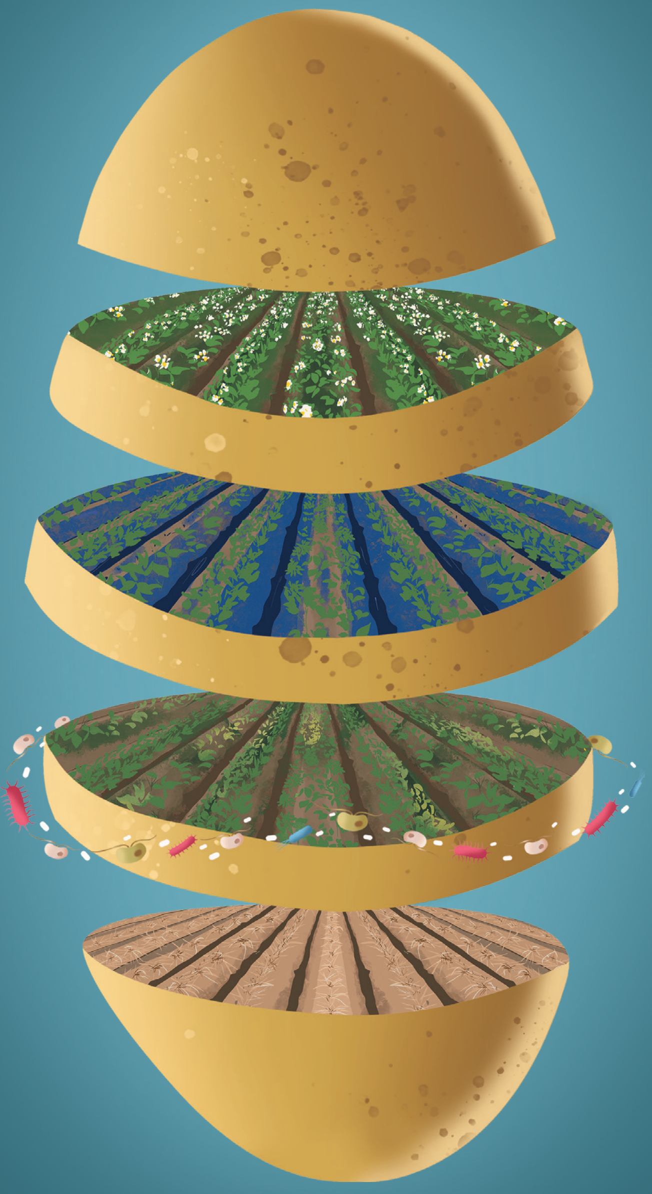
Exploring variability in yield, resource use efficiency and environmental impact of ware potato production in the Netherlands



Arie Pieter Paulus Ravensbergen

Propositions

1. Improved soil moisture management is key to increase ware potato yield in the Netherlands.
   (this thesis)

2. Nitrogen input reduction improves sustainability of ware potato production in the Netherlands without sacrificing yield.
   (this thesis)

3. Collecting high quality data advances science more than using artificial intelligence for data analysis.

4. A fully transparent peer review process demands reviewing of raw data to detect improper omission of outliers.

5. Performing arts is the only fuel that does not pollute more when consuming more of it.

6. Media's negative framing of farming hinders addressing environmental challenges in agriculture.

Propositions belonging to the thesis, entitled

Exploring variability in yield, resource use efficiency and environmental impact of ware potato production in the Netherlands

Arie Pieter Paulus Ravensbergen
Wageningen, 5 March 2024

Exploring variability in yield, resource use efficiency and environmental impact of ware potato production in the Netherlands

Arie Pieter Paulus Ravensbergen

Thesis committee

Promotors
Prof. Dr M.K. van Ittersum
Personal chair at the Plant Production Systems Group
Wageningen University & Research

Dr P. Reidsma
Associate professor, Plant Production Systems Group
Wageningen University & Research

Co-promotor
Dr C. Kempenaar
Senior researcher, Agrosystems Research
Wageningen University & Research

Other members
Prof. Dr N.P.R. Anten, Wageningen University & Research
Prof. Dr L. Kooistra, Wageningen University & Research
Prof. Dr M.P.M. Meuwissen, Wageningen University & Research
Dr J.P. Goffart, Walloon Agricultural Research Center, Belgium

This research was conducted under the auspices of the C.T. de Wit Graduate School of Production Ecology & Resource Conservation

Exploring variability in yield, resource use efficiency and environmental impact of ware potato production in the Netherlands

Arie Pieter Paulus Ravensbergen

Thesis

submitted in fulfilment of the requirements for the degree of doctor
at Wageningen University
by the authority of the Rector Magnificus,
Prof. Dr A.P.J. Mol,
in the presence of the
Thesis Committee appointed by the Academic Board
to be defended in public
on Tuesday 5 March 2024
at 1.30 p.m in the Omnia Auditorium.

Arie Pieter Paulus Ravensbergen

Exploring variability in yield, resource use efficiency and environmental impact of ware potato production in the Netherlands,
254 pages.

PhD thesis, Wageningen University, Wageningen, The Netherlands (2024)
With references, with summary in English and Dutch

DOI https://doi.org/10.18174/646034

Abstract

In the Netherlands, the potato is a high value crop that serves as a cash crop for farmers and is economically important for the value chain. Average ware potato yield is high, with a reported mean fresh matter yield around 52 t ha^{-1}. Despite its high mean productivity, large yield variability is observed among fields and farms. This implies that there is potential to increase production and hence farmers' revenues. Moreover, when relatively low yields come with similar input levels, resources are not well utilised leading to low resource use efficiency and larger emissions to the environment. This provides scope to reduce the environmental impact of ware potato production in the Netherlands. This thesis aims to quantify and explain variability in yield, yield gaps, resource use efficiency and environmental impact of ware potato production at field level in the Netherlands. It complements earlier studies by using frequent on-farm monitoring along with datasets at different levels, questionnaires and experiments to better understand variability among fields, and provide solutions towards more sustainable potato production.

The research was approached in three steps: (1) to quantify spatio-temporal yield variability using existing data sources, (2) to identify different productivity levels and assess factors that explain yield (gap) variability using questionnaires, frequent on-farm monitoring and experiments, and (3) to quantify and explain variability in resource use, use efficiency and environmental impact of ware potato production in the Netherlands using on-farm observations.

It was found that spatial yield variability was largest among fields and within fields, while spatial yield variability was lower at higher aggregation levels. Temporal yield variability explained 10 – 55% of the total observed variation in crop yield and its magnitude was equal or larger than the spatial yield variability for almost all datasets. The average yield gap ranged from 20 – 31% depending on the year and soil type. The yield gap of individual fields ranged from 0 – 51%. On clayey soils, the yield gap was mostly attributed to oxygen stress. On sandy soils, the yield gap was mostly attributed to drought stress in 2020, a relatively dry year, and to reducing factors (pests, diseases and poor agronomic practices) in 2021, an average year in terms of precipitation. On both soil types, potential yield could be increased by planting earlier or harvesting later. An assessment of the effect of increasing P and K application rates and the effect of seed potato origin on yield revealed that improving these factors will likely not narrow the potato yield gap and improve potato yield quality in the Netherlands.

Variability in environmental impact of ware potato production was mostly explained by variability in input use. Mean performance across several environmental indicators showed that it was possible to achieve relatively high yields with relatively low N surplus, high water

productivity and low crop protection product use. Yet, in the best performing fields N surplus was still above the environmental threshold for nitrate concentration in the groundwater. In addition, crop protection product use would not meet the 50% reduction (as targeted in the European Union Farm to Fork strategy) compared to the average pesticide use of all fields. Hence, this means that further reduction in input use will be needed to meet environmental targets for N surplus or crop protection product use.

Overall, it was concluded that yields could be increased for individual fields through improved irrigation on sandy soils, better drainage on clay soils, earlier planting and improved disease control. However, there are additional environmental and socio-economic constraints that play a role at farm level and that prevent farmers from obtaining higher yields. Therefore, there is limited scope to increase average actual ware potato yields in the Netherlands. Nevertheless, in particular fields a yield gain could be achievable, which would then result in decreased yield variability. The observed variability among fields suggests that it is possible to maintain high yields while reducing the environmental impact of ware potato production. There is a need to further evaluate how far and under which conditions input reduction is possible without yield loss.

Table of Contents

Chapter 1: Introduction

1.1 Background

The potato (*Solanum tuberosum* L.) began its journey in the Netherlands at the end of the 16th century when it was introduced as an ornamental plant in botanical gardens (van Loon et al., 1993). One century later, the potato emerged as a food crop and developed into a staple crop taking a prominent role in Dutch agriculture. In the 19th century, potato consumption was estimated to range between 100 to 200 kg per person per year (Knibbe, 2007). During that time, potatoes were mostly consumed as boiled potatoes. In the previous century, an increased use of fertilisers and crop protection products as well as the introduction of improved varieties led to a 65% production increase from 1955 to 1980 (van Loon et al., 1993), making ware potato yields per ha in the Netherlands one of the highest in the world (FAOSTAT, 2022). Nowadays, Dutch potato yields are still high, but the potato consumption per capita per year has decreased and the type of products consumed and produced have diversified (Berkhout et al., 2022). It is estimated that in Northwest Europe and North America one to two-thirds of the consumed tubers are in the form of processed products such as french fries (Keijbets, 2008).

In the Netherlands, the potato is an economically important crop for farmers and the value chain. It is a high value crop that serves as a cash crop for farmers (Devaux et al., 2021; Goffart et al., 2022; Schaap et al., 2013). It is cultivated on 50% of the arable farms and occupies in total 30% of the cropped land (CBS, 2022). Revenue largely depends on output price and yield (Goffart et al., 2022) as input costs are relatively low (Neeteson, 1990) and do not change much with an increasing yield. A large industry value chain exists around potato production in the Netherlands. The country is a leading exporter of certified seeds, with 65% of the produced seeds being exported (Goffart et al., 2022). The processing industry adds value to the potato by processing raw material into a wide variety of processed products (Haverkort et al., 2023). Some 28% of the ware potatoes produced in the Netherlands are exported, of which the export of frozen products is an important component (Goffart et al., 2022).

Potato as a crop has three different production purposes: (1) as a ware crop for consumption of fresh potatoes and processed products, (2) as a starch crop with multiple industrial purposes and (3) as a seed crop to produce seed potatoes that will be planted in the next growing season. Potatoes are cultivated across the country, but it depends on the region which type of potato crop is most dominant (CBS, 2022). Starch potatoes are mostly cultivated in the northeast of the Netherlands in an area called the 'Veenkoloniën'. Seed potatoes are mostly cultivated in the northern coastal regions of the Netherlands. Ware potatoes are cultivated across the country, although its dominance is less in the areas where also seed and starch potatoes are cultivated. This thesis focusses on ware potato cultivation as it is the most important production purpose in terms of land area (Fig. 1.1A), and because it is cultivated throughout the country on all three main soil types in the Netherlands, clay, sand and loess.

Average ware potato yield in the Netherlands is high, with a reported mean yield around 52 t ha^{-1} (Silva et al., 2020, 2017). Despite its high mean productivity, yield variability is also high with reported yields ranging from 30 to 90 t ha^{-1} among fields (Mulders et al., 2021; Silva et al., 2020) and from 30 to 80 t ha^{-1} among farms (Silva et al., 2017). This implies that there is potential to increase production and hence farmers' revenues. In addition, when lower yields come with similar input levels, resources are not fully utilised leading to lower resource use efficiency and larger emissions to the environment. There is a societal need for cleaner production using less resources while maintaining yields. This is for instance expressed in the European Commission's Farm to Fork strategy, with the ambition to reduce fertiliser use and losses and pesticide use (European Commission, 2020). Also, as part of EU legislation, the Dutch government is bound to reduce nitrate leaching to groundwater and eutrophication of surface water (LNV, 2021). This thesis explores factors that explain variability in yield, resource use efficiency and environmental impact to promote sustainable potato production in the future.

1.2 Ware potato compared to other important arable crops in the Netherlands

In the Netherlands, ware potato is cultivated in rotation with other crops. In a typical rotation, ware potato is grown once every four years in rotation with sugar beet and cereals, often winter wheat, but also spring barley. Seed potatoes are cultivated once every three (or four) years, also in rotation with sugar beet and cereals. Rotations with starch potatoes are most intensive as these potatoes are typically grown in a two-year rotation with sugar beet or cereals. Spring onion is another important crop in Dutch agriculture and is often a substitute for cereals. The seven mentioned crops have been studied recently (e.g., Silva et al., 2017, 2020, 2021; van Oort et al., 2023), allowing the comparison of ware potato with other crops in terms of land use, crop productivity and environmental impact (Fig. 1.1).

Together with sugar beet, ware potato (14% of cropped land) is second after winter wheat (22% of cropped land) in terms of cultivated land area (Fig. 1.1A). Seed and starch potato cover each half of the arable land that is cultivated with ware potato (roughly 8% of cropped land). Of the seven crops, spring barley and spring onion are grown on the smallest proportion of the cropped land (5%). Gross profit (excluding labour and machinery) of ware potato production is around 3100,- € ha^{-1}, which is 500 € ha^{-1} lower than spring onion and almost double the gross profit of starch potato and sugar beet (Fig. 1.1B). Gross profit is highest for seed potato, which is around 6200,- € ha^{-1} and lowest for the cereals (750 – 1000 € ha^{-1}).

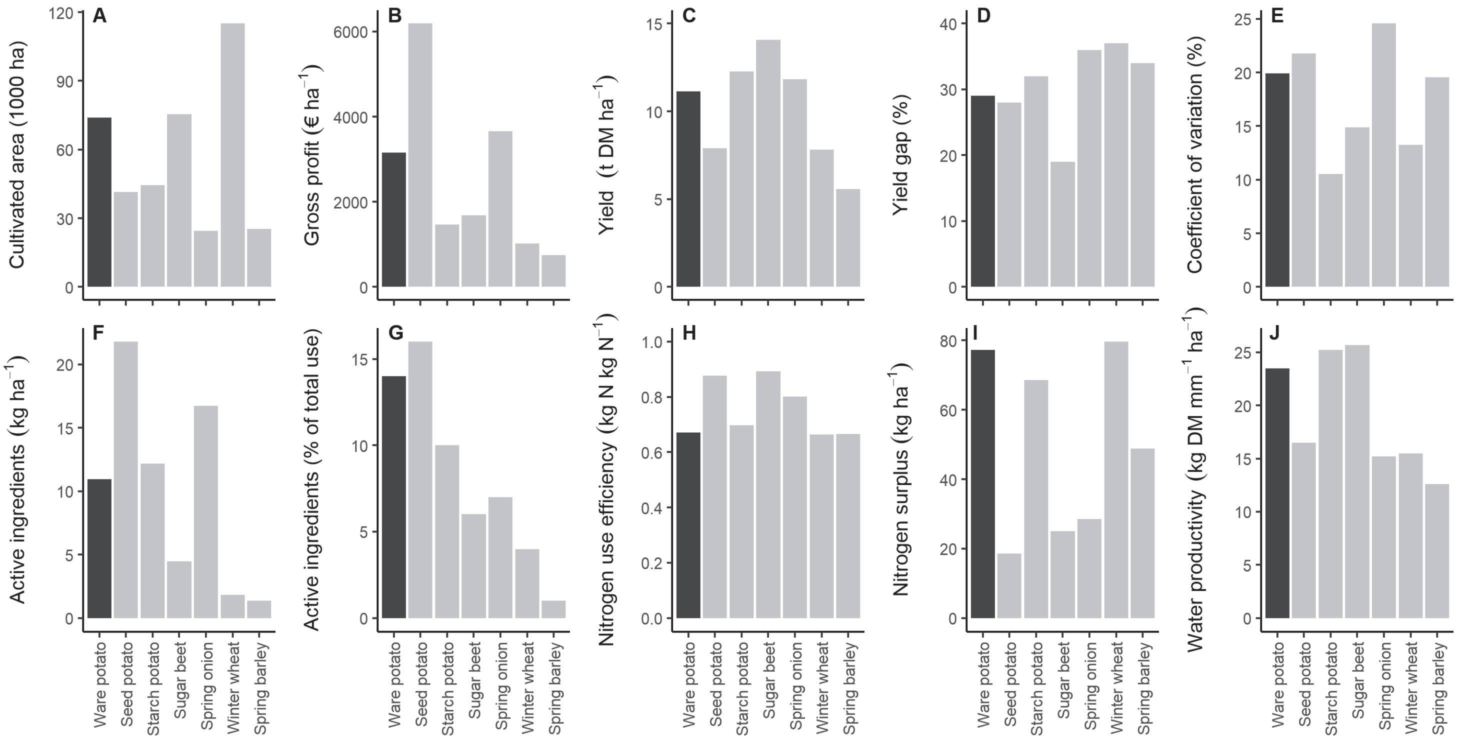


Figure 1.1. Production and resource use efficiency of seven important arable crops in the Netherlands: (A) average cultivated area (in 1000 ha), (B) gross profit (in € ha^{-1}), (C) average crop yield (in t dry matter ha^{-1}), (D) average yield gap (in % of potential yield), (E) coefficient of variation of crop yield (in %), expressing spatial yield variability, (F) average applied active ingredients (in kg active ingredients ha^{-1}), (G) active ingredients (in % of total use), (H) median nitrogen use efficiency (in kg N kg N^{-1}), (I) average nitrogen surplus (in kg ha^{-1}) and (J) average water productivity (kg DM mm^{-1} ha^{-1}). Panel A is based on data from CBS (average of 2011 – 2020). Panel B is based on data from (van der Voort, 2022)***. Panel C, D and E provide averages based on Silva et al. (2017) (data from 2008 – 2012) and Silva et al. (2020) (data from 2015 – 2017). Panel F and G are based on data from CBS (average of 2012, 2016 & 2020, the only years available). Panel H and I refer to data obtained from Silva et al. (2021), and panel J refers to data obtained from Silva et al. (2020).***

Ware potato is among the highest yielding crops with an average dry matter yield of 11.1 t DM ha^{-1} (Fig. 1.1C). It yields similar to spring onion and starch potato, but 3 – 6 t DM ha^{-1} higher than seed potato and cereals. Sugar beet has the highest productivity per ha with a yield of 14.1 t DM ha^{-1}. The yield gap (i.e., the difference between theoretical potential yield and actual farmers' yield, Section 1.3) of ware potato has been estimated at 29% and is similar to the yield gap of starch and seed potato, although for the latter marketable yield (i.e., yield of smaller size classes) is more important than gross yield, compromising the suitability of yield gap as a productivity indicator (Fig. 1.1D). The yield gap is smallest for sugar beet, whilst it is highest for spring onion and cereals.

Spatial yield variability of ware potato, expressed as a coefficient of variation, is roughly 20% of the mean crop yield and is similar to spatial yield variability of seed potato and spring barley (Fig. 1.1E). Only for spring onion, spatial yield variability is notably larger with a coefficient of variation of almost 25%, whilst starch potato, sugar beet, and winter wheat show the lowest spatial yield variability ranging from 10 to 15%. Temporal yield variability is another important constituent of yield variability. It was found that the 5% lowest ware potato yields yielded 21% below average, whilst for sugar beet and winter wheat this was only 14% and 15%, respectively (van Oort et al., 2023). Only spring onion had greater yield extremes (28% reduction) than ware potato. Yield reductions of ware potatoes were for 73% related to an extremely wet growing period, whilst spring onion was equally sensitive to extremely dry and wet conditions (van Oort et al., 2023).

Use of crop protection products in ware potato cultivation is high. Per year, approximately 11 kg of active ingredients in crop protection products ha^{-1} are applied to the ware potato crop (Fig. 1.1F). Per ha, this amount is half of the use in seed potato and one-third less than in spring onion. Compared to sugar beet, application of active ingredients per ha is more than twice as high and compared to the cereals application is seven times higher. When total application of crop protection product use is considered, application of active ingredients in ware potato comprises 14% of the total use of all applied crop protection products in all crops (Fig. 1.1G). This makes ware potato the second largest user of crop protection products, after seed potatoes (16%). Relative total application of active ingredients in the other crops is 10% for starch potato, 7% for spring onion, and 6% or less for sugar beet and the cereals. Lilies and tulips are two other crops with high total application of active ingredients with 12 and 7% of total application, respectively (CBS, 2022).

Nutrient and water use are other important environmental indicators to evaluate the environmental impact of crop production. Median nitrogen (N) use efficiency of ware potato was estimated to be 67% and similar to starch potato and the cereals (Fig. 1.1H). N surplus for ware potatoes was reported at almost 80 kg ha^{-1}, which is together with winter wheat the highest surplus of all crops and three to four times higher compared to seed potato, sugar beet, and spring onion (Fig. 1.1I). The high N surplus observed in ware potato and winter wheat is related to high average N input rates of 260 kg N ha^{-1} (Silva et al., 2021). Ware potato uses water efficiently with a water productivity of 23.5 kg DM mm^{-1} ha^{-1} (Fig. 1.1J). Compared to other crops, its water productivity is similar to starch potato and sugar beet, but at least 50% higher compared to spring onion and cereals.

1.3 Yield gap and yield gap explaining factors

The yield gap concept is useful to analyse productivity of a cropping system per unit area. It is defined as the difference between potential or water-limited potential yield and actual farmers' yield (van Ittersum et al., 2013; van Ittersum and Rabbinge, 1997). Potential yield is determined by radiation, CO_2 concentration, temperature, and cultivar characteristics and can be obtained when diseases are effectively controlled, and nutrients and water are non-limiting. Water-limited potential yield is limited by water stress caused by drought stress due to insufficient rainfall or irrigation, or oxygen stress as a result of excess water. Actual farmers' yield is further limited by nutrients and/or reduced by the impact of pests and diseases or other yield reducing factors. In addition to quantifying crop productivity, yield gap analyses can be used to assess yield gap explaining factors, and can be coupled to resource use efficiency assessments to reveal opportunities to reduce the environmental impact of cultivating crops (Getnet et al., 2016; Rong et al., 2021; Tittonell et al., 2008).

