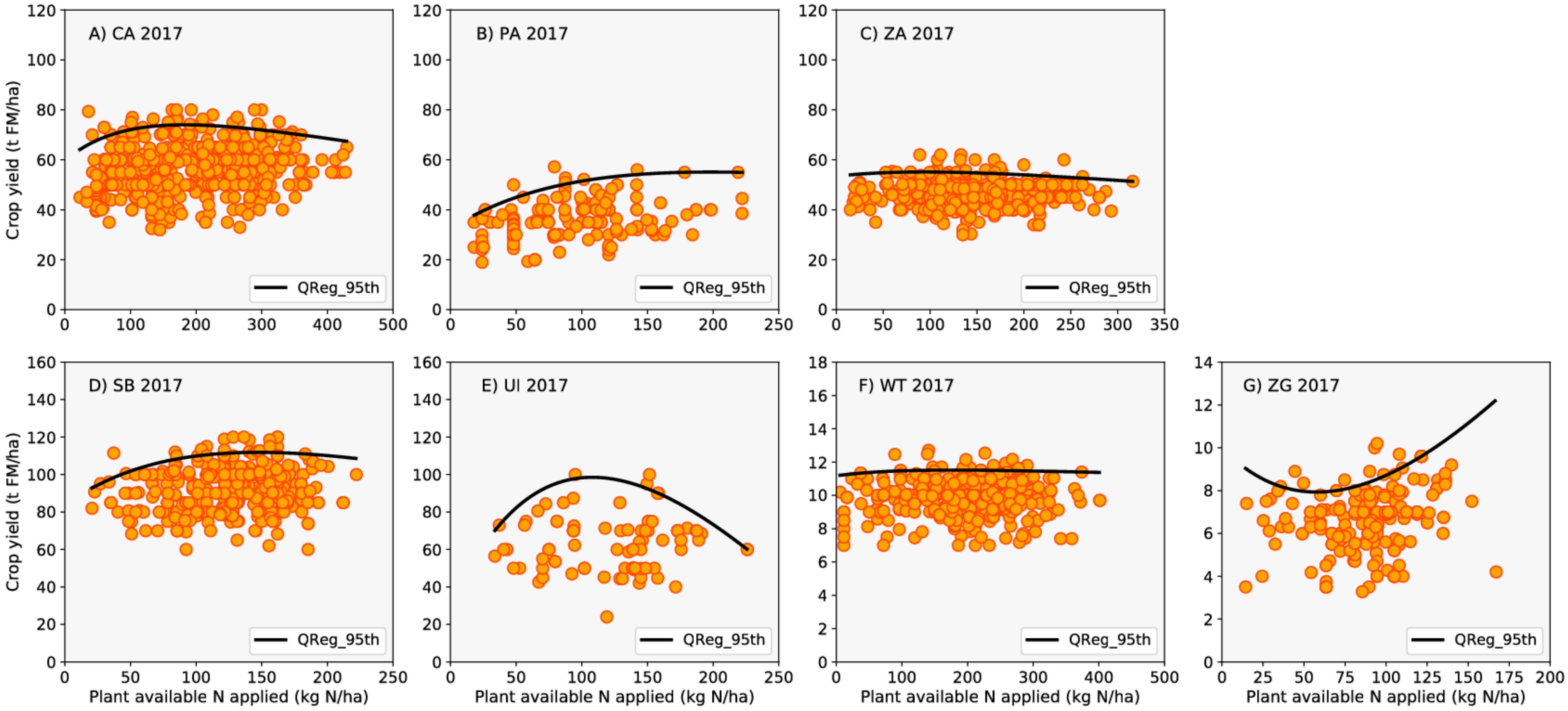

Figure A4. Relationship between Ya and plant available N applied ($PANA_N$) for arable crops in the Netherlands during the year 2017. Solid lines show the quantile regression fitted to the 95th percentile of Ya. Codes: CA = ware potato, PA = seed potato, ZA = starch potato, SB = sugar beet, UI = spring onion, WT = winter wheat, ZG = spring barley.

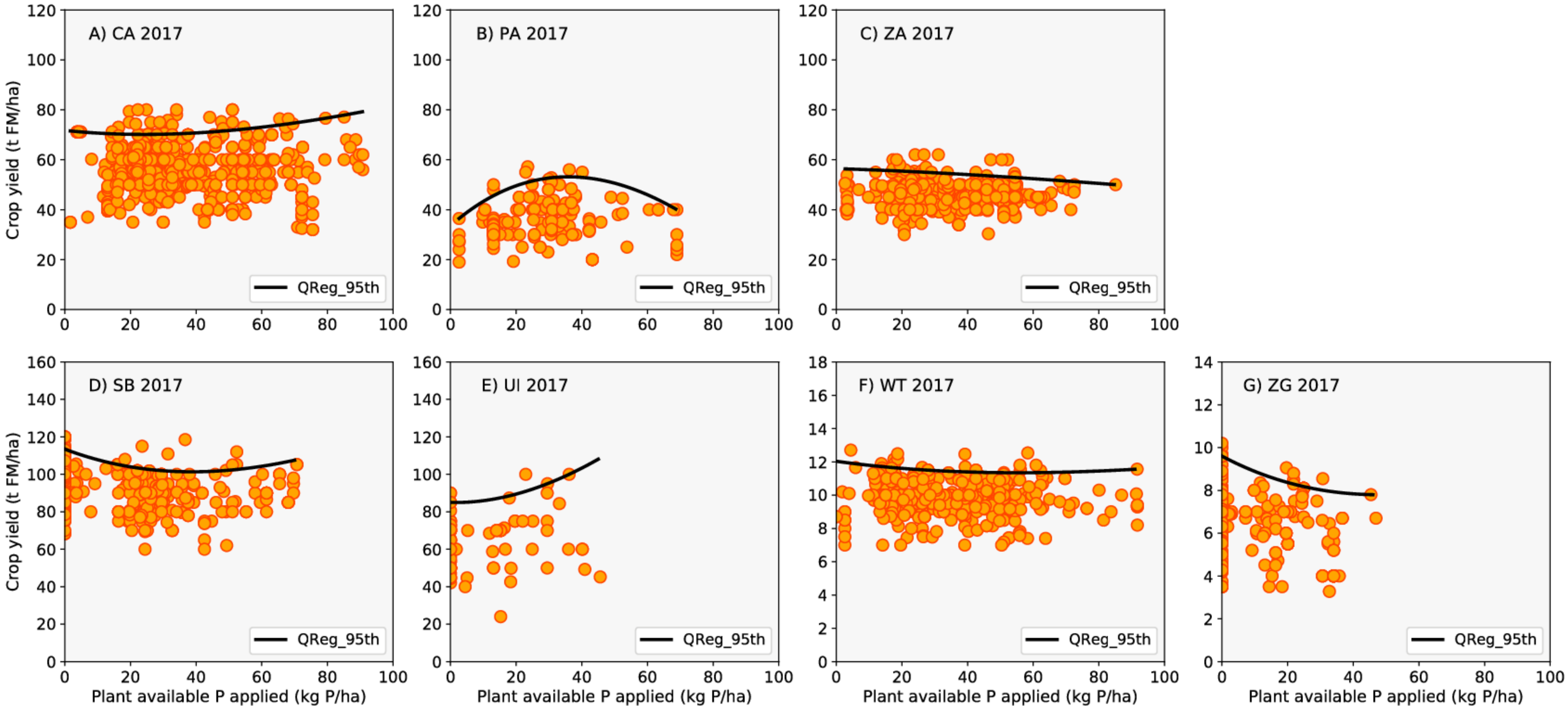

Figure A5. Relationship between Ya and plant available P applied ($PANA_P$) for arable crops in the Netherlands during the year 2017. Solid lines show the quantile regression fitted to the 95th percentile of Ya. Codes: CA = ware potato, PA = seed potato, ZA = starch potato, SB = sugar beet, UI = spring onion, WT = winter wheat, ZG = spring barley.

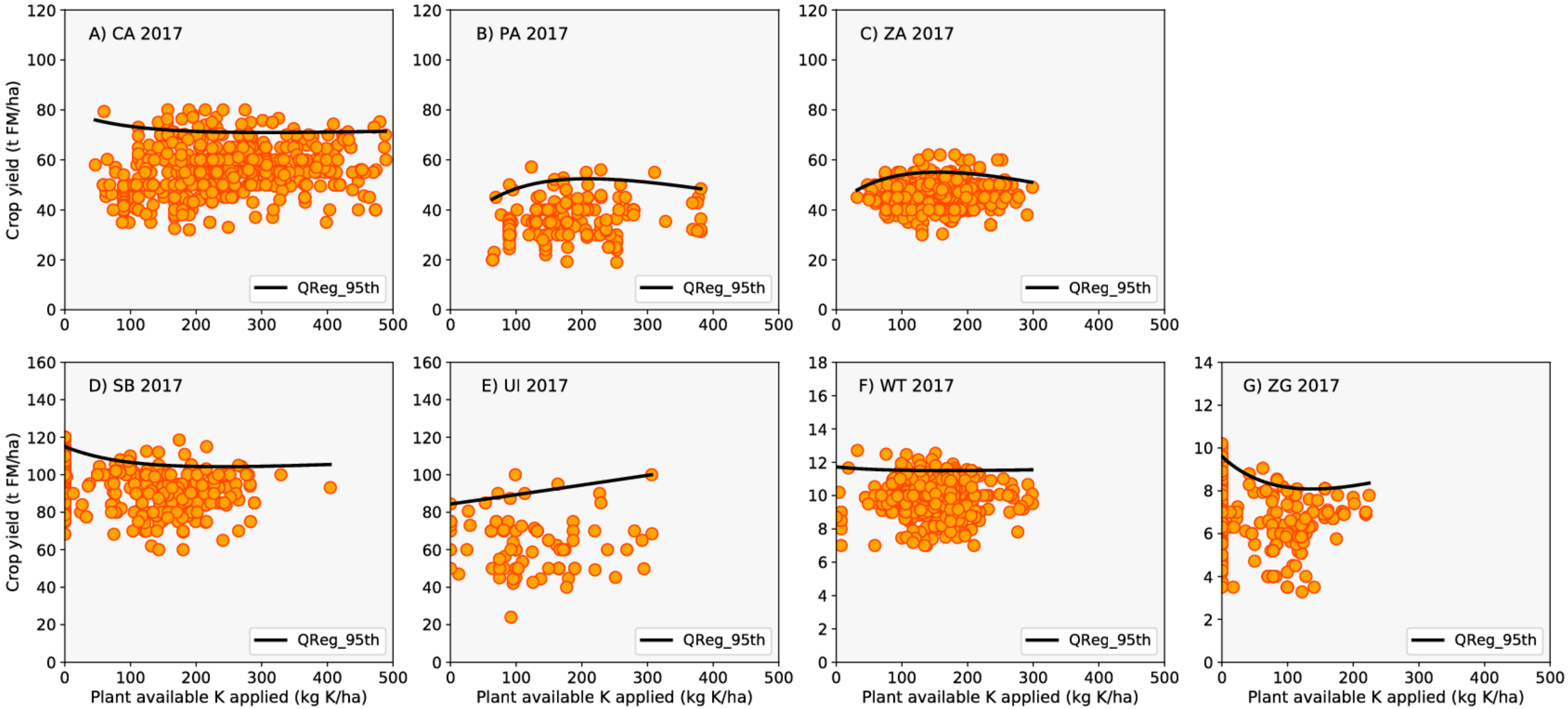

Figure A6. Relationship between Ya and plant available K applied ($PANA_K$) for arable crops in the Netherlands during the year 2017. Solid lines show the quantile regression fitted to the 95th percentile of Ya. Codes: CA = ware potato, PA = seed potato, ZA = starch potato, SB = sugar beet, UI = spring onion, WT = winter wheat, ZG = spring barley.