Factors that potentially explain yield (gap) variability vary with the spatial scale at which analyses are done. Yield (gap) variability can be analysed among regions, farms, fields and within a single field (Fig. 1.2). Potentially more factors explain yield (gap) variability at higher aggregation levels than at lower levels. Within a field, yield (gap) variability can be influenced by different soil properties such as soil texture, soil water content, soil organic matter and soil N concentration (Allaire et al., 2014). Other factors such as planted varieties and crop management are expected to be the same within a field (if precision agriculture techniques are not applied). Within a farm, cultivated crops are part of farming systems where yields can be constrained by suboptimal allocation of resources among fields (Beza et al., 2017; van Ittersum et al., 2013), which could explain yield (gap) variability among fields. Nonetheless, within a farm the same farmer makes decisions on crop management and weather conditions will be largely similar. In contrast, differences in climate and farmer preferences are also expected to play a role in explaining yield (gap) variability when zooming out even further, to the regional scale.

Studying potato yield variability in itself is not new. Already in the 1980's the issue was raised that large variability in yield quantity and quality was observed among farms and fields (Bus et al., 1983). Also recently, attention was given to understanding yield variability in ware potato production in the Netherlands. In these recent studies, yield variability was

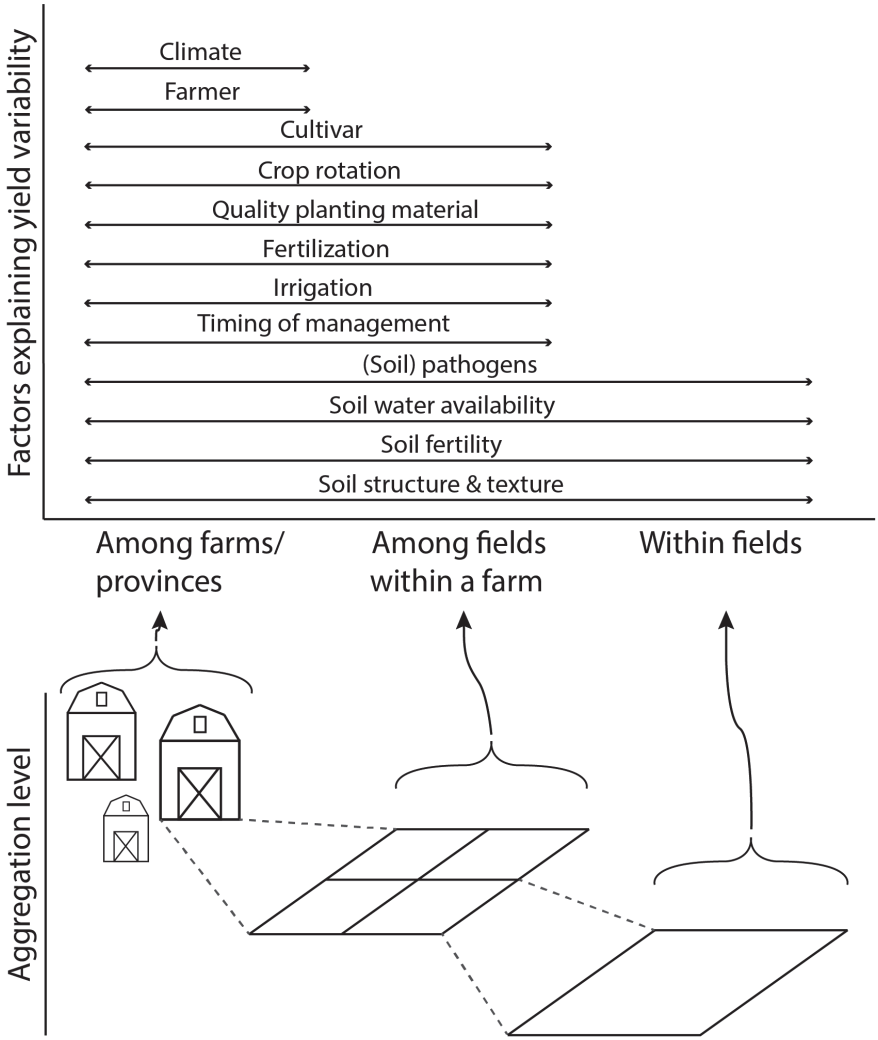


Figure 1.2. Yield variability and factors explaining yield variability can be analysed at different aggregation levels. At the lowest level, within a single field, mainly biophysical factors influence yield variability. Comparing multiple fields within a single farm, not only biophysical conditions, but also management factors become important to explain yield differences. At the highest aggregation level, comparing multiple farms, differences among farmers and climates are added to the complexity of explaining yield variability.

attributed to differences in sowing and harvesting dates (Mulders et al., 2021; Silva et al., 2020), irrigation (Mulders et al., 2021; Silva et al., 2020), variety (Mulders et al., 2021; Silva et al., 2020), fungicide use (Silva et al., 2017) and preceding crops (Mulders et al., 2021). Effects of soil properties and fertiliser application on yield showed less clear or contradicting effects (Mulders et al., 2021; Silva et al., 2021; Vonk et al., 2020).

There are various limitations of the mentioned studies that provide uncertainties in the outcomes or that limit wider applicability of the results. The mentioned studies were performed on a single farm only (Mulders et al., 2021), for single production parameters such as soil organic matter content (Vonk et al., 2020), at farm level neglecting the variation that exists within a farm (Silva et al., 2017), or using farmer reported data which contain uncertainties about data accuracy (Silva et al., 2021, 2020). In addition, data was collected after the growing season, limiting the possibility of ground truthing observations, especially in relation to the effect of yield reducing factors. Hence, there is a need to evaluate yield (gap) variability across a wide variety of conditions. In addition, the previously used data are insufficient to test specific hypothesis that require testing under controlled conditions or to evaluate factors that are not commonly reported on farm level. For instance, it is hypothesised that current ware potato yields are limited by insufficient phosphorus (P) and potassium (K) fertilisation (Dekker and Postma, 2008; López-Porrero, 2016; van Rotterdam, 2021) and that origin of seed potatoes can influence yield (Mulders et al., 2021; van der Zaag and van Loon, 1987). On-farm experiments under controlled conditions need to be performed to evaluate the effect of these factors.

1.4 Environmental impact of ware potato production

Arable farming in the Netherlands is intensive. Fertiliser and crop protection product use is high and heavy machinery is used for farming operations. Their use is indispensable to obtain a high productivity. However, overuse or inefficient use of inputs comes at a cost of the environment. In the Netherlands, arable farming contributes substantially to different environmental issues (Ros et al., 2023). Nitrate leaching poses a threat to groundwater quality, particularly in sandy soils (de Vries et al., 2021; Oenema et al., 2005). The use of crop protection products puts pressure on the groundwater quality and organisms (Schipper et al., 2008). Drought extremes that have been observed in recent years result in yield limitation and lower nutrient utilisation (Ros et al., 2023). Use of heavy machinery under unfavourable (wet) conditions poses a threat to soil compaction (Alakukku et al., 2003; van den Akker and Hoogland, 2011). Lastly, high concentrations of P in the groundwater are a cause of lower surface water quality (Chardon and Schoumans, 2007).

An often used argument to keep using large amounts of inputs, is the risk that crop productivity may decline when inputs are reduced or that the cost of overapplication is lower compared to the cost of underapplication, because of a risk to loose income as a result of lower yields (Meyer-Aurich and Karatay, 2019; Rajsic and Weersink, 2008). However, reducing input use and thereby increasing efficiency is essential to move towards a more circular and sustainable agriculture that has a lower environmental impact (Dobermann et al., 2022). Also, society demands a cleaner production, such as is expressed in the Farm to Fork strategy, which aims to reduce nutrient losses by 50% which should reduce fertiliser use by at least 20% and to reduce chemical pesticide use by 50% (European Commission, 2020).

In ware potato production in the Netherlands, large variability is observed in N surplus, pesticide use and water productivity (De Jong and De Snoo, 2002; Silva et al., 2021, 2020). In addition, very low responses to input rates are observed (Mulders et al., 2021; Silva et al., 2021, 2017). These results indicate that in part of the production fields input rates are higher than necessary to attain current yield levels and suggest there is scope to reduce input use in part of the ware potato production fields, while maintaining similar yield levels. Indeed, this would reduce the impact of ware potato cultivation on the environment.

1.5 Assessing and addressing variability

Yield gaps have been estimated for various crops in different environments (Caldiz and Struik, 1999; Dadrasi et al., 2022; Espe et al., 2016; Gobbett et al., 2017; Rattalino Edreira et al., 2017; Vanongeval and Gobin, 2023; Wang et al., 2018). In these yield gap assessments, actual yield levels are usually based on national or regional statistics data (Dadrasi et al., 2022; Espe et al., 2016; Gobbett et al., 2017; Vanongeval and Gobin, 2023; Wang et al., 2018) or farmer reported survey data (Caldiz and Struik, 1999; Rattalino Edreira et al., 2017). This provided useful information on productivity levels and yield gap explaining factors at higher aggregation levels, but were insufficient to understand yield gap variability and causes of the yield gap at individual fields. To better understand variability among fields, there is a need to zoom in further, which will require additional data collection at field level.

Detailed explanations of yield gaps at field level can be useful in various crop production systems, but are particularly important for highly productive cropping systems with large field-to-field variability. While a relatively high average yield in such systems suggests limited scope for improving yield at regional level, yield gains can still be made for particular fields and resource use efficiency can be improved when resource utilisation is inefficient. Relatively low yields, associated with large yield variability, are undesirable because they translate into lower resource use efficiency and lower profitability if inputs are not adjusted to target yield levels (Silva et al., 2021). Addressing yield variability could thus increase crop production, while reducing the impact of crop production on the environment and improving farmers' income.

1.6 Objectives

This thesis aims to quantify and explain variability in yield, yield gaps, resource use efficiency and environmental impact of ware potato production in the Netherlands. The results can be used to provide recommendations on how to increase yields, improve resource use efficiency and reduce the environmental impact of ware potato production. The following research questions are addressed:

1. What is the spatiotemporal ware potato yield variability across different spatial scales? (Chapter 2)
2. What do farmers currently perceive as the yield gap and yield gap explaining factors in ware potato cultivation? (Chapter 2)
3. What is the ware potato yield (gap) variability among fields and how can it be explained? (Chapter 3)
4. Are phosphorus and potassium fertiliser application rates (Chapter 4) and seed potato origin (Chapter 5) important explanatory variables of variability in potato yield and quality?
5. What is the variability among fields in resource use efficiency and environmental impact of ware potato production and how can this be explained? (Chapter 6)

1.7 Methodological approach

In the digitised era we nowadays live in, numerous data collection methods and methodological approaches have become available providing a multitude of opportunities for data analyses. For instance, crop modelling has proven a useful tool to benchmark cropping systems (Boote et al., 1996; van Ittersum et al., 2003). Also, use of digital technologies by farmers has taken off, providing opportunities to collect data in an automated way (Wiseman et al., 2019). Overall, much more data is being collected at a much larger scale, allowing to do for example yield variability analyses for a larger quantity of data at once (Mourtzinis et al., 2018) or at low aggregation levels, taking into account not only variability among fields, but also within fields (Maestrini and Basso, 2018).

An analysis of yield variability and its causes starts with the availability of data. Different data sources with information on yield and crop management are already available. Statistics Netherlands (CBS) provides national statistics on yield per province. Data from the European Farming Accountancy Data Network contain information on yield and crop management information at farm level. The potato processing industry also collects yield data to monitor yield development throughout the growing season. Farmers collect yield and crop management data at field and within-field level. Yield data is thus available at multiple scales and sometimes these data are coupled with crop management data. The available data provided opportunity for a spatiotemporal yield variability analysis across multiple scales for a longer period of time and at large scale (Chapter 2). However, available data has proven insufficient for a detailed understanding of yield gap variability and its explaining factors at field level and for a large number of farms. In addition, existing farmer reported data can contain inaccuracies, providing uncertainty about reported findings (Fraval et al., 2019; Steinke et al., 2017).

To better understand yield variability and its causes, there is a need to collect data from farmers' fields. Hence, a large part of the methodological approach in this thesis involved collecting and analysing new data. To this end, a questionnaire was disseminated among farmers and three on-farm trials were set up. The questionnaire aimed at understanding farmers' perspective on the yield gap and yield gap explaining factors (Chapter 2). The first trial was a large scale on-farm observational study, where 96 fields were closely monitored throughout two growing seasons to assess yield (gap) variability and its causes. This observational study provided insight in the effect of several yield gap explaining factors and variability in resource use efficiency (Chapter 3 and 6). However, it was insufficient to study the effect of specific factors on potato yield. Hence, two additional trials in the form of on-farm experiments were set up. In the first experiment, additional P and K fertilisers were applied on top of farmers fertiliser application rates to assess the added effect of increased fertiliser rates (Chapter 4). This was analysed across 46 different ware potato fields, in two growing seasons. In the second experiment, the effect of seed potato origin on yield was analysed in interaction with growing conditions and planting date, in two fields of one farm (Chapter 5).

A last important step in the methodological approach was to compare field measurements with a benchmark to assess production levels and yield gaps. To this end, crop growth modelling was used. The crop growth model WOFOST (De Wit et al., 2019; De Wit et al., 2020), recently calibrated for modern potato cultivars (ten Den et al., 2022), was combined with the soil hydrological model SWAP to estimate potential and water-limited potential yield (Kroes et al., 2017). In addition, crop growth modelling was used to assess drought and oxygen stress in farmers' fields. Several statistical techniques were applied to analyse yield (gap) variability and its explaining factors.

1.8 Outline

The analyses in this thesis are done in three steps and presented in five research chapters (Fig. 1.3). In the first step, an overview of spatial and temporal yield variability across different spatial scales is provided. In Chapter 2, yield data from five different sources are combined to quantify spatial and temporal yield variability across regions, across farms, across fields within a farm and within fields.

In the second step, the yield gap is quantified and causes of yield (gap) variability are explored. Chapter 2 describes the outcome of a questionnaire aimed at understanding farmers' perception with regards to the existing yield gap and yield gap explaining factors at their farm. In Chapter 3, yield (gap) variability among fields is further explored. In this chapter, the results of a large-scale observational study across 96 different farmers' fields are described. First, different production levels are quantified, followed by a statistical analysis that aims to explain the variability in yield and yield gaps among fields. To further explore causes of yield variability, the results of two detailed on-farm experiments are presented that examine the effect of additional P and K fertiliser application on potato yield (Chapter 4) and the effect of seed potato origin on yield, in interaction with growing conditions and planting date (Chapter 5).

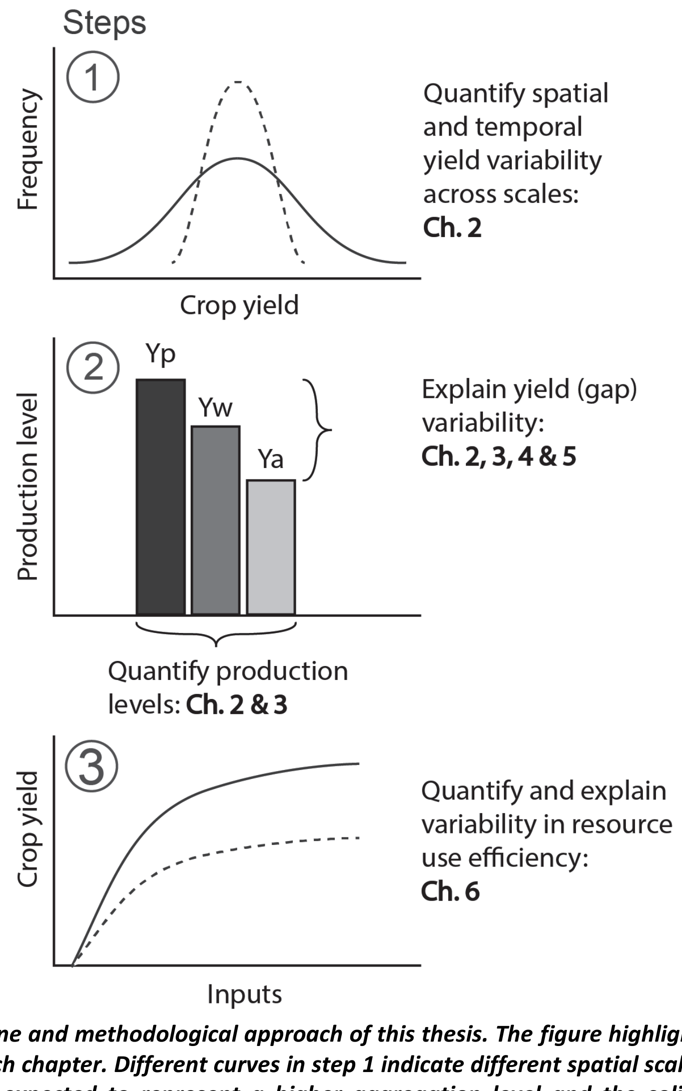


Figure 1.3. Outline and methodological approach of this thesis. The figure highlights the approach addressed in each chapter. Different curves in step 1 indicate different spatial scales, for which the dotted curve is expected to represent a higher aggregation level and the solid curve a lower aggregation level. Yp in step 2 refers to potential yield, Yw to water-limited potential yield, and Ya to actual yield. Different curves in step 3 indicate different levels of resource constraints, for which in the dotted curve crop yield is constrained by a second input variable.

In the third and final step (Fig. 1.3), variability in resource use, use efficiency and environmental impact of ware potato production is quantified and explained. Chapter 6 employs the same dataset as Chapter 3 and presents an analysis on other production indicators than yield that are relevant to assess environmental performance of ware potato production. This thesis concludes in Chapter 7 with a general discussion that presents the key findings and explores opportunities for future improvement of ware potato production in the Netherlands.

Chapter 2: Yield variability across spatial scales in high input farming: Data and farmers' perceptions for potato crops in the Netherlands

This chapter has been published as:

Ravensbergen, A. P. P., van Ittersum, M. K., Silva, J. V., Maestrini, B., Kempenaar, C., & Reidsma, P. (2023). Yield variability across spatial scales in high input farming: Data and farmers' perceptions for potato crops in the Netherlands. *European Journal of Agronomy*, *150*, 126925

Abstract

Crop yields are determined by the biophysical environment and by farm management decisions, which in turn depend on socio-economic conditions of the farm(er). The interaction of these factors results in spatial and temporal yield variability. We assessed ware potato yield variability in the Netherlands across four agronomically relevant scales (among provinces, farms and fields and within fields) using five datasets with data on potato yield across space and time. Furthermore, we disseminated an online questionnaire among farmers to identify the perceived yield gap and the key yield gap explaining factors at farm level. Spatial yield variability was largest among fields, with a standard deviation of 8.5 – 11.1 t ha^{-1}, and within fields, with a standard deviation of 7.7 – 8.7 t ha^{-1}. Spatial yield variability decreased at higher aggregation levels, i.e., the standard deviation of among-farm yield variability was 4.0 – 6.1 t ha^{-1} and that of among-provinces 1.6 – 3.5 t ha^{-1}. Mean yields of the datasets ranged from 46 to 52 t ha^{-1}. Temporal yield variability explained 10 – 55% of the total observed variation in crop yield and its magnitude was equal or larger than the spatial yield variability for almost all datasets. Farmers estimated the ware potato yield gap at 13 – 18 t ha^{-1}, corresponding to 20 – 24% of estimated yield potential, depending on the soil type and variety. Water deficit and water excess were considered the most important yield gap explaining biophysical factors. In addition, soil structure was an important biophysical factor on clayey soils and diseases on sandy soils. Irrigation and fertilisation were identified as the most important yield gap explaining management factors, whereas legislation and potato prices were identified as the key socio-economic factors influencing potato yields. However, the perceived yield gap explaining factors varied with soil type, variety and year. We conclude that reducing potato yield variability in the Netherlands can be achieved best at the field and within-field level, rather than at farm or regional level. When reducing yield variability is not feasible and/or desirable, inputs should be adapted to actual yield levels to achieve optimal environmental and economic sustainability.

Keywords

Solanum tuberosum | climate variability | linear mixed effects models | long-term yield data | weather extremes | yield gap

2.1 Introduction

Crop yields are determined by the biophysical environment and by farm management decisions, which in turn depend on the socio-economic conditions of the farm(er) (Beza et al., 2017; van Ittersum et al., 2013). These factors affect crop yield differently over time and space resulting in temporal and spatial yield variability (Grassini et al., 2015). Analysing yield variability across different scales can be useful to determine at which scale addressing yield variability is most impactful. Yield variability analyses can be used to prioritise policies at regional scale (van Dijk et al., 2020), tailor management advices to specific farms, or justify the promotion of precision agriculture technologies to manage yield variability at field or within-field scale. Examples of policy measures are to stimulate irrigation in regions that are more severely affected by drought or to use variable rate application of fertilisers in heterogeneous soils. Relatively low yields, associated with large yield variability, are undesirable because they translate into lower resource use efficiency and lower profitability if inputs are not adjusted to target yield levels (Silva et al., 2021). Addressing yield variability could thus increase crop production, while reducing the impact of crop production on the environment and improving farmers' income.

In the Netherlands, ware potato was found to be more impacted by weather extremes than other arable crops (van Oort et al., 2023), and large yield variability can be expected for this crop as a result. A regional analysis of the effect of weather extremes on potato yield found that the lowest yields were up to 20% lower than the average yield (van Oort et al., 2023). At farm level, ware potato yield averaged 51 t ha^{-1}, with a range from 30 to 80 t ha^{-1} (Silva et al., 2017). At field level within a single farm, Mulders et al. (2021) found that average potato yield ranged from 50 to 60 t ha^{-1} with a 95% confidence interval of 30 to 90 t ha^{-1}. In another study at field level, ware potato yield was, on average 50 to 54 t ha^{-1} , depending on the maturity group, with a range between 30 and 90 t ha^{-1} (Silva et al., 2020). Year-to-year variation is also an important constituent of yield variability as in 10% of the years yields were more than 20% lower than the average long-term yield (van Oort et al., 2012). Despite early assessments of ware potato yield variability in the Netherlands, the cited literature does not provide consistent methodologies of yield variability analysis across different spatial scales. The latter limits comparisons of yield variability across spatial scales, making it difficult to devise and prioritise strategies to manage yield variability. This study adds to the existing knowledge by quantifying yield variability across agronomically relevant spatial scales with a consistent protocol.

Beyond quantifying yield variability across temporal and spatial scales, it is also important to identify the factors explaining yield variability (Taylor et al., 2018). Studies on yield gaps often rely on farm-field data with detailed information on crop management and biophysical conditions (e.g., Hochman et al., 2016; Mourtzinis et al., 2018; Mulders et al., 2021; Silva et al., 2017). However, such analyses often neglect socio-economic factors (Beza et al., 2017), which are important to understand farmers' decision making. Moreover, measuring which factors are constraining yields is time consuming (van Bussel et al., 2015) as a wide variety of factors could explain yield gaps (Beza et al., 2017). Farmer-based assessments may thus help identifying the most important yield gap explaining factors influencing yield variability. This could provide insights in the socio-economic constraints at farm level in addition to biophysical and crop management limitations (Kwambai et al., 2022). Variability in ware potato yield in the Netherlands was previously associated with planting and harvesting dates, irrigation, fungicide use, and preceding crops, rather than with soil properties and fertiliser application rates (Mulders et al., 2021; Silva et al., 2020, 2017). Yet, the aforementioned analyses did not include farmers' perceptions on yield gap explaining factors.

In this study, we analysed different datasets with yield data for ware potato in the Netherlands across multiple spatio-temporal scales. We quantified actual yield and yield variability across years and four agronomically relevant spatial scales using a consistent protocol. Despite inconsistencies across datasets, our approach was helpful to understand and draw numerical conclusions on how yield levels and variability are affected by different scales of observation and analysis. We also identified the yield gap explaining factors for ware potato based on farmers' expert knowledge. We hypothesised that (1) yield variability increases from regional to farm, field, and within-field levels, and that (2) ware potato production in the Netherlands is more constrained by water stress and yield-reducing factors, particularly pests and diseases, than by nutrient limitations.

2.2 Materials and methods

2.2.1 Yield variability analysis across spatial scales

Spatial scales

Yield variability is conditional on the spatial scale at which data are analysed. Therefore, we considered spatial scales that are relevant for targeting policies, extension services or management interventions. The four spatial scales considered in this study were thus region, farm, field, and within-field (Table 2.1). At the regional scale (i.e., 2000 – 5000 km^2), we compared yield variability across provinces (i.e., administrative boundaries) in the Netherlands as such information is commonly available in yield datasets. At the farm scale (i.e., 10 – 1000 ha), different farms were compared within a province. At the field scale (i.e., 1 – 20 ha), we compared different fields within a single farm. At the within-field scale (90 m^2), yield variability was assessed within a single field.

Ideally one single dataset should be used to compare yield variability from within-field to regional level. Yet, to the best of our knowledge such a dataset is not available. Therefore, we analysed multiple datasets in this study (Table 2.1). The first dataset contained average yield per year per province collected by Statistics Netherlands (CBS, Dutch governmental organisation) (CBS, 2022) and was used to analyse yield variability among provinces. The second dataset consisted of yield data measured by the potato processing industry and was also used to analyse yield variability among provinces. The third dataset was derived from the Farm Accountancy Data Network (FADN; cf. Silva et al., 2017) to analyse yield variability at the provincial and farm scale. The fourth dataset included yield data at provincial and farm scale as well and was obtained through a questionnaire that was disseminated among farmers. The last dataset was obtained from two large scale commercial farms in the Netherlands, named 'Van Den Borne Aardappelen' and 'Scholtenszathe'. This dataset was used to analyse yield variability at the field and within-field scale. All datasets refer to ware potato yield only and thus excluded data for seed and starch potato.

Table 2.1. Overview of different data sources and their respective spatial and temporal scales for yield variability analysis. Resolution refers to the lowest spatial unit at which the data was available in each dataset.

Data source	Spatial scale				Temporal scale	Resolution
	Province	Farm	Field	Within-field		
CBS statistics	x				1994 – 2020	Province
Industry samples	x				2013 – 2019	Field
FADN database	x	x			2006 – 2020	Farm
Questionnaire	x	x			2020 – 2021	Field
Commercial farms			x	x	2015 – 2020[1]	Grid cell (3 – 4 m^2)

[1] For the commercial farm 'Scholtenszathe' no data from 2017 were available.

Data sources and processing

Statistics Netherlands (CBS) requests Dutch farmers to report marketable ware potato yields at farm level every year. This dataset did not report potato yield for different varieties, which could then not be controlled for in the analysis. Yields are summarised per province per year and made publicly available (CBS, 2022). From the dataset, we filtered out the province of Utrecht as no yield data was available for this province in the other datasets (see below). This resulted in 297 province x year observations from 1994 till 2020.

The industry samples dataset consisted of marketable yield data of varieties used to produce french fries. Yield data were collected at field level by four different potato processing companies. These companies took biweekly tuber samples from multiple potato fields to assess tuber weight and size distribution throughout the growing season. In our case, samples were collected from week 30 onwards from a total harvested area of 3 – 4.5 m^2, which resulted in a time series of yield measurements per field. For each field with at least three measurements, final yield estimated using regression analysis. Three regression models were used for that purpose: linear, quadratic plateau, or linear upper plateau models (Grassini et al., 2013). The three estimated regression models were compared based on the Akaike Information Criterion (AIC) and the model with the lowest AIC was selected as the best model to describe yield development for each field. Each of the three functional forms was most appropriate for about one-third of the data. After processing, the industry dataset contained yield observations from 1393 field x year combinations (2013 – 2019).

The FADN dataset for the Netherlands contained marketable ware potato yield data at farm level from a representative group of 1500 Dutch farms for the period 2000 – 2020, without differentiating between varieties. After removing missing values, a dataset with 2471 observations of farm x year combinations remained. We removed data from the period 2000 – 2005, for which no information on soil type was available, and two more observations were discarded (which was the only observation available for the province of Utrecht and the only observation for the peat soil type) resulting in 1889 observations over the period 2006 – 2020.

We disseminated an online questionnaire for the growing seasons 2020 and 2021 requesting farmers to report the yield obtained on their farm. In addition, farmers who cultivated the variety Innovator on clayey soils or the variety Fontane on sandy soils were specifically asked to report yields for these varieties as they are the most cultivated varieties in the country, for the respective soil types. Farmers were also asked to indicate the yield of the highest and lowest yielding fields for these two varieties. Information was specifically requested for the two varieties to remove confounding effects of genotype and soil type in the analysis. For the comparative analysis with other datasets (Section 2.2.1) we used the yield data at farm level, hence yield of different varieties were pooled.

Potential respondents to the questionnaire were reached through different communication channels (i.e., newsletters, farmers’ webpages, targeted e-mails, news article in a farmers’ magazine, and social media). In total we received 170 useful responses for the 2020 growing season. Of the 170 responses in 2020, 41 farmers cultivated Fontane on sandy soils and 40 farmers cultivated Innovator on clayey soils. For growing season 2021, we asked the respondents of 2020 to fill in the questionnaire once more. In this way, we received in total 62 responses in 2021 with 20 observations from farmers who cultivated Innovator on clayey soils and twelve observations from farmers who cultivated Fontane on sandy soils.

The last dataset consisted of yield measurements on two large commercial farms in the Netherlands. We note that these two farms are not representative of an average Dutch potato farm, due to their large cultivated area, specialisation towards potato production, and large share of potato cultivation on rented land. Yet, the spatial and temporal coverage of these datasets make it valuable to study yield variability at field and within-field scales. The first farm, 'Scholtenszathe', is an arable farm in the northeast of the Netherlands in a sandy soil region. On this farm, ca. 1000 ha are cultivated each year of which approximately 200 ha are used for ware potato cultivation. The second farm, 'Van Den Borne Aardappelen', is an arable farm in the south of the Netherlands in a sandy soil region, mostly focused on potato production (Mulders et al., 2021). On this farm, ca. 1000 ha are cultivated each year of which approximately 600 ha are allocated to ware potato (land renting makes it possible to grow potato on such large shares of the total area). On both farms, gross yield was measured using a harvesting machine, resulting in yield maps per field. The resolution of these yield maps ranged between 3 – 4 m^2 per grid cell, depending on the driving speed of the harvesting machine. From these maps, all measurement points with yield values equal to 0 t ha^{-1} and above 150 t ha^{-1} were discarded. Values of 0 t ha^{-1} are registered when the harvesting machine is driving on the field without harvesting. For Scholtenszathe, all headlands and any parts of the field with irregular driving patterns (for harvesting) were removed. For van den Borne Aardappelen, the outer 10 m of each field was removed. Finally, from all measured values 15% tare was subtracted to represent marketable yield (Mulders et al., 2021), consistent with the other datasets. For both farms, only fields with the variety Fontane were selected to remove confounding effects of genotypes. Yield per field was determined by averaging the yield of all grid cells. Yield for within-field sub-area was determined in a similar way for grid cells of 30 x 30 m resolution, excluding grid cells with less than 50 observations per cell. After processing, the dataset of Scholtenszathe included 68 field x year combinations from the years 2015, 2016, 2018, 2019, 2020 with a total cultivated area of 806 ha, resulting in an average field size of 11.9 ha. The dataset of Van Den Borne Aardappelen included 789 field x year combinations between 2015 and 2020 with a total cultivated area of 2681 ha, resulting in an average field size of 3.4 ha.

Comparing yield variability across spatial scales

Different descriptive statistics were used to determine the average yield and yield variability at each spatial scale because datasets differed in available variables (e.g., variety or soil type) and resolution at which data were collected. A comparative analysis was performed to assess yield variability across the four spatial scales using a consistent protocol, built upon linear mixed models. When boxplots were used for visualisation, whiskers were set to represent the 10^{th} and 90^{th} percentile of the data.

At the regional scale, linear mixed models were used to estimate the average yield per province for the CBS, industry samples, and FADN datasets using the 'lmerTest' package in R version 4.2.0 (Kuznetsova et al., 2015). For all three datasets, potato yield was set as the dependent variable, province as a fixed factor, and year as a random factor. Variety and company were also added as fixed factors to the linear mixed model of the industry samples dataset and soil type was added to the model of the FADN dataset. ANOVA was used for all three datasets to test for significant yield differences among provinces, using a Tukey's HSD test as post-hoc test. Temporal yield variability among provinces was visualised using boxplots for each year x dataset combination.

At the farm scale, two different approaches were used to describe among-farm yield variability for two datasets. For the FADN dataset, yield variability was assessed by comparing long-term average yields among farms. First, we excluded all farms with less than 5 years of yield observations. For the remaining observations, yield was rescaled as follows:

$$Yij_{scaled} = \frac{Yij}{Mj}\ M \qquad \text{Eq. 2.1}$$

where Yij_{scaled} is the scaled yield of farm *i* in year *j*, *Yij* is the actual yield of farm *i* in year *j*, *Mj* is the median yield in year *j*, and *M* is the overall median yield of the whole dataset. The long-term average yield was then calculated by taking the farm average of Yij_{scaled}. Furthermore, we calculated how often each farm had a higher than median yield. Finally, boxplots were used to visualise the among-farm long-term yield variability for a given province and to assess if a farm consistently obtained a higher or lower yield than the median yield of the pooled data. Results are only shown for provinces with at least ten farms, to adhere to privacy regulations. Hence, we employed data from 104 farms and 1255 farm x year combinations. For the questionnaire dataset, responses were divided into three groups: farms with Fontane cultivated on sandy soils, farms with Innovator cultivated on clayey soils, and farms with none of these cultivars cultivated on the respective soil types. Among-farm yield variability was visualised for each group and for the two years separately using boxplots.

For the questionnaire dataset, among-field yield variability was calculated as the difference between the highest and lowest obtained yield per field within a single farm. This was calculated for farms with Innovator cultivated on clayey soils and farms with Fontane cultivated on sandy soils. We used quantile regression to assess if there was a significant relation between among-field yield variability and farm size for the 10^{th} percentile ('quantreg' package in R version 4.2.0; Koenker et al., 2018). For the commercial farms datasets, among-field yield variability was summarised for each year using boxplots. The range, expressed as the difference between 10^{th} and 90^{th} percentile of among-field yield variability, was calculated for each year.

At the within-field scale, boxplots were used to visualise the within-field yield variability for each field x year combination. The range, expressed as the difference between 10th and 90th percentile of the within-field yield variability per field, was calculated for each field and averaged across all fields per year.

Finally, we compared yield variability across spatial scales and years with a random effects model fitted with year and spatial scale as random effects (see also Silva et al., 2023). Random effects models are a particular type of linear mixed models that consider only random effects. Within the tested models, spatial scales were nested within each other if a dataset contained yield data of multiple scales (Table 2.1). Year and province were used as random effects for the CBS and industry samples dataset. Year and farm nested within province were used as random effects for the FADN and questionnaire datasets. Finally, year and within-field nested within fields were used as random effects for the commercial farm datasets. Interactions between year and spatial scales were not included to ease interpretation of the results. Spatial and temporal yield variability were expressed as a standard deviation in t ha^{-1}. For a fair temporal comparison across scales, we included for this analysis data from the same growing seasons (2015 – 2020). However, there were some exceptions due to the structure and availability of the data. We already noted that no data were available for 2020 in the industry samples dataset and no data were available for 2017 in the Scholtenszathe dataset. Thus, these datasets miss one year for the comparative analysis. For the questionnaire dataset, only data from 2020 and 2021 were available and hence 2021 was included in the comparative analysis.

2.2.2 Expert-based assessment of yield gap explaining factors

The questionnaire described in Section 2.2.1 was also used to ask farmers which factors affected potato production at their farm, which was done in two steps. First, farmers were asked to estimate the potential yield at farm level under optimal cultivation conditions. We indicated to farmers that potential yield refers to the maximum achievable yield under given climatic conditions, assuming agronomically perfect crop management (van Ittersum et al., 2013). Farmers who cultivated Innovator on clayey soils or Fontane on sandy soils were asked to estimate the potential yield for these specific varieties. Farmers who did not cultivate these varieties on the respective soil types were asked to estimate the average potential yield at farm level for the varieties they cultivated. From the estimated potential yield, the yield gap was calculated as the difference between the farmer estimated potential yield and the reported actual yield (van Ittersum et al., 2013).

In the second step, we requested information about what farmers perceived as the most important factors explaining the potato yield gap on their farm. The yield gap explaining factors were divided into three categories (Table 2.2): biophysical, management, and socio-economic factors. For each category, farmers were asked through a multiple-choice question which factors explained the yield gap on their farm. Farmers were then given the opportunity to explain their selection through an open question.

Table 2.2. Possible yield gap explaining factors in relation to biophysical conditions, crop management practices, and socio-economic conditions in the disseminated questionnaire.

Biophysical factors	Management factors	Socio-economic factors
Heat	Planting too early	Lack of irrigation guns
Frost damage	Planting too late	Lack of machinery
Water deficit	Too little irrigation applied	Lack of labour
Water excess	Irrigation applied too late	Farm is too large to manage optimally
Nutrient deficit in the soil	No irrigation applied	Economically not interesting to aim for potential yield
Poor soil structure	Poor drainage	Aim of cultivation is not maximum yield
Hail damage	Too little fertilisation	Legislation
Presence of diseases	Use of heavy machinery	No successor
Presence of nematodes	Preceding crop	
	Too narrow rotation	
	Insufficient use of crop protection products	
	Crop damage due to herbicide treatment	

The questionnaire disseminated in 2021 was expanded based on the answers to the 2020 questionnaire. For 2020, two results were striking (Section 2.3.2): (1) 'too little fertilisation' was an important management factor and 'legislation' was an important socio-economic factor explaining the yield gap and (2) farmers indicated that low potato prices (due to the COVID-19 pandemic) was one of the reasons to invest less in inputs, particularly irrigation. To explore these results further, farmers were asked additional questions in 2021, based on a Likert scale, to indicate to what extent input use was reduced due to low potato prices and how more lenient legislation would affect soil and crop conditions and yield on their farm.

2.3 Results

2.3.1 Yield variability analysis

Among provinces

Ware potato yield was significantly different among provinces in all three datasets, with maximum yield differences ranging from 8 to 14 t ha^{-1}, depending on the dataset. In the CBS dataset, average yield per province ranged from 45 to 53 t ha^{-1} (Fig. 2.1A). Based on the industry samples dataset, average yield ranged from 45 to 51 t ha^{-1} (Fig. 2.1B). In the FADN dataset, average yield ranged from 39 to 53 t ha^{-1} (Fig. 2.1C). In all three datasets, yield in Flevoland and Noord-Brabant were among the top three, indicating these were the highest yielding provinces.

Large temporal yield variability was observed in all three datasets as well. Over time, median yield ranged from 41 to 53 t ha^{-1} in the CBS dataset, 45 – 57 t ha^{-1} in the industry samples dataset, and 40 – 51 ha^{-1} in the FADN dataset (Fig. 2.1D). Although average yield in the industry samples dataset was slightly higher, yield variability among the years followed similar patterns for the different datasets.

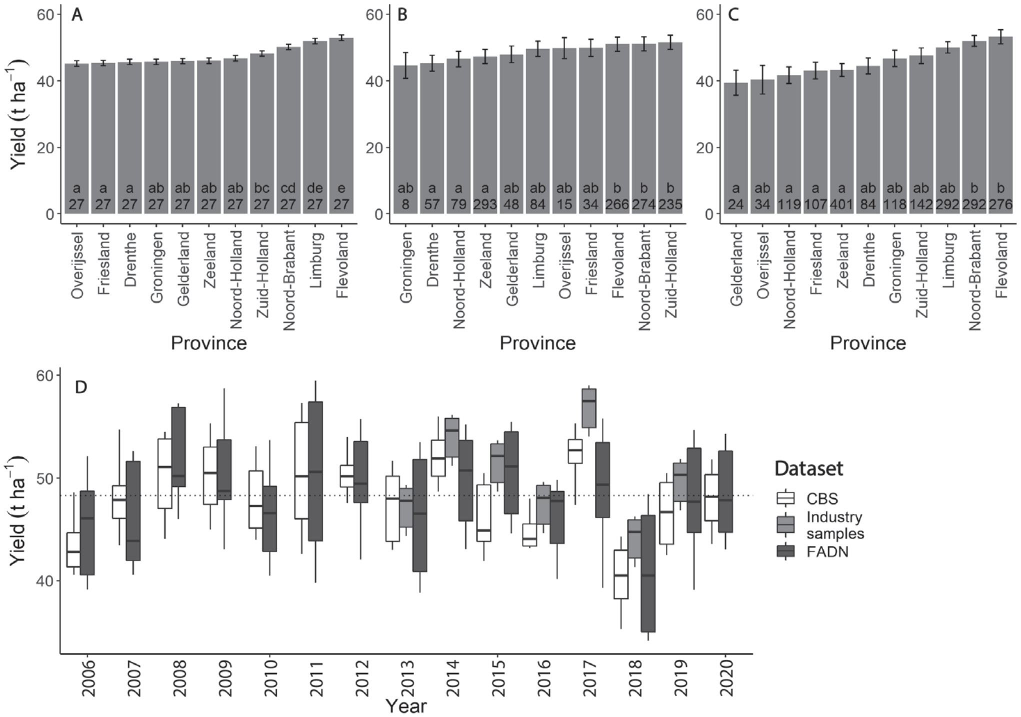


Figure 2.1. Average yield (in t ha^{-1}) for different provinces in the Netherlands calculated with the CBS (1994 – 2000) (A), industry samples (2013 – 2019) (B) and FADN dataset (2006 – 2020) (C). Panel D shows variability among provinces for each year from 2006 onwards. Error bars in panels A – C indicate standard errors. Different letters indicate significant differences between provinces. Numbers at the bottom of the bars indicate the number of observations (number of years for panel A, number of field x year combinations for panel B and number of farms x year combinations for panel C) an estimate is based on. Boxplot whiskers in panel D indicate 10th and 90th percentile of the data.

Among farms

Large among-farm yield variability was observed in both the FADN and questionnaire datasets. For the FADN dataset, long-term average yield at farm level ranged from 37 to 60 t ha^{-1} (Fig. 2.2A). Based on the questionnaire dataset, among-farm yield variability ranged from 42 to 68 t ha^{-1}, but varied by variety/soil type and year (Fig. 2.2B). For Innovator on clayey soils, average yield was approximately 10 t ha^{-1} lower in 2021 than in 2020, whereas the yield variability range was similar between the two years. For Fontane on sandy soils, both the average yield and yield range were similar across the two years.