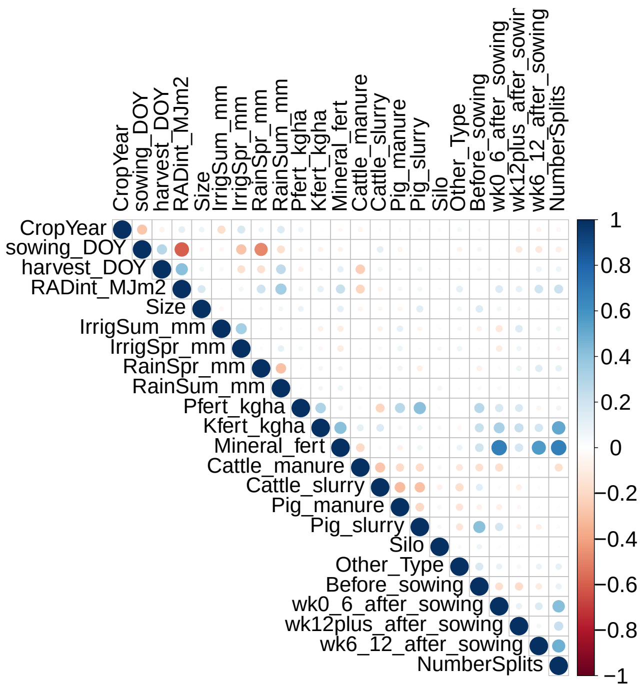

Figure A7. Matrix with Pearson correlation coefficients $(1 \leq r \leq 1)$ for the main variables used in the multiple regression analysis of **ware potato**.

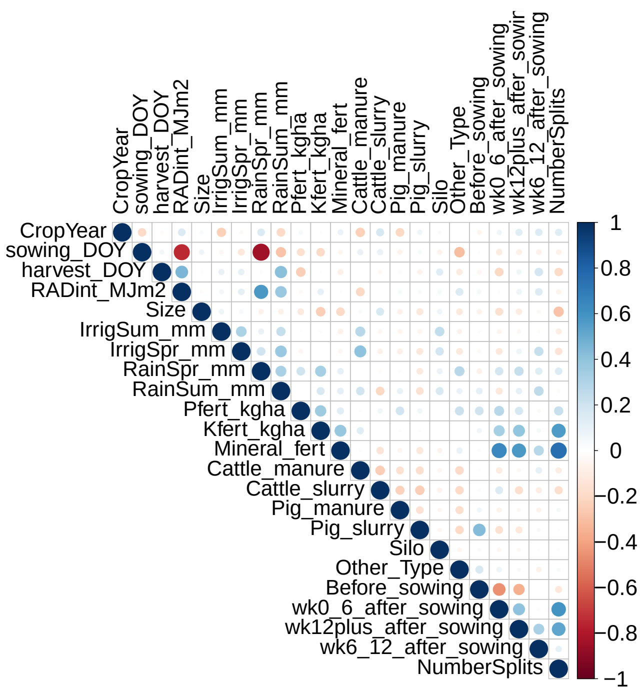

Figure A8. Matrix with Pearson correlation coefficients $(1 \leq r \leq 1)$ for the main variables used in the multiple regression analysis of **seed potato**.

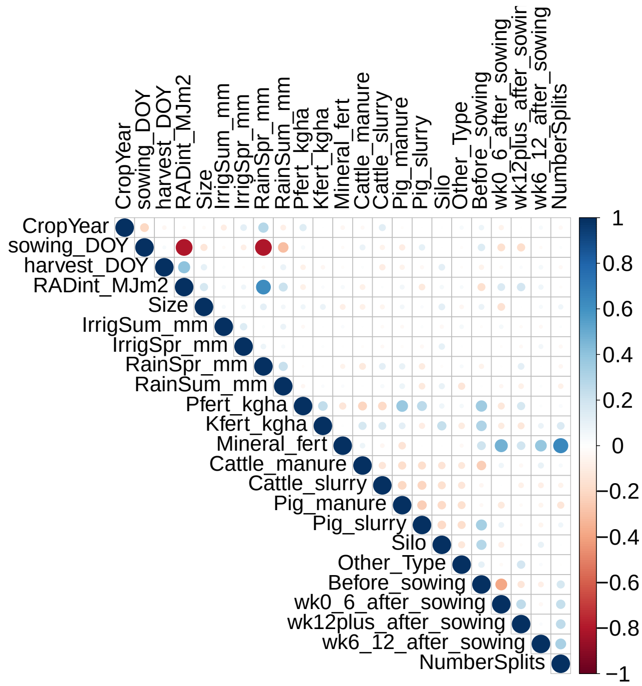

Figure A9. Matrix with Pearson correlation coefficients ($1 \leq r \leq 1$) for the main variables used in the multiple regression analysis of **starch potato**.