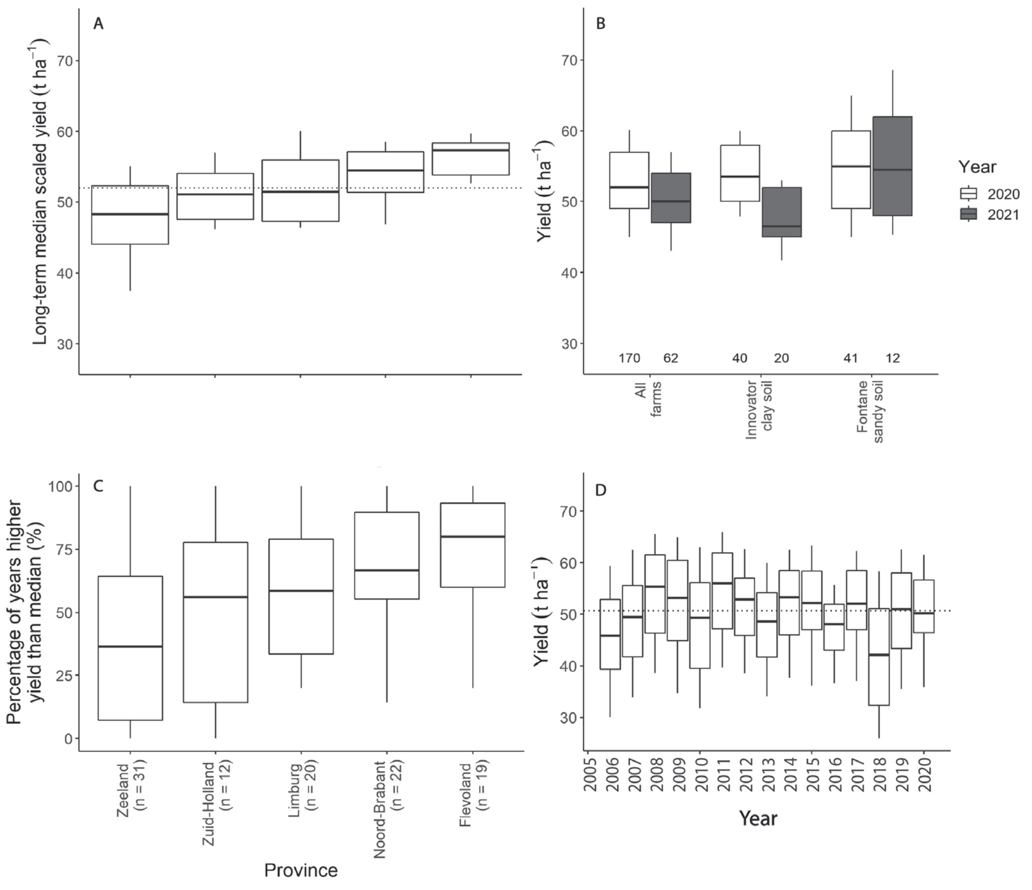


Figure 2.2. Long-term median scaled yield per farm (in t ha^{-1}) for five different provinces based on the FADN dataset (A). Yield per farm (in t ha^{-1}), based on the questionnaire dataset (B). Percentage of years that a farmer had a higher than median yield for all yield observations of that year, based on the FADN dataset (C). Among-farm yield variability for each year, based on the FADN dataset (D). The dotted line in panels A and D indicates the median yield of all farms and years. Different greyscales in panel B indicate different years. Whiskers of the boxplots indicate 10th and 90th percentile of the data. Labels and number of observations indicated in panel C apply to panel A and C. Numbers in panel B indicate number of observations per group.

The FADN dataset showed that 9% of the farms obtained higher than median yield (across all farms) in all years, 12% of the farms never obtained higher than median yield, and the remaining farms obtained higher and lower than median yield (Fig. 2.2C). Farms with higher than median yield were found in all provinces. However, in Noord-Brabant and Flevoland there were relatively more farms which obtained higher than median yield. Among farms, the yield range was roughly 20 – 30 t ha^{-1} and varied from year to year (Fig. 2.2D).

Among fields

Large among-field yield variability within a single farm was observed in both the questionnaire and commercial farm datasets. For the questionnaire dataset, among-field yield variability (i.e., difference between the highest and lowest yielding field, Section 2.2.1) averaged 10 t ha^{-1} on clayey soils with cv. Innovator and 23 t ha^{-1} on sandy soils with cv. Fontane (Fig. 2.3). There was no clear difference in yield variability between the two years. Furthermore, for sandy soils with cv. Fontane, quantile regression showed that among-field yield variability increased with increasing cultivated potato area for the 10th percentile, indicating larger among-field yield variability in larger farms. This relation was robust when excluding the three farms with cultivated potato area above 400 ha.

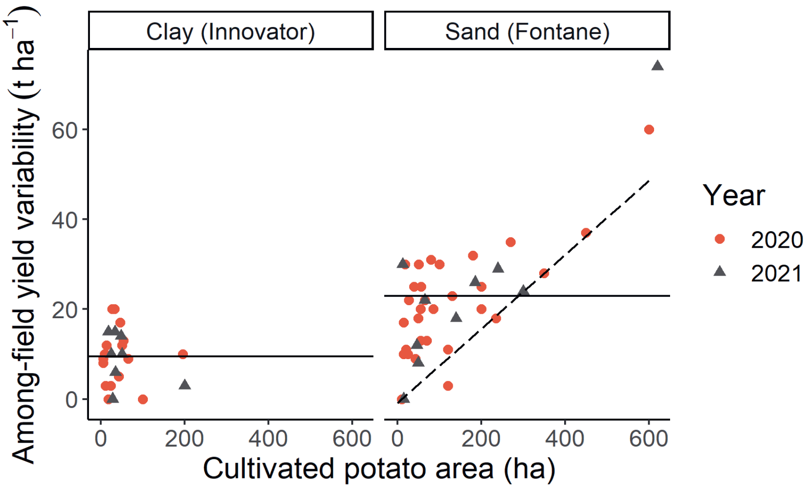


Figure 2.3. Among-field yield variability (in t ha^{-1}) calculated as the difference between the highest and lowest yielding fields against the total cultivated potato area per farm (ha). Different colours indicate different years. The solid lines indicate the average among-field yield variability per soil type. The dashed line indicates the quantile regression line for the 10th percentile including all data points. Figure is based on the questionnaire dataset.

The yield range among fields (i.e., the difference between the 90th and 10th percentiles) varied from 13.5 to 20.2 t ha^{-1} for Scholtenszathe and 22.6 – 34.8 t ha^{-1} for Van Den Borne Aardappelen (Fig. 2.4). Median yield differed considerably across years at both farms, while yield variability was similar across years with standard deviations ranging from 12 to 21% of the mean for Scholtenszathe and 19 – 39% of the mean for Van Den Borne Aardappelen.

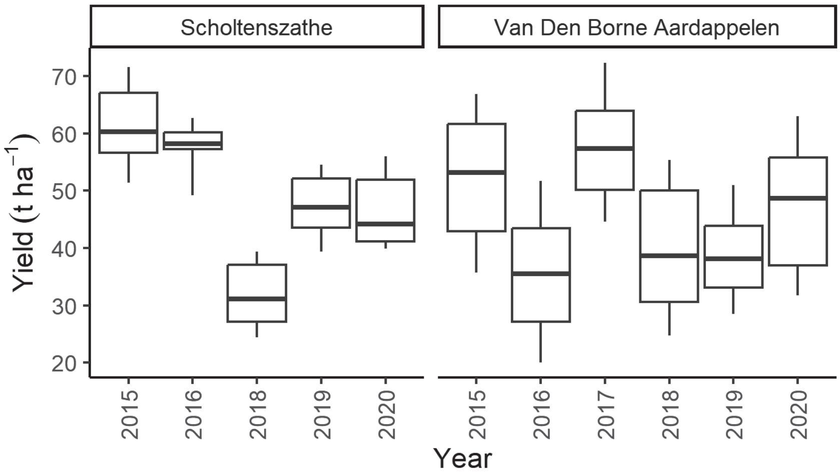


Figure 2.4. Boxplots showing among field yield variability (in t ha^{-1}) per year for the farms Scholtenszathe and Van Den Borne Aardappelen. Figure is based on the commercial farms dataset. Whiskers of the boxplots indicate 10th and 90th percentile of the data.

Within fields

Large differences were observed among fields in terms of within-field yield variability. The yield range per field (i.e., the difference between the 90th and 10th percentiles) varied from less than 10 t ha^{-1} to more than 40 t ha^{-1}. The average range of within-field yield variability per year and farm varied from 9.6 to 16.8 t ha^{-1} for Scholtenszathe and from 18.5 to 25 t ha^{-1} for Van den Borne Aardappelen. Figure 2.5 presents results for two extreme years. In 2016 (year with highest yield variability), the southern sandy soils of Van Den Borne Aardappelen experienced high intensity rainfalls. In 2018 (year with lowest yield variability), an extreme drought affected potato cultivation across the Netherlands. Appendix A.1 shows that mean ranges are slightly different across years, but that the distribution of within-field yield variability remained similar.

Yield variability across spatial scales over the period 2015 – 2020

Random effects model results, using only data for the period 2015 – 2020, indicated that yield variability was lowest at the regional scale, greater at farm scale, and even greater at both field and within-field scales (Fig. 2.6). The standard deviation of among-field yield variability ranged from 8.5 to 11.1 t ha^{-1}. Within-field yield variability was at a similar or slightly lower level, with a standard deviation from 7.7 to 8.7 t ha^{-1}. Standard deviation of

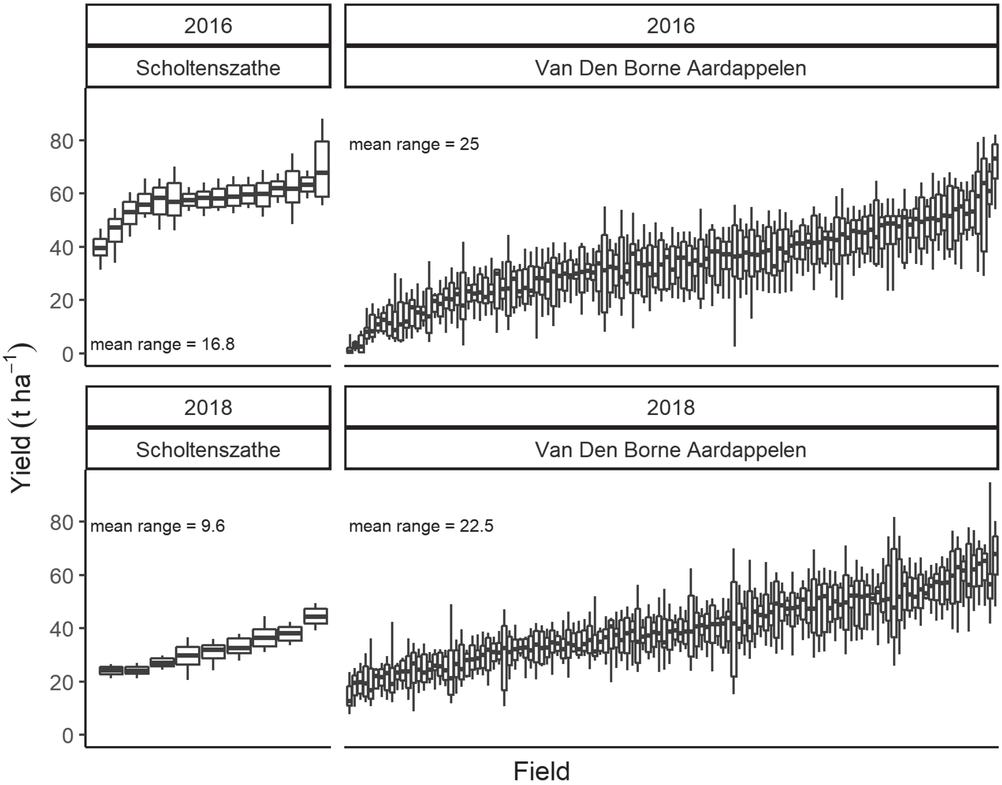


Figure 2.5. Boxplots showing within-field yield variability (in t ha^{-1}) per field per year for the farms Scholtenszathe and Van Den Borne Aardappelen for 2016 (an exceptionally wet year) and 2018 (an exceptionally dry year). Figure is based on the commercial farms dataset. Boxplot whiskers indicate 10th and 90th percentile of the data. The mean range provided in each figure represents the average range of within-field yield variability per year (in t ha^{-1}).

among-farm yield variability ranged from 4.0 to 6.1 t ha^{-1} and of among-province yield variability ranged from 1.6 to 3.5 t ha^{-1}. The mean yields of the different datasets ranged from 45 to 52 t ha^{-1} (Fig. 2.6).

The temporal scale was another important source of yield variability. In the CBS, industry samples, and Scholtenszathe datasets, temporal yield variability was approximately twice that of the observed spatial yield variability (Fig. 2.6). In the FADN dataset, temporal yield variability was similar to the spatial yield variability among provinces and roughly half of the yield variability among farms. For the dataset of Van den Borne Aardappelen, temporal yield variability was similar to within-field yield variability and almost 20% lower than among-field yield variability. Appendix A.2 provides a comparison of yield variability across scales for all available years in the datasets.

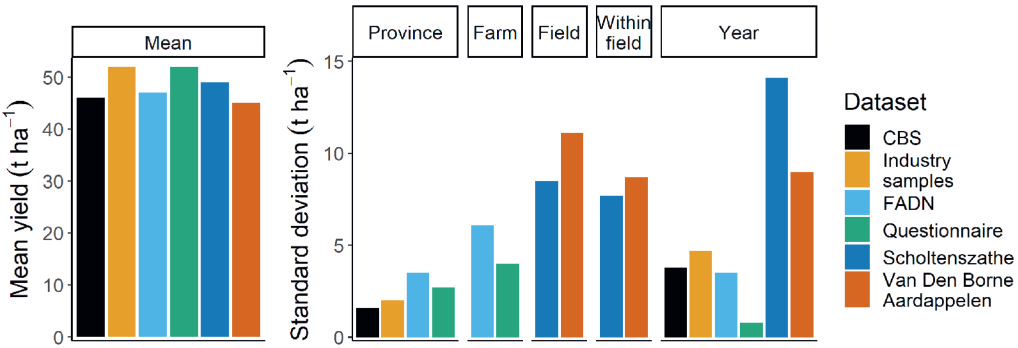


Figure 2.6. Mean yield per dataset and standard deviation (in t ha^{-1}) for each scale and data source for the period 2015 – 2020. For the industry samples dataset, no data were available for 2020. For Scholtenszathe, no data were available for 2017. For the questionnaire dataset only data from 2020 and 2021 were available.

Roughly half of the yield variability in all datasets was explained by temporal and spatial variability (Fig. 2.7). Differences among provinces explained 3 – 14% of the observed variation. Among-farm yield variability explained 28 – 32% of the observed variation. Variation among fields was about 15 – 21% and variation within fields was about 12 – 13% of the total variance. Excluding the questionnaire dataset, 10 – 55% of the total variance in all datasets was explained by temporal variability. In all datasets, 30 – 75% of the yield variability remained unexplained (Fig. 2.7), which may be attributed to other factors not included in the analysis (e.g., crop management practices, disease pressure) or measurement errors. Appendix A.3 presents a comparison of explained variance for all available years in the datasets.

2.3.2 Constraints to potato production based on farm survey

On average, farmers estimated the potential yield at farm level, including all varieties, at 63 t ha^{-1}. Potential yield for Innovator on clayey soils was estimated at 64 t ha^{-1} and for Fontane on sandy soils at 75 t ha^{-1} (Fig. 2.8A). Nonetheless, there was large variability in the estimated potential yield with a lower range of 50 – 65 t ha^{-1} and an upper range of 73 – 95 t ha^{-1}. Large variability was also observed in the estimated yield gap between potential and actual yield, ranging from nil to ca. 40 t ha^{-1} (Fig. 2.8B). The average yield gap was ca. 13 t ha^{-1} at farm level, including all varieties, 13 t ha^{-1} for Innovator on clayey soils, and 18 t ha^{-1} for Fontane on sandy soils, corresponding to a yield gap of 20 – 24% of potential yield.

Among the two years, farmers identified different biophysical factors as yield gap explaining factors (Fig. 2.9). For 2020, heat and water deficit were mentioned (each by 69% of the respondents) as the most important yield gap explaining factors by all three respondent groups. For 2021, water excess was considered an important yield gap explaining factor on

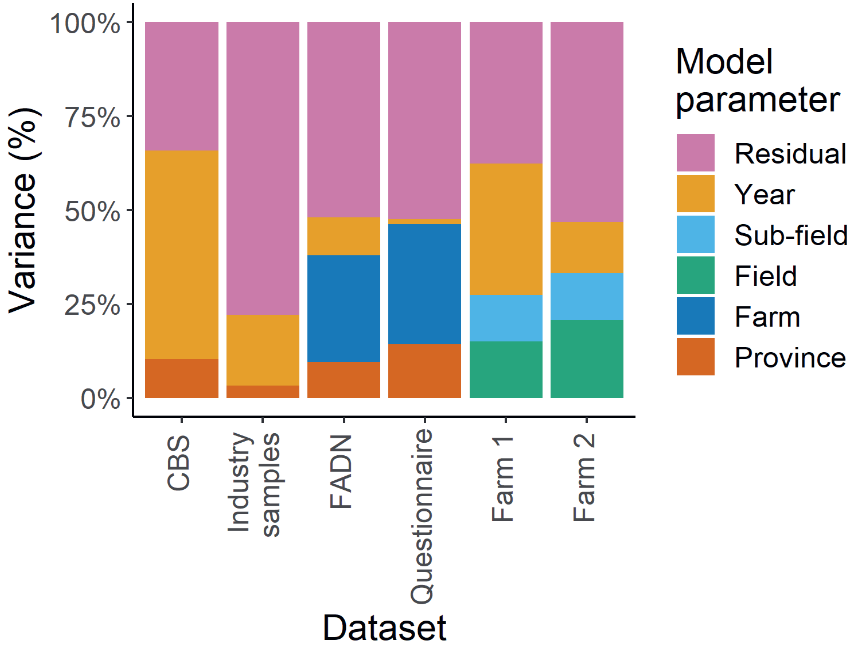


Figure 2.7. Variance explained (in % of total variance) by the different model parameters for each dataset for the period 2015 – 2020. Different colours indicate different sources of variance.

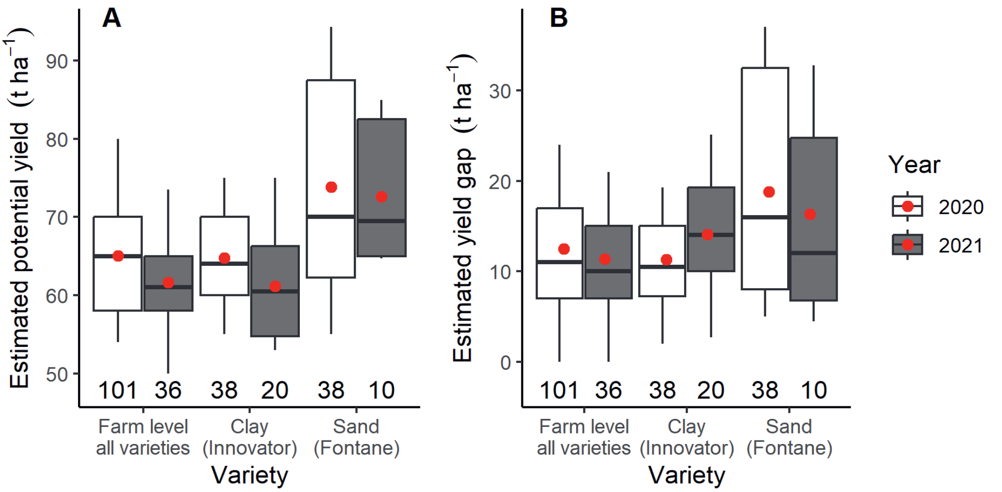


Figure 2.8. Potential yield estimated by farmers (in t ha^{-1}) (A) and yield gap (in t ha^{-1}) for three different groups (B): Farm level estimates including all varieties, estimates for Innovator on clayey soils and for Fontane on sandy soils. Different greyscales indicate different years. The red dots indicate the mean estimated potential yield or yield gap. Numbers at the bottom of the graph indicate number of observations

clay and sandy soils (51% on average). Diseases were indicated as a yield gap explaining factor by farmers who cultivated Fontane on sandy soils in 2021 (70%) but not by farmers who cultivated Innovator on clayey soils (11%). Conversely, farmers on clayey soils considered soil structure an important yield gap explaining factor in both years (37% in 2020 and 42% in 2021), but only few farmers on sandy soils considered soil structure a yield gap explaining factor (9% in 2020 and 20% in 2021).

Farmers indicated several management factors that could explain the yield gap (Fig. 2.9). For 2020, farmers mainly mentioned irrigation as an important yield gap explaining factor (60% on average). Applying too little irrigation was most often mentioned on sandy soils (51%) whereas delayed irrigation (26%) or no irrigation (26%) were considered more relevant to explain the yield gap on clayey soils. Lack of fertilisation was selected as a yield gap explaining factor by 16 – 35% of the farmers in both years, which contrasts to the fact that nutrient deficit was not selected by any farmer as a biophysical yield gap explaining factor. Preceding crop, use of heavy machinery, and crop protection were relevant yield gap explaining factors according to 9 – 20% of the farmers. Timing of planting, drainage, spraying damage, and crop rotation were hardly mentioned by farmers as plausible causes for yield gaps.

Both in 2020 and 2021, legislation was mentioned as a relevant yield gap explaining factor by 20% of the farmers on average (Fig. 2.9). Moreover, in 2020 socio-economic factors related to drought stress were indicated as important to explain yield gaps. For instance, farmers pointed out that it was not always economic to strive for high yields (35%), i.e., the cost of irrigation did not compensate the expected additional income. The answers to the open questions revealed that it was mainly the low potato price in 2020 that negatively affected the economic return of using inputs. Lastly, for some farms on sandy soils with cv. Fontane, availability of irrigation guns was deemed insufficient (36%) and/or the cultivated potato area was too large to be fully irrigated (30%).

The additional questions in the 2021 questionnaire (Section 2.2.2) revealed that 29% of the farmers irrigated less frequently if potato prices were (expected to be) low (Fig. 2.10). Moreover, 20% of the farmers indicated to apply less water per irrigation event because of low potato prices. At the same time, farmers indicated negligible effect of potato prices on the use of other inputs, i.e., only 14% of the farmers applied less mineral fertilisers due to low potato prices, and even fewer farmers reduced pesticide or organic manure inputs due to low potato prices.

Legislation had a large effect on potato cultivation according to most farmers. Over 90% of the farmers indicated that soil fertility could be improved if they were allowed to apply more organic fertilisers. Almost 70% of the farmers indicated that yield would increase if higher nitrogen and/or phosphorus applications would be allowed on their fields. A slightly smaller percentage of farmers indicated that plant health would increase if they were allowed to apply more manure under the assumption that plants would better cope to stresses under high fertility conditions. In 2020, some farmers also stated that yields were lower because the herbicide Reglone was no longer allowed for haulm killing at the end of the growing season, which forced farmers to use other herbicides or haulm killing methods. The questionnaire of 2021 revealed that an equal share of farmers agreed or disagreed with this statement.

2.4 Discussion

2.4.1 Spatial and temporal yield variability

This study assessed ware potato yield variability in the Netherlands across four spatial scales. We found that yield variability was lowest at the regional scale, greater at farm scale, and even greater at both field and within-field scales. Our findings are in agreement with our hypothesis and confirm earlier findings that yield variability decreases at higher aggregation levels (Debrah and Hall, 1989; Górski and Górska, 2003; Lobell et al., 2007). However, this study showed for the first time that the latter does not necessarily apply to the lowest spatial scale as yield variability within a field was comparable with yield variability among fields. Temporal variability was another important constituent of yield variability explaining 10 – 55% of the yield variation in all datasets, highlighting the importance of weather conditions on yield at all scales (Fig. 2.7; see also Ray et al., 2015; Silva et al., 2023). Our method allowed us to compare temporal yield variability with spatial yield variability revealing that temporal yield variability was particularly important for the two large commercial farms, for which most fields were distributed across a relatively small area. We also note that potato fields at Van Den Borne Aardappelen were irrigated, while at Scholtenszathe potato was cultivated under rainfed conditions, further explaining the differences in temporal yield variability between the two farms.

Weather extremes have a large influence on crop yield variability (Brown, 2013; Van Oort et al., 2012), as captured by the period covered in our analysis. In 2018 there was an extremely dry period (van Oort et al., 2023) resulting in far below average yields in all datasets. Conversely, 2016 was an extremely wet year in the south of the Netherlands, with almost one-third of the annual precipitation occurring in June when the potato crops started to establish. The latter had a strong impact on the commercial farm 'Van Den Borne Aardappelen' (Fig. 2.4). As extreme weather events are likely to occur more frequently in future (van den Hurk et al., 2014), yield variability is also expected to increase in space and time, particularly at lower aggregation levels (Adams et al., 2003). The sandy regions in the south and east of the Netherlands are specifically vulnerable because of somewhat larger temperature increases and larger risk of water deficits (Diogo et al., 2017).

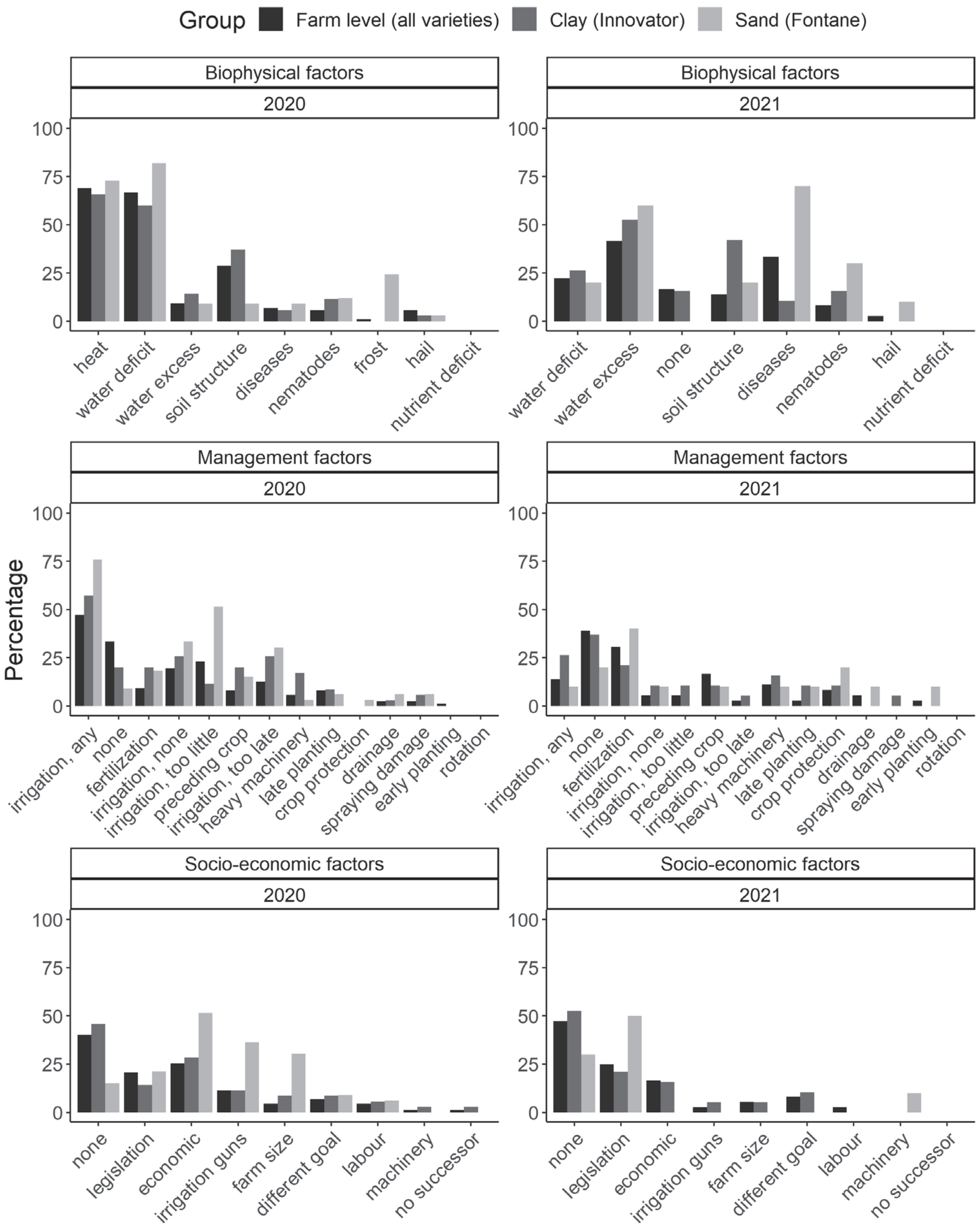


Figure 2.9. Percentage of farmers that considered one of the indicated biophysical, management, or socio-economic factors relevant for explaining the yield gap at their farm in 2020 and/or 2021. Different greyscales indicate different groups of farmers.

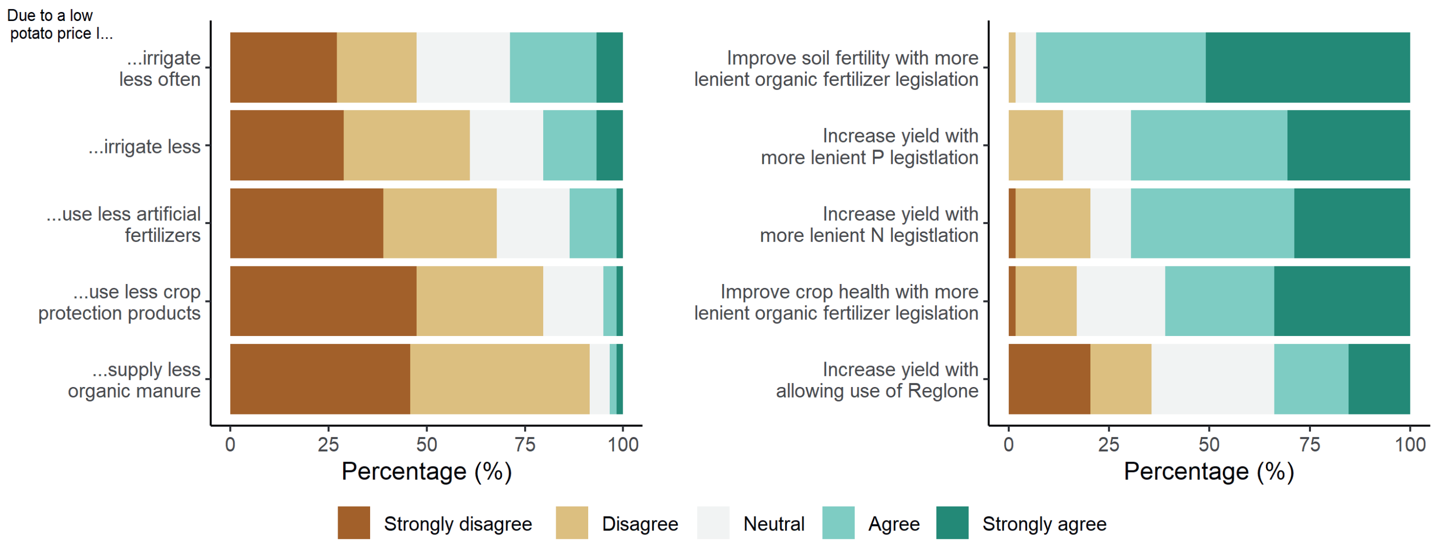


Figure 2.10. Percentage of farmers that agreed or disagreed with the indicated statements in the 2021 version of the questionnaire. Different colours indicate whether a respondent (strongly) agreed, (strongly) disagreed or was neutral regarding the statement (n = 59).

The comparison of yield variability across spatial scales and the fact that yield variability increased with farm size on sandy soils suggest that local variability in biophysical conditions and crop management have a larger impact on yield variability than farm(er) characteristics. Yield variability across space can be best addressed at field and within-field level, but this requires understanding the drivers of yield variability (Mulders et al., 2021; Silva et al., 2021), and needs to consider temporal yield variability. Precision agriculture offers potential to manage yield variability, but it should be focused at within-field and among-field yield variability assuming yield potential is comparable within and between fields, respectively. In case of differences in yield potential within and among fields, precision agricultural techniques based on real-time observation of crop conditions can help attuning crop management to realistic target yields under field conditions (Al-Gaadi et al., 2016; van Evert et al., 2012b, 2012a). The latter will likely not reduce yield variability *per se* but contributes to increasing resource use efficiency and achieving environmental and economic sustainability. However, temporal variability affects crop production each year differently, and therefore it can be challenging for farmers to adjust precision farming techniques to seasonal weather patterns.

Whether addressing spatial yield variability is beneficial, depends on the farm characteristics and the socio-economic context. The economic break-even point for investing in precision agriculture techniques is lower on farms with larger observed variability (English et al., 1999) or with larger acreage (Barnes et al., 2019; Kempenaar et al., 2010). Furthermore, crop yield could be constrained by persistent factors that are difficult to overcome (Lobell et al., 2010). Some farmers indicated in the questionnaire that in 2020 (a relatively dry year) the irrigation capacity was limited (Fig. 2.9) or that it was not economically viable to irrigate (Fig. 2.10), leading to larger yield variability. Similarly, time bound activities such as planting are dependent on the availability of machinery and labour, and a lack of these translates into wider planting windows and greater among-field yield variability.

2.4.2 Methodological considerations of the yield variability analysis

Ideally one dataset containing yield data across all four studied scales should be available to analyse spatial and temporal yield variability. This would allow to make a direct comparison between the highest and lowest spatial scales and to study the impact of yield data aggregation from one spatial scale to the next. To the best of our knowledge such a dataset combining yield levels across all scales is not available. Instead, regional to farm level data are more readily available to replicate our analysis to other crops and geographies. Within-field yield data will remain a challenge to access in most regions despite new developments to study yield variability at lower aggregation levels (Basso and Antle, 2020).

The use of multiple sources of data, as presented in this study, makes it difficult to properly control for different cultivars and management practices when quantifying yield variability. We acknowledge that some of our analysis suffers from such limitations, particularly at farm and regional levels, but note that the magnitude and patterns of yield variability among provinces were similar for the different datasets analysed in this study (Figs. 2.1 and 2.6). Beyond differences in data sources, some other considerations are required for proper interpretation of the results. First, estimates of among-field and within-field yield variability are based on yield data from two atypical large farms. The questionnaire dataset revealed that yield variability was larger on sandy soils than on clayey soils (Fig. 2.2B and Fig. 2.3) and increased with cultivation area on sandy soils (with cv. Fontane; Fig. 2.3). Hence, among-field and within-field yield variability estimates are likely to be lower for smaller farms or other soil types than analysed in this study. Second, interactions between spatial and temporal variability were not analysed to avoid complexity, despite their importance to understand yield stability over time (e.g., Maestrini and Basso, 2018). Lastly, datasets differed in the way yield data was aggregated (Table 2.1). For instance, yield data was aggregated at province, farm, and field level in the CBS, FADN, and industry samples datasets, respectively. These different aggregation levels could potentially explain differences in standard errors for the yield estimates per province (Fig. 2.1), differences in yield variability attributed to the time scale (Fig. 2.6), or differences in unexplained variability (Fig. 2.7).

2.4.3 Yield gap explaining factors of potato production

Farmers indicated a yield gap for ware potato in the Netherlands of 13 – 18 t ha^{-1}, corresponding to 20 – 24% of the potential yield (Fig. 2.8). This yield gap is slightly lower than that reported in other studies (25 – 30% of potential yield), where crop growth models were used to simulate the potential yield (Silva et al., 2020, 2017). Farmers may have a different interpretation of the potential yield than researchers, which then explains the slightly lower yield gap found in this study. As the highest farmers' yield is generally lower than the potential yield and only reached by few farms (Silva et al., 2017), farmers may underestimate the potential yield as defined based on what is achievable with optimal farm management as simulated by crop growth models (van Ittersum et al., 2013).

Yield gap explaining factors indicated by farmers were largely in agreement with our hypothesis that ware potato yield is constrained by water stress and yield reducing factors. Indeed, farmers specified that water stress and use of irrigation were the most important biophysical and management factors explaining the yield gap on their farm (Fig. 2.9). Yield-limiting factors related to drought stress were acknowledged as yield gap explaining factors for potato production in the Netherlands in other studies as well (Mulders et al., 2021; Silva et al., 2020). The questionnaire revealed that disease management and (poor) soil structure were other important yield gap explaining factors at farm level as also found by Silva et al. (2017). In addition to earlier findings, our analyses revealed that farmers consider legislation and potato prices important socio-economic constraints to potato production on their farms. Contrary to our hypothesis, farmers considered fertilisation among the most important yield gap explaining factors at farm level. Roughly 70% of the farmers indicated that potato yield could be increased if they were allowed to apply higher rates of N and P fertilisers (Fig. 2.10). Yet, in earlier studies the relationships between fertiliser application and yield in farmers' fields were weak or absent (Silva et al., 2021; Mulders et al., 2021; Silva et al., 2017). These studies thus indicate that empirical data do not confirm farmers' perception that nutrients are limiting potato yield in the Netherlands.

2.5 Conclusion

In this study we quantified potato yield variability in the Netherlands across four agronomically relevant spatial scales. We showed that spatial yield variability was largest among fields, with a standard deviation of 8.5 – 11.1 t ha^{-1}, and within fields, with a standard deviation of 7.7 – 8.7 t ha^{-1}. Spatial yield variability decreased at higher aggregation levels, i.e., the standard deviation of among-farm yield variability was 4.0 – 6.1 t ha^{-1} and that of among-provinces 1.6 – 3.5 t ha^{-1}. Mean yields of the datasets ranged from 46 to 52 t ha^{-1}. Temporal (year-to-year) variability was another important constituent of yield variability, explaining between 10 and 55% of the total observed variation in crop yield. Moreover, temporal yield variability was equal or larger than spatial yield variability. We conclude that reducing yield variability can best be addressed at field and within-field level, which requires site-specific crop management practices attuned to local field conditions. However, when reducing yield variability is not feasible or desirable, inputs should be tailored to realistic target yield levels under field conditions to increase resource use efficiency and farm profitability.

We also assessed farmers' perceptions about the magnitude and causes of potato yield gaps at farm level. Depending on the soil type and variety, farmers estimated the ware potato yield gap at 13 – 18 t ha^{-1}, corresponding to 20 – 24% of the estimated potential yield. Water deficit, water excess, heat, diseases, and soil structure were indicated as the most important biophysical factors explaining the yield gap. Irrigation and fertilisation were indicated as the most important management factors and legislation and potato prices were identified as the most important socio-economic factors. Farmers' perceptions were not always confirmed by empirical data, which shows that there is a need to better understand the socio-economic context of the farmer.

2.6 Acknowledgements

One dataset originated from the Dutch FADN system and was collected and managed by Wageningen Economic Research. We acknowledge Ir. Ruud van der Meer (Wageningen Economic Research) for organizing and sharing the FADN data used in this study. Results shown are and remain entirely the responsibility of the authors; neither they represent Wageningen Economic Research / CEI (Centre of Economic Information) views nor constitute official statistics. We are grateful to all farmers who responded to our questionnaire and to the potato processing companies who shared their yield data. We acknowledge the farms 'Scholtenszathe' and 'Van Den Borne Aardappelen' for allowing us to use their data and supporting us in organising the data. This research was part of the project Potato Gap NL (project number 16891) of the research programme Holland Innovative Potato which was (partly) financed by the Dutch Research Council (NWO).

Chapter 3: Field monitoring coupled with crop growth modelling allows for a detailed yield gap assessment at field level: a case study on ware potato production in the Netherlands

This chapter has been accepted for publication in Field Crops Research as:

Ravensbergen, A. P. P., van Ittersum, M. K., Kempenaar, C., Ramsebner, N., de Wit, D. & Reidsma, P. Coupling field monitoring with crop growth modelling provides detailed insights on yield gaps at field level: a case study on ware potato production in the Netherlands.

Abstract

Yield gap analyses are useful to assess and benchmark the productivity of cropping systems. Often such analyses are performed at higher aggregation levels and these lack the details to explain yield gaps at field level and hence make it difficult to translate findings into precise recommendations to farmers and extensionists. This study provides a detailed approach for yield gap assessments at field level through frequent field monitoring in farmers' fields coupled with crop growth modelling. We used ware potato production in the Netherlands as a case study to study yield gaps at field level, as average productivity is high, whilst yields are still highly variable among fields, and as ware potato is an important cash crop for farmers. Over two growing seasons, 96 ware potato fields were monitored throughout the growing season on a biweekly basis, taking measurements on soil, crop growth and yield. The crop growth model SWAP-WOFOST was used to simulate potential (Yp) and water-limited potential yields (Yw). Various statistical methods were used to quantify yield gap explaining factors. The average yield gap ranged from 20 to 31% depending on the year and soil type. Among fields, the yield gap ranged from 0 to 51%. On clayey soils, the yield gap was mostly attributed to oxygen stress. On sandy soils, the yield gap was mostly determined by drought stress in 2020, a relatively dry year, and by reducing factors (pests, diseases and poor agronomic practices) in 2021, an average year in terms of precipitation. The type of reducing factors differed per field. Furthermore, earlier planting and later harvesting can increase yields, as Yp was limited by radiation. Overall, there is limited scope to narrow the yield gap as current ware potato production is already close to 80% of the potential yield, which is assumed to be approximately the maximum farmers can attain. However, yield and resource use efficiency gains are to be made for individual fields. Furthermore, we conclude that frequent field monitoring coupled with crop growth modelling is a powerful way to assess yield gap variability and to get detailed insight in the yield gap explaining factors at field level.

Keywords

Solanum tuberosum | yield variability | yield response | farm management |on-farm experiments

3.1 Introduction

The productivity per unit area of a cropping system can be assessed using yield gap analyses. Yield gaps are referred to as the difference between potential or water-limited potential yield and actual farmers' yield (van Ittersum et al., 2013; van Ittersum and Rabbinge, 1997). Potential yield is defined by radiation, CO_2 concentration, temperature, and cultivar characteristics. Water-limited potential yield is defined by the same factors but also accounts for yield limitation due to drought or water excess. Actual yield levels are further limited by nutrients and/or reduced by the impact of pests and diseases or other yield reducing factors. Next to an assessment of productivity levels, yield gap analyses are used to assess which factors explain yield gaps (Beza et al., 2017). In addition, yield gap analyses can be coupled with resource use efficiency assessments to improve ecological sustainability of cropping systems (Getnet et al., 2016; Rong et al., 2021; Tittonell et al., 2008).

Yield gaps have been estimated for various crops in different environments (Caldiz and Struik, 1999; Dadrasi et al., 2022; Espe et al., 2016; Gobbett et al., 2017; Rattalino Edreira et al., 2017; van Loon et al., 2019; Wang et al., 2018). In these yield gap assessments, actual yield levels are usually based on national or regional statistics data (Dadrasi et al., 2022; Espe et al., 2016; Gobbett et al., 2017; Wang et al., 2018) or farmer reported survey data (Caldiz and Struik, 1999; Rattalino Edreira et al., 2017). This provides useful information on yield and yield gap levels in different contexts. However, these levels are often determined at higher aggregation levels or could contain inaccuracies as they are based on farmer reported data (Fraval et al., 2019). Moreover, data is mostly collected after the growing season, making it impossible to ground truth measurements on yield and yield gap explaining factors. As such, yield gap analyses often lack detailed information to explain yield gaps at field level, which could be used by farmers and extensionists to adjust management.

Detailed explanations of yield gaps at field level are important for highly productive cropping systems with large field-to-field variability. While a high average yield in such systems suggests limited scope for improving yield at regional level, yield and/or resource use efficiency gains can still be made for particular fields. An example of a highly productive cropping system with large field-to-field variability is ware potato production in the Netherlands. For this system, actual yields were reported to be 70 – 75% of potential yield (Silva et al., 2020, 2017), which is close to the exploitable yield (which is assumed to be approximately 80% of potential yield considering economic and environmental efficiency (Grassini et al., 2011; van Ittersum et al., 2013)) and suggests limited options for yield improvements. Simultaneously, large yield variability was reported among farms (Silva et al., 2017) and fields (Mulders et al., 2021a; Chapter 2), resulting in relatively low productivity in some fields, as well as low resource use efficiency when such low yielding fields are cultivated with similar input levels (Silva et al., 2021). Improving productivity and resource use efficiency of these relatively poorly performing fields thus requires proper understanding of the yield gap variability and the associated yield gap explaining factors at field level.