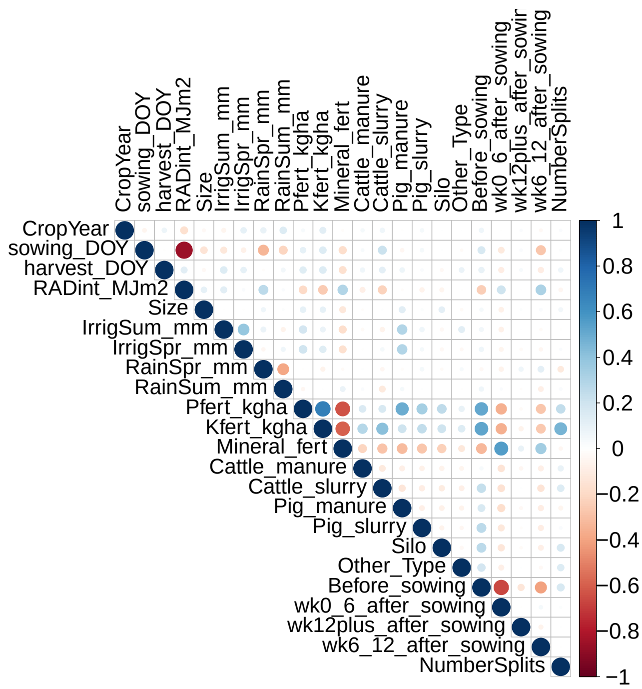

Figure A10. Matrix with Pearson correlation coefficients ($1 \leq r \leq 1$) for the main variables used in the multiple regression analysis of **sugar beet**.

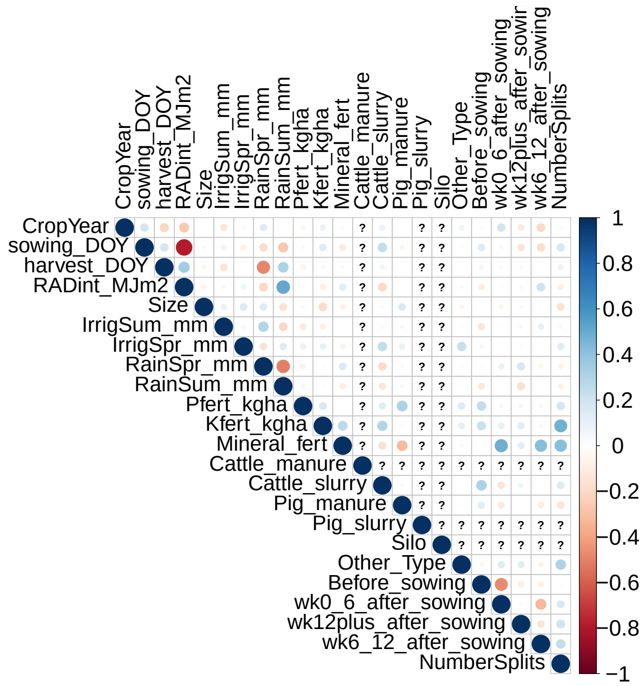

Figure A11. Matrix with Pearson correlation coefficients ($1 \leq r \leq 1$) for the main variables used in the multiple regression analysis of **spring onion**.

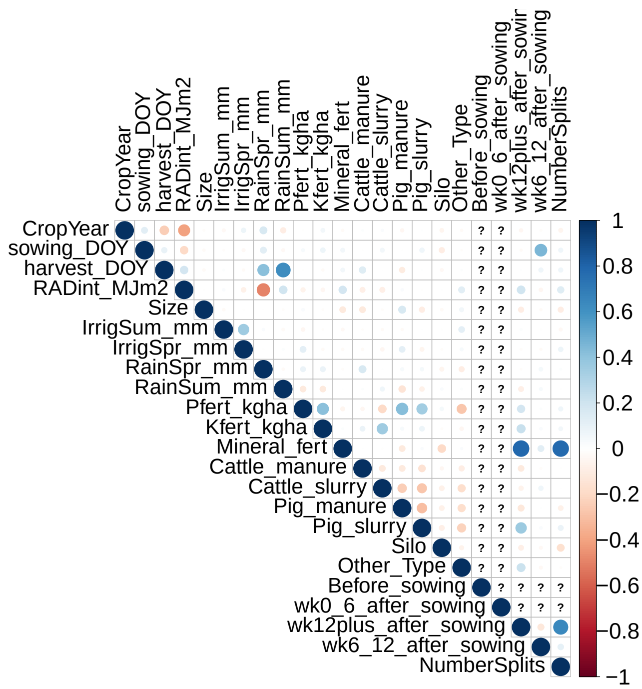

Figure A12. Matrix with Pearson correlation coefficients ($1 \leq r \leq 1$) for the main variables used in the multiple regression analysis of **winter wheat**.

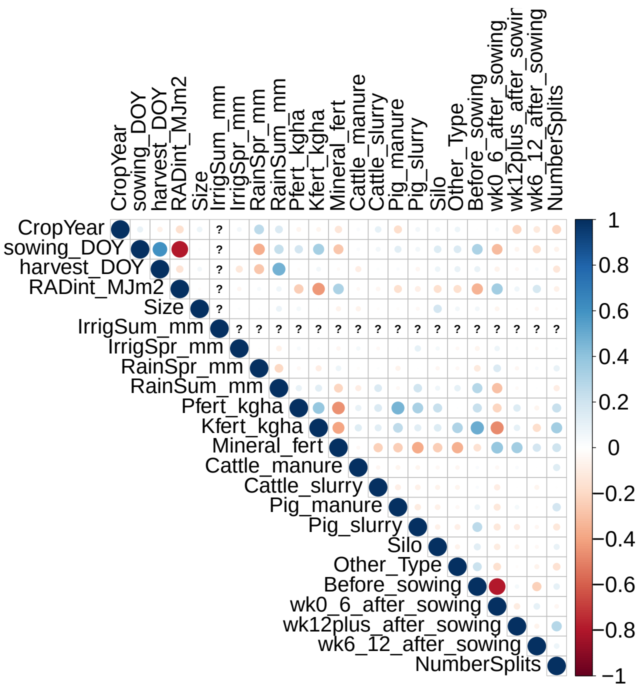

Figure A13. Matrix with Pearson correlation coefficients ($1 \leq r \leq 1$) for the main variables used in the multiple regression analysis of **spring barley**.