Analyses on yield and yield gap variability have been performed for ware potato production in the Netherlands (Mulders et al., 2021a; Silva et al., 2021, 2020a, 2017a; Vonk et al., 2020; Chapter 2), and have provided useful insights in the yield gap explaining factors for ware potato production in the Netherlands. However, these studies were performed for a single farm only (Mulders et al., 2021), for single production parameters as fertiliser application rates or soil organic matter content (Vonk et al., 2020), at farm level neglecting the variation that exists within a farm (Silva et al., 2017) or using farmer reported data which contain uncertainties as to data accuracy (Silva et al., 2021, 2020). In addition, data was collected after the growing season, limiting the possibility of ground truthing observations, especially in relation to the effect of yield reducing factors. Hence, these studies lack detailed information to assess yield gap variability at field level across a wide range of farms and fields.

In this study, we provide a detailed approach for estimating yield gaps at field level. We estimated yield levels and yield gaps by coupling frequent field monitoring and detailed crop growth modelling of potential and water-limited potential yield. We used various statistical methods and field observations to quantify and describe the effect of yield gap explaining factors on the yield gap at field level in a high input cropping system. We used ware potato production in the Netherlands as a case study as productivity is high, whilst yields are still highly variable among fields, and as ware potato is an important cash crop for farmers (Goffart et al., 2022).

3.2 Conceptual framework

3.2.1 Yield levels

Potential yield represents the yield that can be obtained under optimal growing conditions in which the crop is not limited by water stress or nutrients, pests and diseases are effectively controlled, and poor agronomic practices do not limit yield in another way (van Ittersum et al., 2013; van Ittersum and Rabbinge, 1997) (Fig. 3.1). In this study we define two different potential yield levels: maximum and field-specific potential yields. Maximum potential yield (Yp_{max}) is the potential yield given optimal planting and harvesting dates (planting as early and harvesting as late in the growing season as possible because of temperatures and accessibility to the field), which results in maximum radiation interception throughout the growing season. At farm level, limited availability of machinery and/or labour prevents farmers from planting all crops and fields on the optimal planting dates. We therefore consider the field-specific potential yield (Yp_{fs}) as the potential yield given field-specific planting and harvesting dates. Yp_{max} and Yp_{fs} are always indicated in tonnes dry matter ha^{-1}.

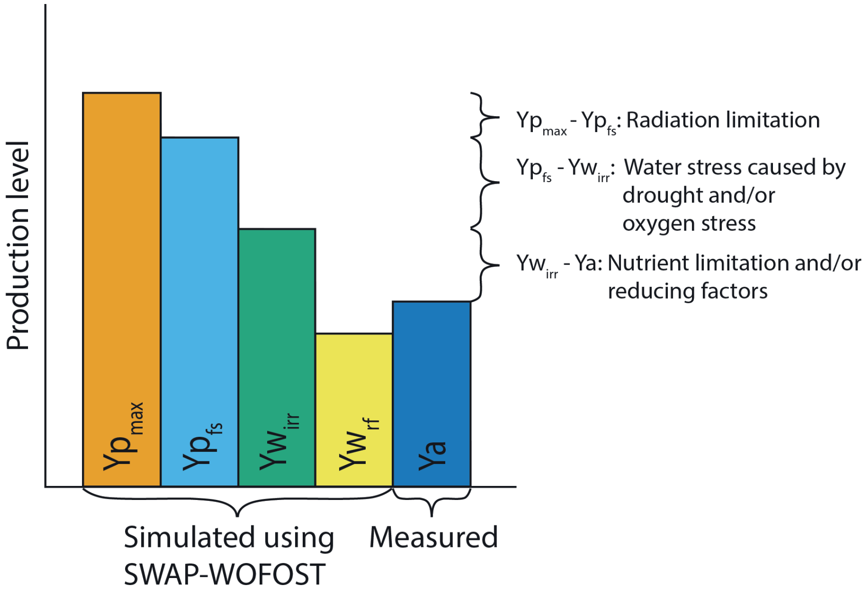


Figure 3.1. Conceptual framework for visualising yield levels and associated yield gaps. Production level refers to the yield in t ha^{-1}. Yp_{max} is the maximum potential yield with earliest possible planting and latest possible harvesting dates. Yp_{fs} is the potential yield based on farmers' planting and harvesting dates. Yw_{irr} is the water-limited potential yield considering irrigation applied by the farmer. Yw_{rf} is the water-limited potential yield under rainfed conditions. Ya is the actual yield. Yp_{max}, Yp_{fs}, Yw_{irr} and Yw_{rf} are simulated using SWAP-WOFOST (see Section 3.3.3), Ya is measured in the field (see Section 3.3.2).

Water-limited potential yield is determined by water stress caused by drought stress due to insufficient rainfall or irrigation or oxygen stress as a result of excess water (van Ittersum and Rabbinge, 1997) (Fig. 3.1). Commonly, this yield level is calculated as the maximum yield that can be obtained when a crop is cultivated under rainfed conditions (without receiving irrigation). The Dutch potato farming system is a partially irrigated system. Therefore, two distinct levels of water-limited potential yield are defined. Water-limited potential yield under partially irrigated conditions (Yw_{irr}) represents the yield that can be obtained with the actual irrigation applied by the farmer and can be calculated as it is known for each field how much irrigation is applied (see Section 3.3.2). Yw_{irr} is equal to Yp when farmers apply full irrigation completely avoiding water stress. Likewise, Yw_{irr} is lower than Yp when farmers apply partial irrigation. Water-limited potential yield under rainfed conditions (Yw_{rf}) represents the yield that can be attained if no irrigation is applied. Yw_{irr} and Yw_{rf} are always indicated in t dry matter ha^{-1}

Actual yield (Ya) is the yield that is obtained in farmers' fields. Ya is lower than Yp and Yw_{irr} when a lack of nutrients limits optimal growth or when weeds, pests and diseases or poor agronomic practices reduce yields. Ya can be higher than Yw_{rf} if farmers apply irrigation. Actual yields are both expressed in t dry matter ha^{-1} (Ya_{DM}) and in t fresh matter ha^{-1} (Ya_{FM}).

3.2.2 Yield gap levels

Different yield gap levels are considered in this study (Fig. 3.1). The (Yp_{max} – Yp_{fs}) yield gap is explained by radiation limitation and indicates the extra yield that can potentially be gained if the crop is planted earlier or harvested later, which is determined by temperature and accessibility to the field. At farm level it is not always possible to close this gap because of limited availability of machinery and/or labour around critical moments. The (Yp_{fs} – Yw_{irr}) yield gap is explained by water limitation as a result of drought and/or oxygen stress. This gap represents the extra yield that can be obtained if farmers apply an optimal irrigation and drainage strategy, compared to their current practice. An important condition for closing the (Yp_{fs} – Yw_{irr}) gap is that the crop is not limited by nutrient availability and that pests and diseases are effectively controlled. The (Yw_{irr} – Ya) yield gap is explained by nutrient limitation and/or yield reduction by pests and diseases. The (Yp_{fs} – Ya) yield gap is used to assess the yield gap at field level that is determined by the combined effect of drought and/or oxygen stress, nutrient limitation and reducing factors. The (Yp_{max} – Ya) yield gap is used to determine the maximum potential yield gain, compared to Ya, if also planting and harvesting dates were changed.

3.3 Materials and Methods

3.3.1 Study area

We collected data from 96 different commercial ware potato fields in 2020 and 2021 (Fig. 3.2). Fields were selected in six different important potato growing regions in the Netherlands: Tholen/West-Brabant (1), Zuid-Holland (2), Flevoland (3), Noord-Brabant (4), Limburg (5) and Drenthe (6). Soils in the first three regions are characterised as clayey soils and in the latter three regions as sandy soils. In the regions with clayey soils, we selected fields with the variety Innovator and in regions with sandy soils, we selected fields with the variety Fontane. These varieties were chosen as they are among the main cultivated varieties on the respective soil types. We selected eight potato fields per region per year to get an equal number of the sampled fields. Hence, we collected data from a total of 48 fields for each soil type and for each year. Further on in this manuscript fields from 2020 are labelled with 2 digits and fields from 2021 are labelled with 3 digits.

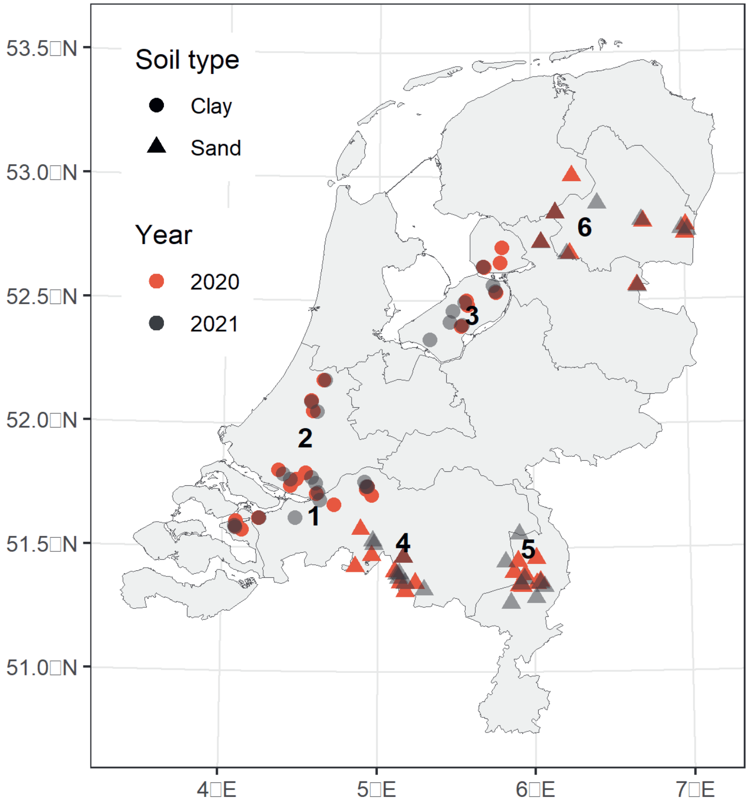


Figure 3.2. Map of the Netherlands with field locations. Different colours indicate different years. Different symbols indicate different soil types. Different numbers indicate different potato growing regions in the Netherlands.

Farmers and fields for this study were selected in several ways. In 2020, farmers were selected based on established contacts from earlier research, via contacts from the potato processing industry and via the network of participating farmers. Most farmers who participated in 2020 also participated in 2021. However, some farmers dropped out as they were growing different cultivars in 2021. Newly participating farmers were selected from the respondents lists of the survey employed in Chapter 2. Over the two years, in total 55 different farmers participated in this research. From each farmer, 1 to 2 fields per year were selected. Overall, the selected fields represented a broad range in soil conditions and nutrient management (Table 3.1).

The years 2020 and 2021 were distinct in terms of weather conditions. The first year could be characterised as dry to average in terms of rainfall, with cumulative precipitation over the growing season ranging from 153 to 387 mm (long-term average 416 mm) (Fig. 3.3A)

Table 3.1. Soil properties and fertiliser application rates of the 96 fields (2020 and 2021). Indicated for each variable are the mean, standard deviation, minimum value, and maximum value. See Section 3.3.2 for more details on the measurements and calculations.

		2020				2021			
Variable	Soil type	Mean	SD	Min	Max	Mean	SD	Min	Max
SOM (%)	Clay	3.9	1.4	2.4	8.2	4.1	0.7	2.7	5.4
	Sand	5.0	2.2	2.5	9.5	4.9	3	2.7	17.4
pH (-)	Clay	7.6	0.2	7.3	7.9	7.5	0.2	6.7	7.7
	Sand	5.5	0.4	4.7	6.2	5.3	0.5	4.2	6.1
Plant available N (mg kg^{-1})	Clay	116	60	12	238	91	46	14.5	167
	Sand	60	50	16	202	60	53	11.4	227
Plant available P (mg kg^{-1})	Clay	2.1	2.1	0.3	6.9	1.6	1.2	0.5	4.9
	Sand	5.8	3.9	0.6	15.2	5.8	5.1	0.3	16.4
Plant available K (mg kg^{-1})	Clay	132	94	39	459	157	71	82	305
	Sand	95	62	27	265	133	72	37	341
Total N (g kg^{-1})	Clay	1.8	0.7	1.0	3.7	1.8	0.4	1.0	2.6
	Sand	1.6	0.5	0.8	2.7	1.6	0.7	1.0	4.1
Total P (g kg^{-1})	Clay	0.9	0.1	0.7	1.2	0.9	0.1	0.8	1.2
	Sand	0.7	0.2	0.3	1.3	0.9	0.3	0.4	1.5
N applied (kg ha^{-1})*	Clay	429	146	248	956	420	129	250	696
	Sand	287	62	123	379	299	72	136	503
Effective N applied (kg ha^{-1})*	Clay	347	74	248	545	337	66	234	450
	Sand	222	52	88	304	226	47	98	334
P applied (kg ha^{-1})	Clay	55	32	0	154	58	35	0	133
	Sand	28	14	12	66	33	17	9	85
K applied (kg ha^{-1})	Clay	340	165	131	720	332	140	124	643
	Sand	280	87	49	431	277	103	41	552

* *N applied is calculated as the total N applied between the harvest of the previous crop and the harvest of the potatoes. Effective N applied is calculated over the same period, but then the nitrogen fertiliser replacement values of the organic manures are taken into account (Section 3.3.2).*

(KNMI, 2022a). The second year of the study could be characterised as an average year, with cumulative precipitation over the growing season ranging from 317 to 461 mm. The cumulative precipitation deficit was on average 200 mm in 2020 and 70 mm in 2021 (KNMI, 2022b). Cumulative global radiation was 15% higher in 2020 and 3% higher in 2021 than the long-term average (Fig. 3.3B). Lastly, temperatures in 2020 were different from those in 2021. In 2020, the summer was relatively hot with a heat wave in August, while in 2021 spring was relatively cold (Fig. 3.3C).

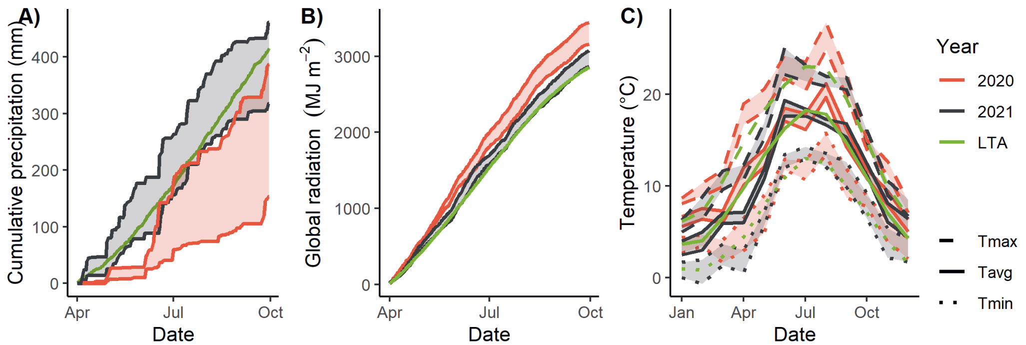


Figure 3.3. Cumulative precipitation (in mm) (A), cumulative global radiation (in MJ m^{-2}) (B), and temperature (in °C) (C) over time. Different colours indicate different years. Shaded areas present the range of observed values across the six regions. LTA = long-term average (period 1991 – 2021).

In each field, we selected a small measurement area to minimise the effect of within-field variability. The selected measurement area was always located in a part of the field where limited effect of other factors was expected. For instance, the measurement area was never in the headlands where heavier soil compaction is expected due to machine traffic. Nor was it located directly adjacent to a neighbouring field to prevent irrigation from the neighbouring field influencing potato growth in the measurement area. The selected measurement area was divided into four plots which served as measurement replicates. In 2020 the size of each plot was 7 m long and 6 m (8 ridges) wide. In 2021 the size of each plot was 7 m long and 9 m wide (12 ridges). Fields within one region were sampled within one day (or two days when conditions were very wet) and fields within the same soil type were always sampled within five subsequent days.

3.3.2 Data collection

Soil measurements

In each field, one composite soil sample was taken from the plots at the beginning of the growing season. Soil organic matter (SOM) was measured using the loss on ignition method by placing the sample in a furnace at 550 °C for 3 hours. SOM was corrected for clay content using Hoogsteen et al. (2015), where clay content was provided by the farmer or taken from a soil map. Soil pH was measured in water in a 1:2.5 soil:water ratio. Plant available N and P were measured spectrophotometrically with a Skalar san++ system from a 0.01 M $CaCl_2$ extraction (Houba et al., 2000). Total N and P were measured in the same way after a digestion with a mixture of H_2SO_4–Se and salicylic acid. Plant available K was measured with a Varian AA240FS fast sequential atomic absorption spectrometer from the same extracts. All soil samples were analysed by an external laboratory. Soil penetration resistance was measured using a penetrologger (Royal Eijkelkamp, 2022) at the beginning of the growing season when it could be assumed that the soil moisture content was at field capacity. The measurements were repeated on three locations per plot. Lastly, potato cyst nematode pressure was measured in each field in 2021. From the final harvest area one square meter was intensively sampled for potato cyst nematodes at the start of the growing season. For each sample, the number of living eggs and larvae per gram dry soil was counted. Appendix B.1 provides a full overview of the measurements performed for this study, including the measurements that were not used for analyses.

Crop growth monitoring

Each field was visited at least once every two weeks from planting to harvest, resulting in 10 – 13 field visits per field during the entire growing season. Crop developmental stages were recorded throughout the growing season. Emergence was assumed when 80% of the plants in the middle two ridges of a plot emerged. Tuber initiation was assumed when three out of four plants formed three or more tubers with a diameter of at least 1 cm. Flowering was assumed to take place when 50% of the plants flowered (Appendix B.2 provides an overview of the dates of the different developmental stages). Furthermore, crop health was scored at each visit using a scale from 1 to 5. A score of 5 indicates a healthy crop and a score of 1 indicates a very diseased crop. Scoring was done based on visual inspection. The average crop health score was calculated by averaging all scores of the crop throughout the growing season. Before full canopy closure, the emergence rate was assessed by counting the number of emerged plants per plot.

Yield and yield quality measurements

Yield was measured during and at the end of the growing season. Sampling strategies differed between the two years. In 2020, two intermediate harvests were done in August on a 2 m^2 area to measure gross tuber yield, which is referred to as the total harvested tuber weight. Final yield sampling was done from a 3 m^2 area after haulm killing or natural senescence, or just before harvesting by the farmer in case haulms had not senesced. From each plot of the final harvest, a 6 kg subsample was taken to measure underwater weight. In 2021, throughout the growing season four intermediate harvests were done for Innovator and five intermediate harvests were taken for Fontane from a 2 m^2 area. We measured gross tuber yield at each harvest. A composite tuber sample (from all plots) was analysed for dry matter concentration early in the season and for underwater weight when the weight of the composite sample reached more than 5 kg. Final yield was measured in the same way as in 2020.

Crop management information

Farmers were asked to report their crop management information for each field. Farmers informed us when they applied irrigation and how much they applied per event.

Information was collected on the type, timing and quantity of the applied fertilisers and crop protection products. We processed the information on applied fertilisers to calculate the total applied nitrogen, phosphorus, and potassium. The amounts were calculated as the sum of famer applied nutrients starting from the harvest of the previous crop till the end of the potato growing season and exclude deposition and mineralisation. We calculated effective applied nitrogen in the same way, but used nitrogen fertiliser replacement values from the Dutch government to correct for the readily available nitrogen (RVO, 2018). We further processed the information on crop protection products to calculate the total amount of active ingredients and the Environmental Impact Points of the product application, using the Environmental Yardstick tool (Reus and Leendertse, 2000). It is a tool that combines information on the applied quantity and harmfulness of the applied product to soil and aquatic organisms and ground water. It can be used to calculate the environmental pressure of the applied crop protection products. Farmers reported planting, haulm killing and harvesting dates (Appendix B.2). From two fields the crop management information was incomplete, and these fields were excluded in analyses that required crop management information.

3.3.3 Using SWAP-WOFOST to estimate different yield levels and water stress

The model SWAP-WOFOST was used to estimate Yp_{max}, Yp_{fs}, Yw_{irr}, Yw_{rf} and the respective yield gaps. WOFOST (de Wit et al., 2019) is a process-based crop growth model that has recently been calibrated for the varieties used in this study (ten Den et al., 2022). The model simulates dry matter accumulation of the crop as a function of irradiation, temperature and crop characteristics, with daily time steps (de Wit et al., 2020). Soil water availability is simulated using a classical water balance in which it is assumed that soil water can drain freely to deeper groundwater layers.

For more detailed simulations of soil water availability in the rooted zone, WOFOST can also be coupled with the soil hydrological model SWAP (Kroes et al., 2017). In SWAP, the soil profile can be divided into multiple compartments with different soil characteristics for each compartment. Furthermore, SWAP can deal with interactions between available water in the rooted zone and the groundwater level. Using SWAP, it is possible to simulate not only the effect of drought stress on crop growth, but also the effect of oxygen stress.