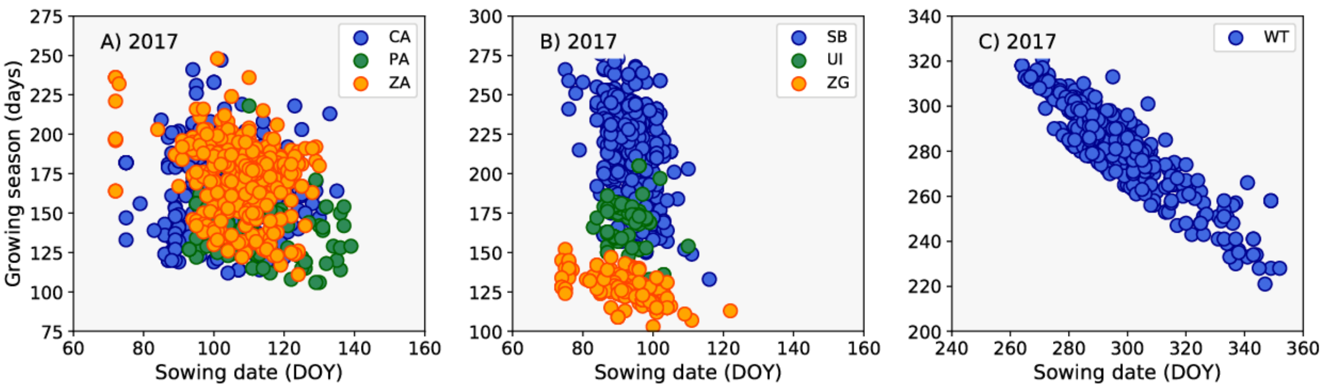

Figure A14. Duration of the growing season in relation to sowing date (A - C). In A), B) and C), the adjusted R^2 of fitted linear regressions is smaller than 10% for all crops except winter wheat (adj-R^2 = 78.7%) and spring barley (adj-R^2 = 38.7%). Codes: CA = ware potato, PA = seed potato, ZA = starch potato, SB = sugar beet, UI = spring onion, WT = winter wheat, ZG = spring barley.