SWAP-WOFOST was run with two different assumptions on the interaction between water in the rooting zone and the groundwater level. In the first run, we assumed no interaction between the two. In this case, water in the rooting zone was assumed to drain freely to deeper groundwater layers below the rooting zone. In the second run, we assumed that there was an interaction between water in the rooting zone and the groundwater level via capillary rise. We used the free drainage situation for yield gap calculations and statistical analyses in the sandy soils, as groundwater levels in these soils are relatively deep during the growing season. We used the interaction situation for yield gap calculations and statistical analyses in the clayey soils, as groundwater levels in these soils are relatively shallow during the growing season. In both runs, drought stress was simulated using Feddes (1982) and oxygen stress using Bartholomeus et al. (2008).

Field-specific values needed to run SWAP-WOFOST were assigned based on our measurements or publicly available data. The nearest KNMI-weather station data was used for the weather data. However, rainfall data was replaced with farmer's rainfall measurements in case a farmer owned a weather station. Rooting depth was estimated as the average depth at which the measured soil penetration resistance was larger than 2 MPa, with a maximum rooting depth of 50 cm (Silva et al., 2020). Soil type and profile were taken from the BOFEK soil map (Heinen et al., 2022). Crop management information (planting, irrigation, haulm killing) was taken from the crop management information provided by the farmer. The groundwater levels were collected from the 'Landelijk Hydrologisch Model' (NHI, 2023).

SWAP-WOFOST was used to simulate different yield levels and estimate water stress. Yp_{max} was modelled assuming planting on April 1 and haulm killing on September 21 on clayey soils and on September 30 on sandy soils and correspond approximately to the 5th percentile for planting date and the 95th percentile for harvesting date of the studied fields. In practice, planting date is determined by temperatures and accessibility to the field. Harvesting date is determined by an anticipation on trafficability of the field in autumn. Only if the farmer planted earlier or harvested later than these dates, the farmer's planting or harvesting dates were used. Yp_{fs}, Yw_{irr} and Yw_{rf} were modelled with field specific planting and harvesting dates. Total water stress was estimated as the difference between potential transpiration and actual transpiration and expressed in mm water per growing season. The reduction in transpiration that was attributed to insufficient water availability is referred to as drought stress and the reduction in transpiration as a result of excess water is referred to as oxygen stress.

3.3.4 Statistical analysis

ANOVA was used to test for significant yield differences between years and soil types, where Tukey HSD was used a post-hoc test.

Various statistical methods were used to explain yield and yield gap variability among the studied fields. First, a comparison was made between the best and worst performing fields in terms of Ya_{DM}, Ya_{FM}, the (Yp_{fs} – Ya) yield gap or the (Yw_{irr} – Ya) yield gap. This was done per soil type and variety and for both years together and separately. Groups were made with the highest yielding fields (or fields with smallest yield gap) and lowest yielding fields (or fields with largest yield gap) and consisted of 12 fields when the analyses were done for both years together and of 6 fields when done for a single year. Following, we assessed whether there was a significant difference between the two groups for each of the measured yield gap explaining factors. A student t-test was used for normally distributed data and a Mann-Whitney U test was used for non-normally distributed data. Normality was assessed using a Shapiro-Wilk test.

Linear regression models were used to test for correlations between yield or the yield gap and measured variables. To avoid risk of overfitting, a selection of variables that were to be included in the statistical models had to be made. First, a full model was made using either Ya_{DM}, Ya_{FM}, the (Yp_{fs} – Ya) yield gap or the (Yw_{irr} – Ya) yield gap as a dependent variable and all measured variables as explanatory variables. Then, we used the dredge function from the MuMIn package (Barton and Barton, 2015) to run all possible combinations of reduced models, using R version 4.2.2. We added a restriction to the function that only one to a maximum of four explanatory variables could be included in the reduced linear models. Furthermore, we excluded all combinations of variables that were correlated to each other (Pearson correlation test > 0.5). After running all models, the top-ranking models were selected based on the AICc criterium, where all models with ΔAICc < 3 were considered to be top-ranking models. Finally, a model was built with all explanatory variables that were included in one or more of the top-ranking linear models. However, if explanatory variables were correlated to each other, we included only the variable that was used in the majority of the top-ranking models. If explanatory variables were correlated to each other and were used in an equal share of top-ranking models, multiple models were built and the model with the lowest AICc was chosen as the final statistical model. This analysis was performed for only the fields on sandy soils (cv. Fontane), only the fields on clayey soils (cv. Innovator), or all fields together. For the latter group, we included variety as an explanatory variable in all linear models and the maximum number of explanatory variables to be included in the reduced models was changed from four to five.

To further understand the relationships between yield or yield gap and the measured variables, yield or yield gap was plotted against each of the measured variables that had a significant effect on the yield or yield gap in one of the earlier performed statistical analyses. Following, quantile or linear regression was used to test if there was a significant correlation.

3.4 Results

3.4.1 Actual yield

For Innovator on clayey soils, final gross yield averaged 63 t ha^{-1} and ranged from 48 to 77 t ha^{-1} in 2020 and averaged 54 t ha^{-1} and ranged from 34 to 61 t ha^{-1} in 2021 (Fig. 3.4). Already early during the growing season large significant yield differences were observed between the two years, i.e., a 16 t ha^{-1} yield difference between the average yields in week 31 and a 14 t ha^{-1} yield difference between the average yields in week 33. For Fontane on sandy soils, the average final yield was similar for both years with 62 t ha^{-1} in 2020 and 64 t ha^{-1} in 2021. However, a difference in yield range was observed at the end of the growing season. In 2020, the final yield ranged between 40 and 83 t ha^{-1}, and in 2021 between 53 to 81 t ha^{-1}. Earlier on during the growing season, the yield difference between the means of the two years was 6 t ha^{-1} in week 32 and 2 t ha^{-1} in week 34, both differences were significant in favour of 2020.

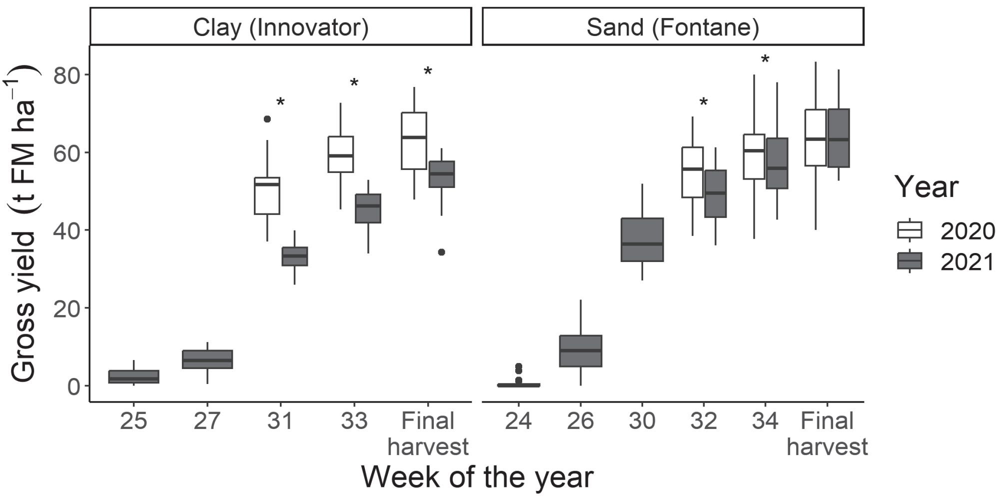


Figure 3.4. Gross yield (in t fresh matter ha^{-1}) over time for two different soil types (with respective varieties) and in two years. Final harvest refers to the final harvest of the growing season and depended on the ripening stage of the crop. A * indicates significant differences between the two years using ANOVA ($p < 0.05$).

3.4.2 Potential and water-limited potential yields as compared to actual yields

Simulated results for Innovator cultivated on clayey soils in 2020 showed that Ya_{DM} was below or similar to Yp_{fs} in all fields (Fig. 3.5). Furthermore, for most of the Innovator fields Ya_{DM} was around the same level as Yw_{irr}. However, for a few fields (46 – 48, 65 – 68) Ya_{DM} was higher than simulated Yw_{irr}. Irrigation resulted only in a few fields with Innovator in higher water-limited potential yields compared to rainfed conditions (Yw_{irr} > Yw_{rf}), but resulted in lower water-limited potential yields (which SWAP-WOFOST attributed to oxygen stress) in other fields (Yw_{irr} < Yw_{rf}). Simulated results for Fontane on sandy soils in 2020 showed that in almost all fields Ya_{DM} remained below or at Yp_{fs}. Only in one field Ya_{DM} was slightly higher than the Yp_{fs}. Irrigation resulted in higher water-limited potential yields in most fields compared to rainfed conditions (Yw_{irr} > Yw_{rf}). Yw_{irr} simulations using SWAP-WOFOST were at the same level or higher than Ya_{DM}.

Simulated results of 2021 show a similar model performance compared to the results of 2020. For Innovator on clayey soils, Yp_{fs} was higher than the Ya in all fields (Fig. 3.6). Furthermore, Ya measurements were in a fair agreement with Yw_{irr}. Only in a few fields, Yw_{irr} was slightly lower compared to Ya. For Fontane in 2021, Ya of most fields remained at or below Yp_{fs} and Yw_{irr}. Furthermore, only in a few fields mild water limitation was observed (Yw_{irr} < Yp_{fs}).

Average Ya_{DM} was 12.7 t ha^{-1} for Innovator in 2020 and 11.3 t ha^{-1} in 2021 (Fig. 3.7). In 2020, average Yw_{irr} and Yw_{rf} were similar to the average Ya_{DM}, whereas in 2021 average Yw_{irr} was 1.2 t ha^{-1} higher than average Ya_{DM} and average Yw_{rf} was 1.4 t ha^{-1} higher. Yp_{fs} was similar for both years (around 16.5 t ha^{-1} on average). Extending the growing season resulted in average Yp_{max} levels which were 1.0 t ha^{-1} higher than Yp_{fs} in 2020 and 0.6 t ha^{-1} higher than Yp_{fs} in 2021.

For Fontane, Ya_{DM} was 12.9 t ha^{-1} in 2020 and 13.9 t ha^{-1} in 2021. Yw_{rf} was on average 10.8 t ha^{-1} in 2020 and 16.7 t ha^{-1} in 2021. Applying irrigation increased Yw_{irr}, on average, by 3.2 t ha^{-1} in 2020 and by 0.2 t ha^{-1} in 2021 compared to Yw_{rf}. Yp_{fs} was 17.7 t ha^{-1} in 2020, whereas it was 17.3 t ha^{-1} in 2021. Extending the growing season resulted in average Yp_{max} levels which were 2.0 t ha^{-1} higher than Yp_{fs} in 2020 and 1.6 t ha^{-1} higher than Yp_{fs} in 2021.

3.4.3 Yield gap components

The average total (Yp_{fs} – Ya) yield gap, was 3.8 t DM ha^{-1} for Innovator in 2020 (23% of Yp_{fs}, range 1 – 43%), 5.0 t DM ha^{-1} for Innovator in 2021 (31% of Yp_{fs}, range 19 – 53%), 4.8 t DM ha^{-1} for Fontane in 2020 (27% of Yp_{fs}, range 0 – 47%) and 3.4 t ha^{-1} for Fontane in 2021 (20% of Yp_{fs}, range 0 – 36%) (Fig. 3.8). For Innovator, yield reduction was largely attributed to oxygen stress in both years. However, there was large variability among fields, i.e., in some fields there was no yield limitation attributed to oxygen stress, whereas in other fields yield was limited by more than 5 t ha^{-1}. Considering that the actual yield development (Ya over time) matched yield development of Yw_{irr} in most fields (Figs. 3.5 and 3.6), yield seemed to be limited by drought and/or oxygen stress and little of the Innovator yield gap seemed to be attributable to nutrient limitation and/or reducing factors. The (Yp_{max} – Yp_{fs}) yield gap was 1.1 t DM ha^{-1} in 2020 and 0.7 t DM ha^{-1} in 2021, suggesting a modest gain from a longer growing season.

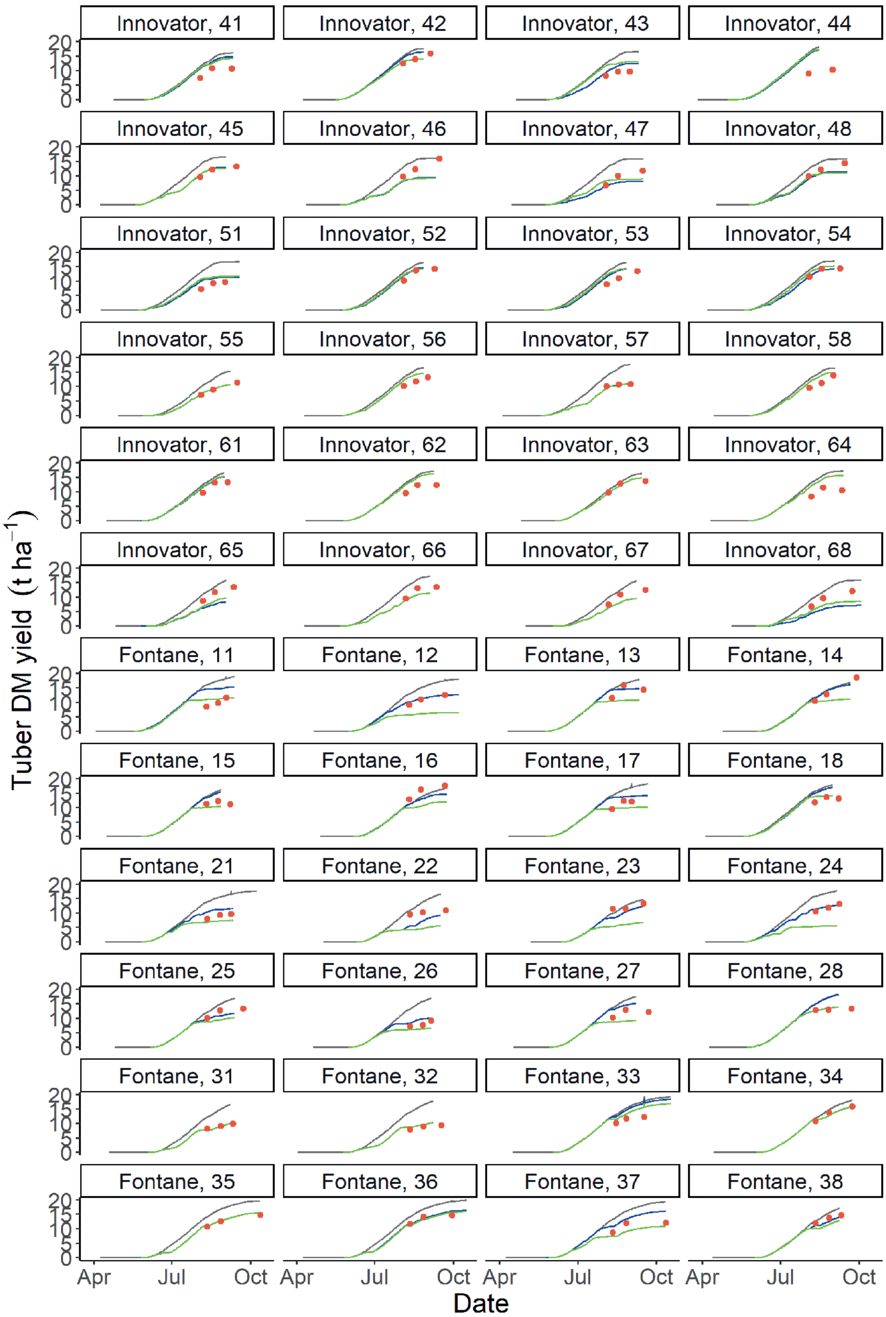


Figure 3.5. Tuber yield (in t DM ha^{-1}) over time for the year 2020. Red dots indicate Ya. Grey lines indicate Yp_{fs}. Blue lines indicate Yw_{irr}. Green lines indicate Yw_{rf}. Innovator was grown on clayey soils; Fontane on sandy soils. Continuous lines indicate simulated values and dots indicate measured values. Numbers in the headers of the plots indicate field numbers.

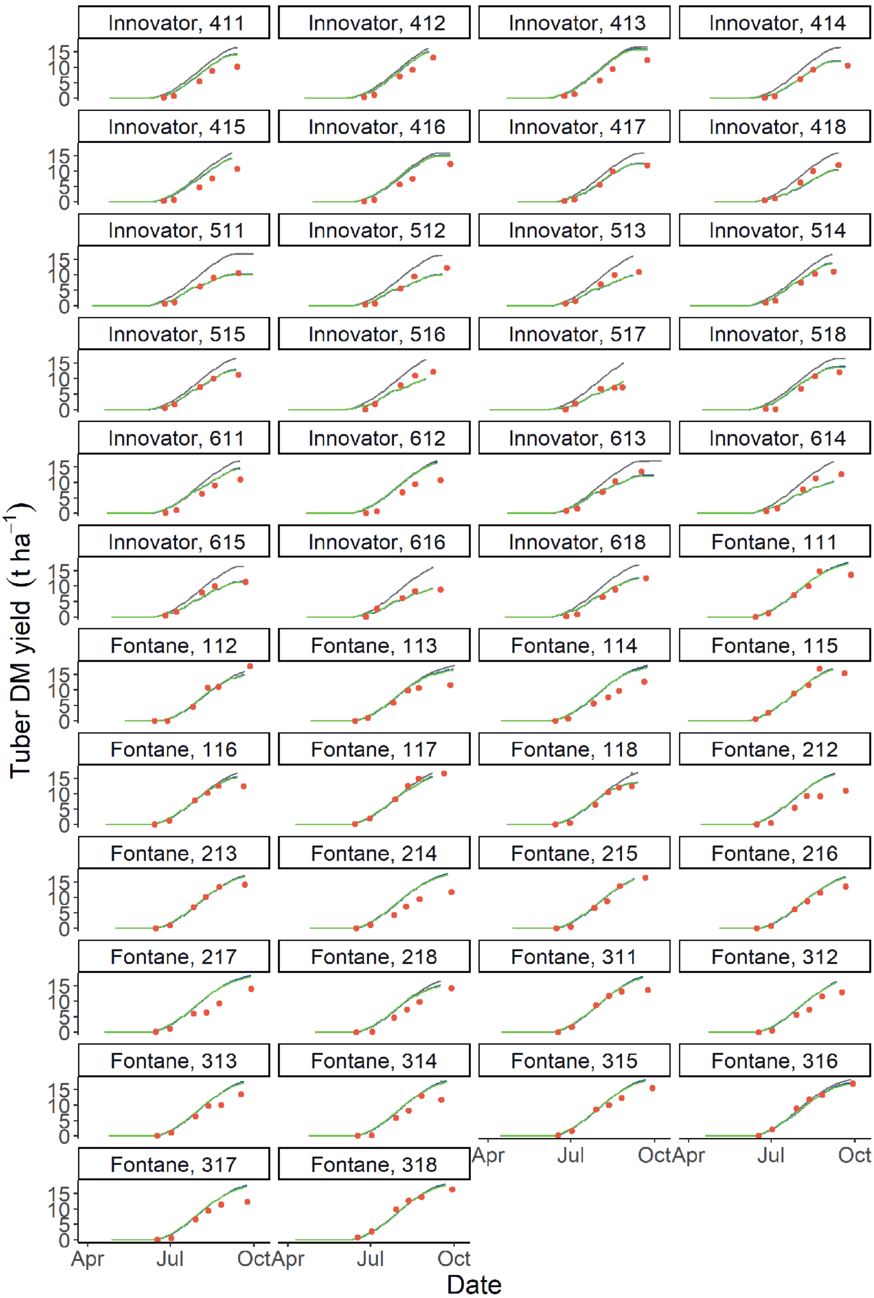


Figure 3.6. Tuber yield (in t DM ha^{-1}) over time for the year 2021. Red dots indicate Ya. Grey lines indicate Yp$_{fs}$. Blue lines indicate Yw$_{irr}$. Green lines indicate Yw$_{rf}$. If lines are not visible they are at the same level. Innovator was grown on clayey soils; Fontane on sandy soils. Continuous lines indicate simulated values and dots indicate measured values. Numbers in the headers of the plots indicate field numbers.

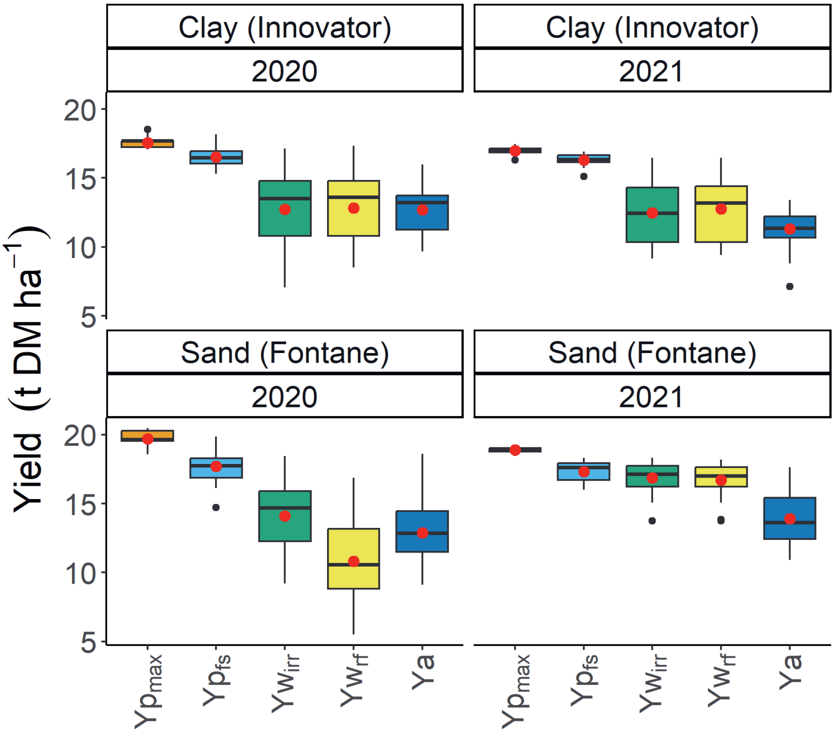


Figure 3.7. Different yield levels (in t DM ha^{-1}) for two different years and soil types (and respective cultivars). Red dots indicate average values. Values of Ya are measured. Other values are modelled.