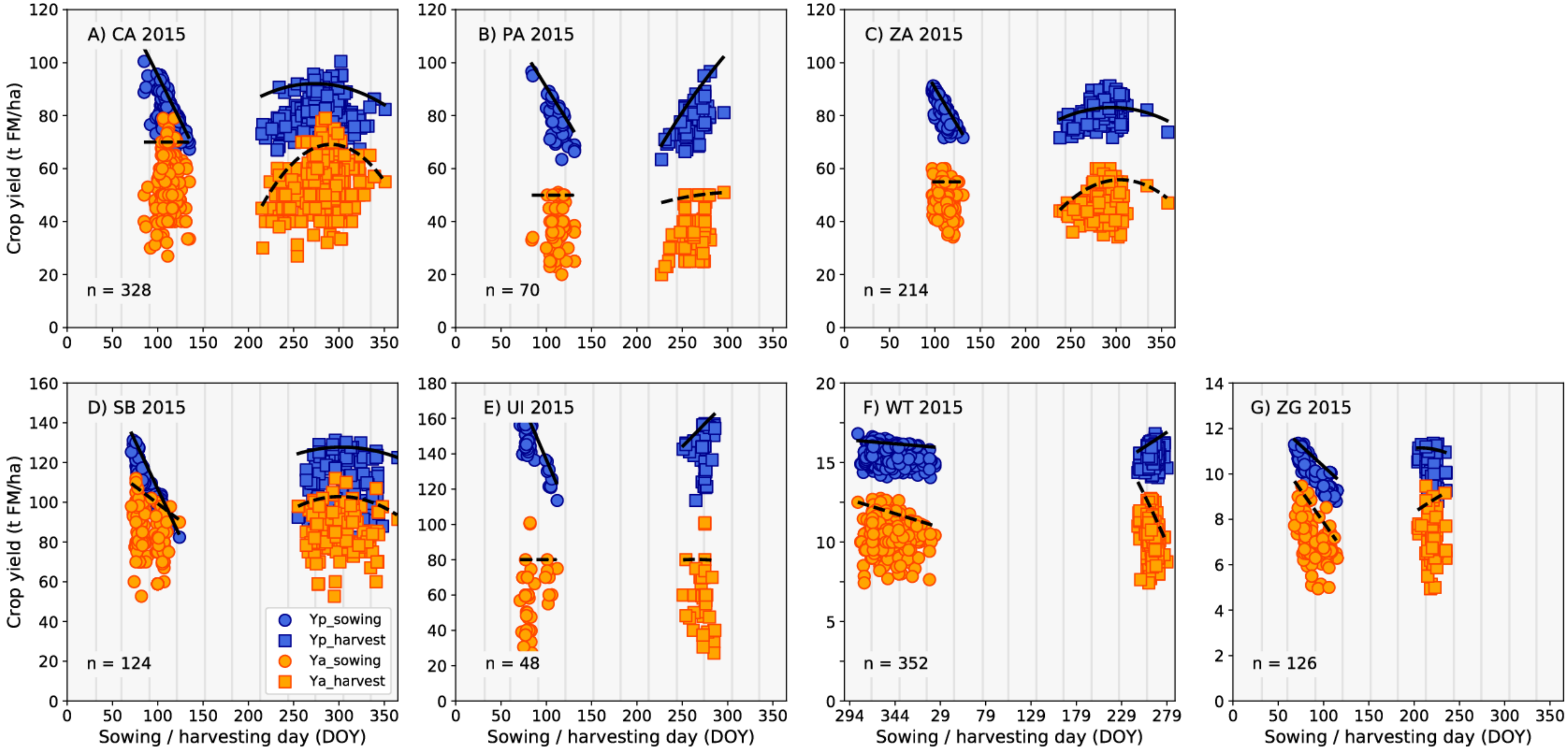

Figure A15. Relationship between sowing and harvest date (day of the year, DOY) and actual and potential yields (t FM ha^{-1}) in the year 2015 for arable crops in the Netherlands: A) ware potato, B) seed potato, C) starch potato, D) sugar beet, E) spring onion, F) winter wheat and G) spring barley. Solid and dashed lines are quantile regressions fitted to the 95^{th} percentile of the potential and actual yields, respectively. The number of fields per crop (n) is shown for each crop and vertical grey lines indicate the different months. The duration of the growing in relation to the sowing date is provided in Figure A14.

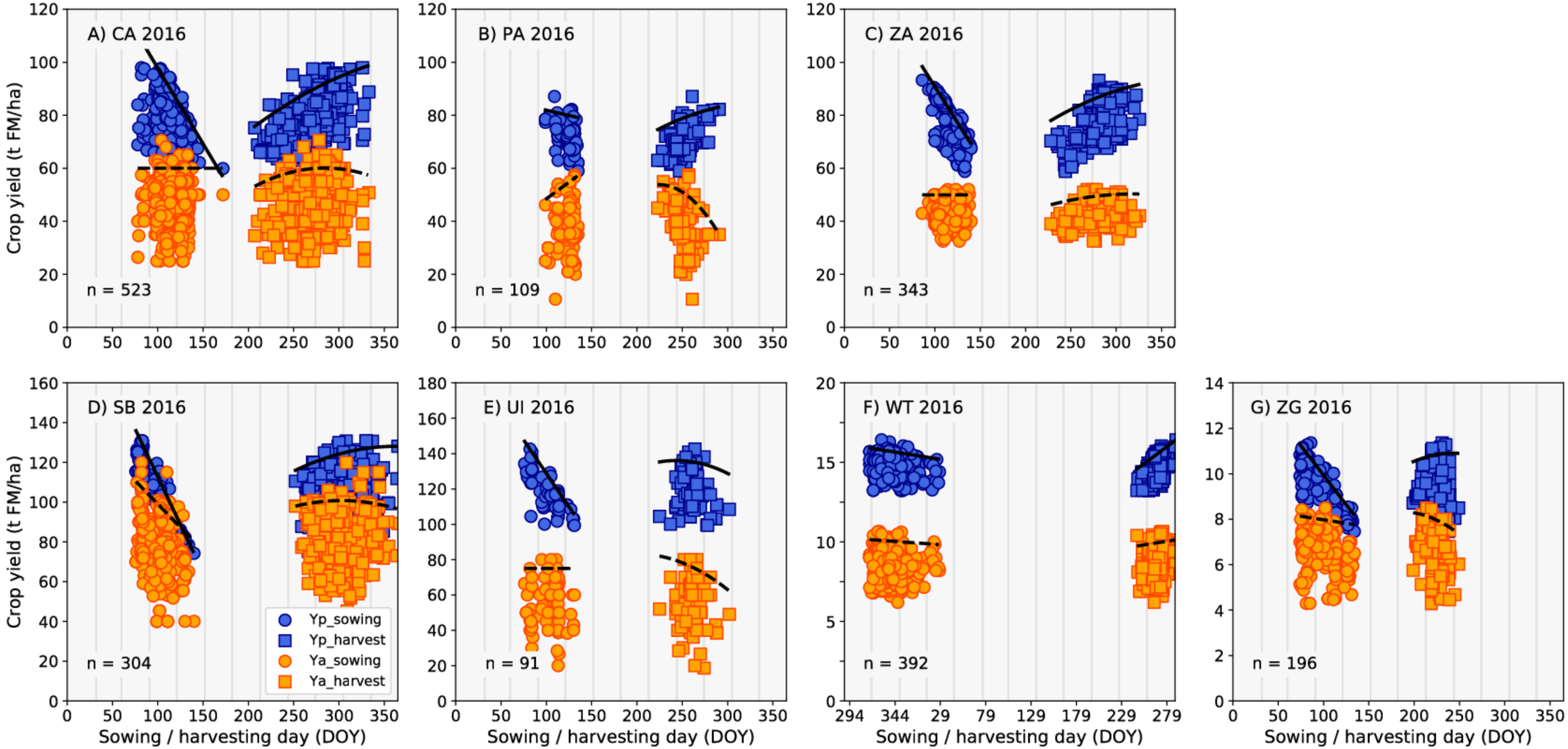

Figure A16. Relationship between sowing and harvest date (day of the year, DOY) and actual and potential yields (t FM ha^{-1}) in the year 2016 for arable crops in the Netherlands: A) ware potato, B) seed potato, C) starch potato, D) sugar beet, E) spring onion, F) winter wheat and G) spring barley. Solid and dashed lines are quantile regressions fitted to the 95th percentile of the potential and actual yields, respectively. The number of fields per crop (n) is shown for each crop and vertical grey lines indicate the different months. The duration of the growing in relation to the sowing date is provided in Figure A14.

Table A1. Average across fields and years of crop yields, biophysical conditions and management practices considered in the multiple regression analysis for arable crops in The Netherlands.

	Ware potato	**Seed potato**	**Starch potato**	**Sugar beet**	**Spring onion**	**Winter wheat**	**Spring barley**
Actual yield (t FM/ha)	52.62	35.56	44.78	86.20	57.16	9.62	6.65
Potential yield (t FM/ha)	82.61	75.36	79.75	103.83	128.50	14.90	9.74
Sowing date (DOY)	109.49	115.41	112.00	95.99	93.93	295.21	92.90
Harvest date (DOY)	276.01	256.54	284.29	307.28	264.48	218.79	220.25
Intercepted PAR (MJ m^{-2})	705.12	643.25	680.71	710.88	738.95	836.36	598.66
Spring rainfall (mm)	136.84	97.70	118.64	167.48	165.67	173.15	162.86
Summer rainfall (mm)	180.86	182.21	195.13	195.97	193.09	99.55	119.88
Spring irrigation (mm)	8.08	2.75	0.85	1.05	2.53	0.67	0.77
Summer irrigation (mm)	8.14	0.53	0.34	1.47	1.20	0.06	0.00
Artificial fertilizer (kg N/ha)	93.13	20.54	52.56	76.38	120.50	104.86	63.47
Cattle manure (kg N/ha)	11.56	8.44	6.49	4.71	0.00	3.43	1.01
Cattle slurry (kg N/ha)	30.40	18.99	12.89	13.60	2.38	16.80	3.47
Pig manure (kg N/ha)	15.30	8.40	17.31	9.12	1.67	18.51	5.62
Pig slurry (kg N/ha)	25.00	14.61	26.97	8.03	0.00	38.32	8.37
Mixed manure (kg N/ha)	1.44	1.00	17.36	6.91	0.00	3.41	3.93
Other organic (kg N/ha)	11.26	12.61	11.82	4.01	0.16	17.29	6.22
Before sowing (kg N/ha)	111.00	66.33	114.62	82.05	24.16	0.00	60.17
0-6 weeks (kg N/ha)	43.92	15.05	17.69	27.88	38.82	0.00	23.43
6-12 weeks (kg N/ha)	30.73	0.86	11.65	10.87	56.94	4.61	2.31
+12 weeks (kg N/ha)	2.45	2.20	1.46	1.94	4.78	198.11	6.20
Total P applied (kg P/ha)	35.88	26.13	33.18	17.70	9.89	35.83	11.60
Total K applied (kg K/ha)	244.70	164.17	158.40	103.55	113.81	146.30	84.77
Number of splits (#)	3.45	2.19	2.59	2.23	3.39	2.55	1.94
Field size (ha)	5.80	3.81	6.16	6.10	5.20	8.02	4.87

Table A2. Determinants of potential yields (Yp), intercepted radiation (RAD_{INT}) and total season water available (TWSA) of the main arable crops in the Netherlands. The reference year is 2015. Significance codes: '***' 0.1% '**' 1% '*' 5% '#' 10%.

	Ware potato	**Seed potato**	**Starch potato**	**Sugar beet**	**Spring onion**	**Winter wheat**	**Spring barley**
Yield potential (kg FM ha^{-1})							
Intercept	84.92 * **	75.21 * **	81.91 * **	105.27 * **	132.79 * **	15.43 * **	9.95 * **
Year_2016	−0.19	0.84	0.30*	2.93 * **	−4.54 * **	−0.89 * **	−0.60 * **
Year_2017	−1.63 * **	0.98#	−2.43 * **	−3.20 * **	−1.86#	−0.63 * **	−0.10 * *
Sowing (DOY)	−0.60 * **	−0.50 * **	−0.55 * **	−0.85 * **	−0.83 * **	−0.01 * **	−0.07 * **
$Sowing^2$	0.00 * **	0.00	0.00	0.00 * **	0.00	0.00	0.00*
Harvest (DOY)	0.18 * **	0.24 * **	0.10 * **	0.05 * **	0.50 * **	0.03 * **	0.07 * **
$Harvest^2$	0.00 * **	0.00 * **	0.00 * **	0.00 * **	−0.01 * **	0.00	0.00
Ajusted-R^2	0.83	0.81	0.95	0.86	0.89	0.30	0.87
Sample size (n)	1293	294	1034	783	196	1080	531
Intercepted PAR (g DM MJ PAR^{-1})							
Intercept	19.72 * **	−1.30	18.50 * **	9.85 * **	24.68 * **	29.70 * **	13.49 * **
Year_2016	−1.60	7.20	2.57*	20.08 * **	−26.13 * **	−49.95 * **	−36.62 * **
Year_2017	−13.88 * **	8.33#	−20.73 * **	−21.93 * **	−10.69#	−35.39 * **	−6.25 * *
Sowing (DOY)	−5.12 * **	−4.26 * **	−4.67 * **	−5.84 * **	−4.80 * **	−0.32 * **	−4.34 * **
$Sowing^2$	0.01 * **	0.01	0.00	0.02 * **	−0.02	0.00	0.01*
Harvest (DOY)	1.55 * **	2.06 * **	0.87 * **	0.32 * **	2.90 * **	1.47 * **	4.01 * **
$Harvest^2$	−0.03 * **	−0.02 * **	−0.03 * **	−0.02 * **	−0.04 * **	0.02	−0.01
Ajusted-R^2	0.83	0.81	0.95	0.86	0.89	0.30	0.87
Sample size (n)	1293	294	1034	783	196	1080	531
Seasonal water available (mm)							
Intercept	533.35 * **	470.75 * **	516.96 * **	657.39 * **	561.41 * **	1035.73 * **	603.07 * **
Year_2016	37.07 * **	52.82 * **	13.71 * **	−57.32 * **	−27.32*	−8.16	0.71
Year_2017	36.20 * **	31.26 * **	74.13 * **	19.16 * **	2.31	−69.25 * **	8.31 * **
Soil_Sand	−22.72 * **	−38.60 * **	−23.58 * **	−44.67 * **	−20.65 * **	−101.02 * **	−63.53 * **
Sowing (DOY)	0.48 * **	0.60*	0.48 * **	−0.63 * **	−1.33 * **	−1.79 * **	−0.83 * **
$Sowing^2$	0.03 * **	0.01	0.04 * **	0.12 * **	0.08 * **	−0.02 * **	0.06 * **
Harvest (DOY)	2.04 * **	2.01 * **	2.00 * **	2.64 * **	2.81 * **	0.73 * *	−0.58 * **
$Harvest^2$	0.01 * **	0.03 * **	0.00	0.01 * **	0.03 * **	0.06 * **	0.11 * **
Spring rainfall (mm)	0.42 * **	0.41 * **	0.38 * **	1.09 * **	1.00 * **	1.30 * **	0.85 * **
Summer rainfall (mm)	0.82 * **	1.30 * **	1.16 * **	1.07 * **	1.08 * **	0.32 * **	0.81 * **
Spring irrigation (mm)	0.90 * **						
Summer irrigation (mm)	0.71 * **						
Ajusted-R^2	0.73	0.91	0.91	0.91	0.87	0.88	0.91
Sample size (n)	1293	294	1034	783	196	1080	531

Table A3. Biophysical and crop management determinants of N use efficiency (kg N kg N^{-1}, note data were log-transformed) of the main arable crops in the Netherlands. The reference level of the categorical variables is as follows: Year = '2015'; Soil = 'Clay'. The amount of $PANA_N$ with mineral fertiliser and before sowing were not included in the model to avoid alias between variables. Significance codes: '***' 0.1% '**' 1% '*' 5% '#' 10%.

	Ware potato	**Seed potato**	**Starch potato**	**Sugar beet**	**Spring onion**	**Winter wheat**	**Spring barley**
Intercept	−0.1620***	−0.0270	−0.0597#	−0.1150**	0.1156	−0.1097***	0.2918***
Year_2016	−0.0482	0.2272**	−0.1768***	0.0458	−0.0098	−0.1508***	−0.0844#
Year_2017	0.1154***	0.1089*	−0.0423	0.0871**	0.0336	−0.0499***	−0.0966**
Soil_Sand	0.0501**	−0.1075**	0.0821***	0.0984***	0.0556	−0.0675*	0.1008**
Sowing (DOY)	−0.0018	0.0127**	−0.0026	−0.0100***	−0.0109#	−0.0006#	0.0023
$Sowing^2$	0.0000	−0.0003*	0.0001**	0.0000	0.0001	0.0000	−0.0001
Harvest (DOY)	0.0012*	−0.0058**	0.0015*	0.0021***	0.0034	−0.0009	−0.0019
$Harvest^2$	0.0000**	0.0000	0.0000	0.0000	−0.0001	0.0000	0.0001
Intercepted PAR (MJ m^{-2})	0.0002	0.0027***	−0.0004	−0.0010*	−0.0026*	0.0003	0.0014#
Spring rainfall (mm)	−0.0002#	0.0004	0.0002	−0.0006*	0.0006	−0.0001	−0.0003
Summer rainfall (mm)	−0.0002	0.0010#	−0.0012***	−0.0005	0.0029***	0.0002	−0.0007#
Spring irrigation (mm)	0.0007						
Summer irrigation (mm)	0.0029***						
Cattle manure (kg N/ha)	−0.0030***	−0.0087***	−0.0066***	−0.0007		−0.0027***	−0.0003
Cattle slurry (kg N/ha)	−0.0044***	−0.0074***	−0.0071***	−0.0033***	−0.0028	−0.0008**	0.0012
Pig manure (kg N/ha)	−0.0047***	−0.0069***	−0.0071***	−0.0024***	−0.0031	−0.0012***	−0.0008
Pig slurry (kg N/ha)	−0.0041***	−0.0067***	−0.0061***	−0.0031***		−0.0004*	−0.0038***
Mixed manure (kg N /ha)	−0.0049***	−0.0059**	−0.0063***	−0.0032***		−0.0016***	−0.0018*
Other organic (kg N/ha)	−0.0043***	−0.0095***	−0.0065***	−0.0041***	0.0135	−0.0003#	−0.0011#
0-6 weeks (kg N/ha)	−0.0024***	−0.0015**	−0.0028***	−0.0021***	−0.0048***		−0.0010*
6-12 weeks (kg N/ha)	−0.0034***	−0.0098**	−0.0026***	−0.0018***	−0.0059***	−0.0055***	−0.0010
+12 weeks (kg N/ha)	−0.0016#	−0.0071*	−0.0005	−0.0015#	−0.0063***	−0.0053***	−0.0057***
Total P applied (kg P/ha)	0.0003	0.0015	0.0021**	−0.0006	−0.0025	0.0007#	0.0014
Total K applied (kg K/ha)	−0.0003**	0.0008**	0.0002	−0.0003	−0.0007*	−0.0001	0.0002
Number of splits (#)	−0.0551***	−0.1371***	−0.1204***	−0.0508***	−0.0219	−0.0067	−0.0500***
Field size (ha)	0.0002	−0.0023	0.0057***	0.0057*	0.0039	0.0012	0.0136***
Ajusted-R^2	0.69	0.53	0.66	0.34	0.57	0.89	0.26
Sample size (n)	1293	294	1034	783	196	1080	531