For Fontane, drought stress limited yields on average by 3.6 t DM ha^{-1} in 2020 and 0.5 t DM ha^{-1} in 2021. Drought stress variability was large among fields, as in some fields no drought stress was simulated whereas in other fields drought stress resulted in a 7 t DM ha^{-1} yield limitation. Nutrient limitation and/or reducing factors were responsible for an additional 1.2 t DM ha^{-1} yield gap in 2020 and an additional 3.0 t DM ha^{-1} yield gap in 2021, with again large variability observed among fields. Planting earlier or harvesting later could have increased potential yield by 2.0 t DM ha^{-1} in 2020 and 1.6 t DM ha^{-1} in 2021.

3.4.4 Explaining yield (gap) variability

A detailed overview of the results from the statistical analysis is provided in Appendix B.3. Here, only a summary with the main findings is provided. Statistical analysis showed that for both Innovator on clayey soils and Fontane on sandy soils, water stress caused lower yields and larger yield gaps. On clayey soils, water stress was caused by excess water, whereas on sandy soils water stress was caused by drought. Crop health score and emergence rate were found to correlate to both the yield and yield gap, where a higher

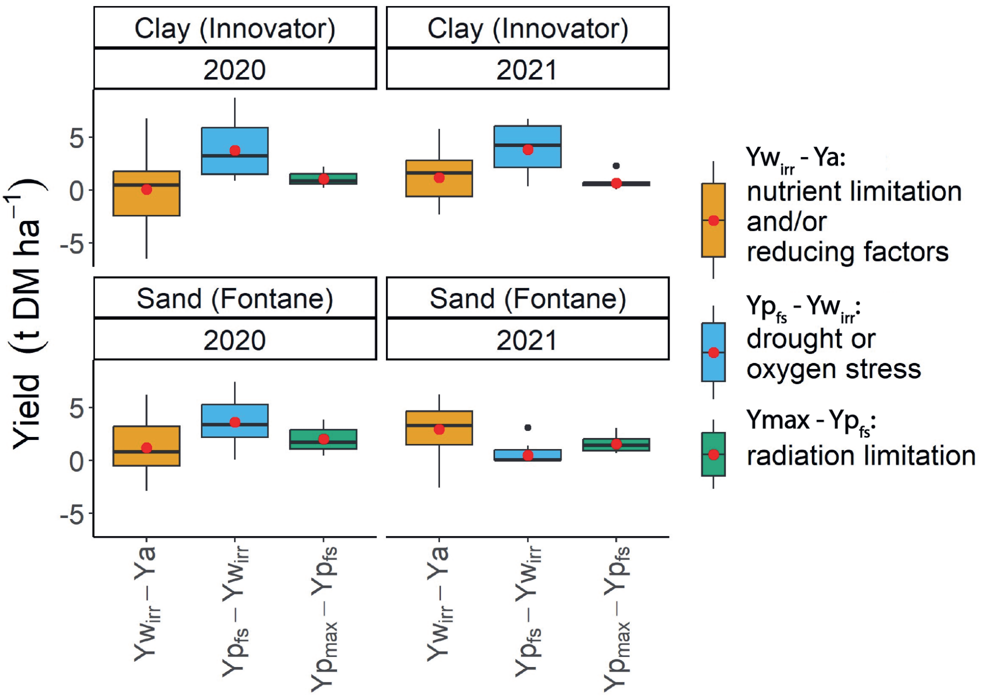


Figure 3.8. Yield gap components (in t DM ha^{-1}) for two different years and soil types (and respective cultivars). Different coloured boxplots indicate different yield gap levels. Red dots indicate average values.

crop health score and emergence rate were related to a higher yield or lower yield gap. Furthermore, for Innovator on clayey soils a positive relationship was found between the use of active ingredients and environmental impact points of crop protection agents and the yield levels. Both for Fontane and Innovator, insignificant or counterintuitive relationships were found between actual yield or the yield gap and soil properties or fertiliser application rates. From the data it could not be concluded that yield increased or the yield gap decreased with increasing fertilisation rates or soil fertility, suggesting limited effect of soil conditions and fertilisation on actual yield or the yield gap.

3.4.5 Yield gap decomposition and field observations

Considering the (Yp_{max} – Ya) yield gap, 12 – 31% of the yield gap could be explained by a limitation in radiation, which can be attributed to late planting or early harvesting (Fig. 3.9). Drought stress explained, on average, 8 – 18% of the Innovator yield gap and 9 – 52% of the Fontane yield gap. In both years, 59% of the Innovator yield gap and less than 1% of the Fontane yield gap was attributed to oxygen stress. Nutrient limitation and/or reducing factors jointly explained 1% and 21% of the Innovator yield gap in 2020 and 2021, respectively. For Fontane, nutrient limitation and/or reducing factors jointly explained 18% of the yield gap in 2020 and 59% of the yield gap in 2021.

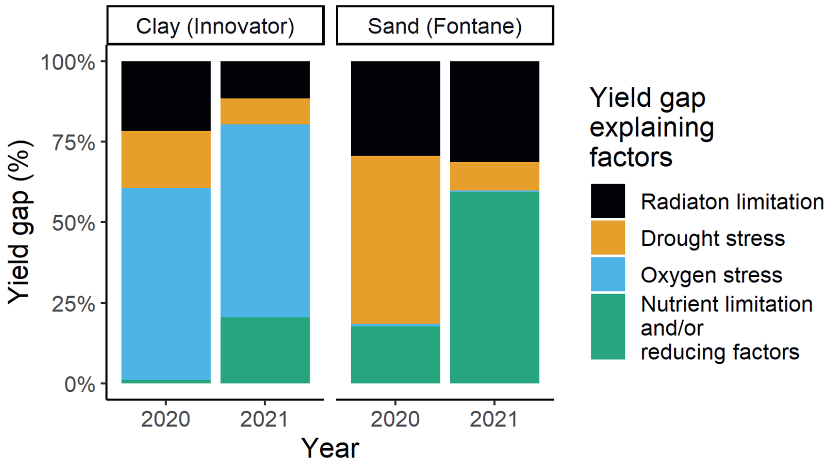


Figure 3.9. Yield gap explaining factors in percentage of the (Yp_{max} – Ya) yield gap. Different colours indicate different yield gap explaining factors.

The reducing factors that explained the yield gap constituted a multitude of factors and varied widely across fields (Table 3.2). For almost all fields with a (Yw_{irr} – Ya) yield gap (Figs. 3.5 and 3.6), logical factors were found to qualitatively explain the remaining yield gap. Diseases were an important component of the reducing factors in most of the fields, but in other fields yield reduction was related to poor agronomic practices such as mal-functioning planting machines or planting cut seeds. In a number of fields, a multitude of yield gap explaining factors reduced yields. In field 113, part of the seed tubers rotted away leading to a lower emergence rate. In the same field, rotting also affected the ware potato tubers at the end of the growing season, resulting in a reduced yield. Furthermore, there was a light late blight infection in this field. In field 212, seed and ware tuber rot were also important reducing factors, caused by a *Pectobacterium* infection. Field 214 suffered from bacterial wilt due to *Pectobacterium*, late blight and early senescence of plants, starting from mid-June. For field 217 we hypothesised that excessive canopy growth slowed down tuber growth, possibly because of overfertilisation with nitrogen on an already rich soil. In addition, there was a late blight infection in this field. In field 415 there was a second flush of tuber initiation in July, which was expected to have slowed down tuber growth in this field. Only for field 15 no logical explanation could be found for the (Yw_{irr} – Ya) yield gap.

Table 3.2. Yield reducing factors and in which fields these occurred. See Appendix B.4 for pictures and more elaborate information on the affected fields.

Yield reducing factor	Field number
Pectobacterium (causing black leg disease or soft rot)	11, 18, 27, 28
Tubers rotten away before emergence, disease unclear	33, 114, 314
Cut seed, irregular emergence	41, 64
Alternaria (causing early blight)	62, 411
Potato cyst nematodes	37*, 317
Fusarium rot	413
Damaged planting machine	612
Senesced sprouts, no emerging stems	311
Tuber rust, possibly because of Ca deficiency	44
Multitude of yield gap explaining factors	113, 212, 214, 217, 415
Unclear	15

** For field 37 potato cyst nematode pressure was not tested, but based on the irregular canopy closure we assumed potato cyst nematodes were the cause of the lower yields.*

3.5 Discussion

3.5.1 Yield gap levels and yield gap explaining factors

This study revealed that by combining frequent field monitoring throughout the growing season combined with crop growth modelling, we were able to provide detailed insight in variability in yield gaps and yield gap explaining factors at field level for ware potato production in the Netherlands. We estimated the average (Yp_{fs} – Ya) yield gap (i.e., potential yield given farmers' planting dates minus actual yield) for the variety Innovator cultivated on clayey soils at 23% of Yp_{fs} in 2020 and 31% in 2021, and for the variety Fontane cultivated on sandy soils at 27% of Yp_{fs} in 2020 and 20% in 2021. At field level the (Yp_{fs} – Ya) yield gap ranged from 1 to 53% for Innovator and from 0 to 47% for Fontane.

A yield gap decomposition analysis showed that the Innovator yield gap could be mostly attributed to oxygen stress in both years, and that the Fontane yield gap was mostly determined by drought stress in 2020 (a relatively dry year) and by reducing factors in 2021 (an average year in terms of precipitation) (Figs. 3.8 and 3.9). Crop growth modelling combined with the statistical analyses were useful to determine the overall effect of reducing and or nutrient limiting factors on the yield gap, but could not be used to identify specific problems at individual fields. Using the field observations throughout the growing season, we could establish that the reducing factors that impacted crop growth were diverse (Table 3.2). A large part of the reducing factors was related to the use of diseased planting material, such as *Pectobacterium* infected tubers. In other fields, there were problems with airborne diseases, such as early and late blight. Poor agronomic practices also caused part of the yield gap in a few fields, where for instance one farmer reported a broken planting machine and other farmers planted cut seed tubers resulting in heterogeneous plant densities. In two fields, yields were reduced by the presence of potato cyst nematodes.

Based on our results, we argue that there is limited scope to narrow the average ware potato yield gap in the Netherlands. Yield gains are only to be made for specific individual fields. At the same time, it is also important to consider resource use efficiency when targeting fields with lower productivity. Our study shows that yield gains can be made through earlier planting, increased irrigation, improved drainage and planting healthy seed material using the same inputs. However, these recommendations are given at field level, while farmers operate at farm level. At farm level it is not always possible to apply optimal or timely management because of limited availability of labour and machinery (Kingwell, 2011; Reidsma et al., 2015), or adverse weather conditions (van Oort et al., 2012). For example, in one specific field in this study, a farmer still had to harvest leeks in April. Therefore, the farmer could not plant earlier than in May. In other fields, farmers were unable to irrigate. In these fields, rather than to increase yield, we would argue to adjust inputs to the expected yield levels based on the biophysical conditions at field level and socio-economic constraints at farm level, with the aim to use resources more efficiently.

3.5.2 Frequent field monitoring compared to big data approaches

In our study, yield (gap) variability was partly attributed to the same yield determining factors as in earlier studies. Previous studies concluded that ware potato yield levels are determined by sowing and harvesting dates (Mulders et al., 2021; Silva et al., 2020), irrigation (Mulders et al., 2021; Silva et al., 2020), variety (Mulders et al., 2021; Silva et al., 2020), fungicide use (Silva et al., 2017) and preceding crops (Mulders et al., 2021). In addition, less clear or contradicting effects were found of soil properties and fertiliser application on yields (Mulders et al., 2021; Silva et al., 2021; Vonk et al., 2020). Our study provided new insights in the potato yield gap variability in the Netherlands. Previous studies did not clearly quantify the yield limiting effect of oxygen stress and yield reducing effects of pest, diseases and poor agronomic practices. Neither did these previous studies show the variability in yield gaps and yield gap explaining factors among fields. Furthermore, the variability explained by (similar types of) regression models was much lower in Silva et al. (2020) (R^2 = 0.34) than in our study (R^2 = 0.39 – 0.65) (Appendix B.3, Table B.4). This shows that our method proved effective for detailed yield gap variability assessments at field level. This contrasts with a big data approach which "*are useful to characterise cropping systems at regional scale and to develop benchmarks for farm performance, but not as much to explain yield variability or make predictions in time and space*" (Silva et al., 2020, p. 11).

While we were not able to quantify the relative contribution of different reducing factors on the yield gap, the qualitative analysis through field observations did provide an overview of the reducing factors at individual fields, and showed that the reducing factors affecting yield were very diverse. This is another benefit compared to other studies where yield gaps were attributed to reducing factors, but where lack of information prevented drawing conclusions as to which pests and diseases or other factors were reducing yields (Deguchi et al., 2016; Silva et al., 2017). When field observations were included, observations were done in only a few fields (Sinton et al., 2022), or excluded important aspects of cultivation, such as water stress (Grados et al., 2020), limiting the applicability to a wider group of farmers.

3.5.3 Methodological considerations

The reported (Yp_{fs} – Ya) yield gap in this study is similar to earlier reported yield gaps of 25 – 30% for ware potato production in the Netherlands (Silva et al., 2020, 2017). However, these earlier analyses reported lower levels of both Yp_{fs} and Ya. The higher simulated potential yields in our study can be attributed to the fact that we used a recently calibrated version of WOFOST (ten Den et al., 2022) to estimate potential yield. Higher observed Ya levels can be explained by different ways of determining Ya. In earlier studies, Ya was assessed at farm level (Silva et al., 2017) or at field level (Silva et al., 2020), which includes non-yielding areas such as spraying tracks and lower yielding areas such as headlands. We measured Ya from a delineated plot, excluding non and lower yielding parts of the field. In addition, manual harvesting prevented loss of small tubers during harvest.

The yield gap analysis in this study is largely based on crop growth model outputs. Model results from the recently calibrated version of WOFOST showed a fair agreement with measured crop growth (Figs. 3.5 and 3.6). However, there were also some uncertainties around the use of SWAP-WOFOST, especially around simulating oxygen stress. In a few clay fields, modelled water-limited potential yield was lower than measured actual yield, which should not be possible according to the yield gap concept. Underestimation seemed to be related to a particular soil type class from the BOFEK soil map (Heinen et al., 2022) in regions 1 and 3 (Fig. 3.2), which we expect to be a result of incorrect soil property classifications for these particular fields. Furthermore, there are other possible reasons for overestimating the effect of oxygen stress. First, groundwater levels were taken from the 'Landelijk Hydrologisch Model' (NHI, 2023). These groundwater levels are simulated levels and have not been validated in the field. Second, rooting depth was estimated using penetrologger measurements. However, the oxygen stress function within SWAP-WOFOST is sensitive to rooting depth (Bartholomeus et al., 2008). Therefore, overestimating rooting depth may have resulted in overestimating oxygen stress. Lastly, oxygen stress is related to water excess, which can be a result of high intensity rainfall events. Such events are erratic and very local. Hence, the employed precipitation from the KNMI weather stations could have overestimated precipitation in farmers' fields and therefore have led to higher simulated oxygen stress levels.

The negative effect of oxygen stress on potato yields in the Netherlands has not been clearly reported earlier. Excessive rainfall was earlier identified as a climate risk (Diogo et al., 2017; Schaap et al., 2011), and it was identified that it can cause a delay in planting and harvesting (van Oort et al., 2012) or resulted in severe water logging during the growing season (Wustman, 2005). However, these studies describe the effect of water excess on the timing of management activities and relatively extreme wet cases of standing water in the field. In our study, we showed that also in wetter periods during the growing season which do not coincide with flooding, water excess can negatively affect potato yields. This was the case for clayey soils, and not for sandy soils, which are usually well drained and therefore have a low risk of excess water (Wagg et al., 2021). An important consideration is that our result is solely based on crop model outputs and have not been validated in the field. Although the crop model simulations align strongly with our observations in the field and it has been shown before that excessive water can reduce potato yields (Benoit and Grant, 1985) and other crops (Hack-ten Broeke et al., 2019), the extent to which we assessed that oxygen stress limited yield requires experimentation and evaluation in the field.

3.6 Conclusion

By combining frequent field monitoring and crop growth modelling, we gained detailed insight in the yield gap and yield gap explaining factors at field level for the Dutch ware potato production system. We found that the average (Yp_{fs} – Ya) yield gap ranged from 20 – 31% depending on the soil type and variety, but that the (Yp_{fs} – Ya) yield gap in individual fields ranged from 0 – 53%. On clayey soils with the variety Innovator, the yield gap was mostly attributed to oxygen stress caused by water excess. While this attribution is based on the crop model results, oxygen stress effects must be better examined in the field. On sandy soils with the variety Fontane, the yield gap was mostly determined by drought stress in 2020, a relatively dry year, and by reducing factors in 2021, an average year in terms of precipitation. The reducing factors that affected potato yields varied from field to field and were mostly related to diseases, but in some cases to pests or poor agronomic practices also. Extending the growing season by earlier planting or later harvesting could potentially increase yields as well, but it is constrained by availability of labour and machinery and adverse weather conditions, and is only possible if no other factors limit or reduce yield. Overall, we see limited scope to narrow the yield gap as current ware potato production is already close to the exploitable yield (i.e., which is assumed to be ca. 80% of potential yield considering economic and environmental efficiency). Yield gains are only to be made for individual fields given they are not constraint by other factors.

We showed that combining frequent field monitoring with crop growth modelling provided detailed insight in the yield gap variability at field level. The crop growth modelling allowed us to break down the yield gap in different components. Through the frequent field monitoring we could identify the wide diversity of yield reducing factors at field level. As such our method contrasts to other yield gap analyses using big data approaches which were less suitable to assess crop yield variability among fields.

3.7 Acknowledgements

We are very grateful to all farmers who participated in this study and allowed us access to their fields. In addition, we thank all colleagues, students and other volunteers who contributed to the extensive field work campaign that was required for this study. This research is part of the project Potato Gap NL (project number 16891) of the research programme Holland Innovative Potato which was (partly) financed by the Dutch Research Council (NWO).

Chapter 4: Current phosphorus and potassium fertiliser application rates do not limit tuber yield and quality in potato production systems in the Netherlands

This chapter has been published as:

Ravensbergen, A. P. P., van Ittersum, M. K., Kempenaar, C., & Reidsma, P. (2023). Current phosphorus and potassium fertiliser application rates do not limit tuber yield and quality in potato production systems in the Netherlands. *Potato Research*, 1-26.

Abstract

Current ware potato production levels in the Netherlands are approximately 70% of their potential. It is hypothesised by several stakeholders within the potato value chain that part of the potato yield gap is caused by a lack of phosphorus (P) and potassium (K) application. In this study we analysed for 46 farmers' fields if increasing P and K fertiliser application rates led to a higher yield and yield quality. We found that, on average, increased P and K fertiliser application did not result in a significantly higher yield for two currently cropped potato cultivars on two different soil types in the Netherlands (Innovator on clayey soils and Fontane on sandy soils) and in two years (2019 and 2020). However, on sandy soils at relatively lower farmer K application rates, our K application led to a small positive yield response up to 5 t ha^{-1}. On clayey soils there was an average positive yield response to our K application at lower yield levels of the control. For P, we did not find any correlation between yield response to P application and the amount of P applied by farmers or any of the measured soil parameters. In terms of yield quality, K application led to a slight reduction in underwater weight on sandy soils in 2019 and a slight increase in yield of large tubers in 2020. We conclude that, although in some fields there was a small positive yield effect of increased K application, increasing P and K application rates will not narrow the potato yield gap and improve potato yield quality in the Netherlands. Instead, increasing P and K application will decrease P and K use efficiency, and hence is not recommended from an environmental and economic perspective.

Keywords

Phosphorus | potassium | yield response | yield gap | fertiliser | nutrient management | *Solanum tuberosum*

4.1 Introduction

Adequate nutrient input is indispensable to obtain high crop yields, including potatoes (Koch et al., 2020). The yield level of a cropping system can be expressed through the yield gap which describes the difference between potential and actual yield (van Ittersum et al., 2013). Potential yield is the maximum yield that can be achieved given climate conditions and planted cultivars in the production region. Actual yield is the yield that is achieved in farmers' fields, considering possible limiting effects of water and nutrients and reducing effects of pest and diseases. Current ware potato production levels in the Netherlands average 52 t ha^{-1}, which is estimated to be approximately 70% of their potential (Silva et al., 2020, 2017; Chapter 3), and varies largely among farms and fields. Hence, there is still scope to increase potato yields; specifically on the lower yielding fields. Farmers and potato agronomists within the potato value chain hypothesise that the existing potato yield gap could be partly explained by a lack of phosphorus (P) and potassium (K) input. Moreover, it is hypothesised that a lack of P and (particularly of) K input has a negative effect on yield quality.

In the case of P, several potato growers argue that their potato yields are limited because of strict regulations on nutrient application rates (Dekker and Postma, 2008; López-Porrero, 2016; van Rotterdam, 2021). Almost 70% of Dutch potato farmers indicated that with less strict phosphorus application legislation they would be able to increase potato yields at their farm (Chapter 2). Nutrient inputs in the Netherlands were increased after the Second World War until approximately the 1990s to stimulate crop productivity (FAOSTAT, 2022; van Dijk et al., 2016). Although this indeed hugely increased crop yields, it also came at an environmental cost. Consequently, the Dutch government, in tandem with European Union legislation, started to restrict nutrient inputs, specifically N and P, in agricultural fields, to reduce nutrient losses to the environment (Neeteson, 2000; Oenema, 2004).

In the case of K, agronomists within the potato industry hypothesise that the ware potato yield gap could be partly explained by too low K fertiliser application rates. The rationale behind this hypothesis is that on sandy soils higher yields were observed in fields with higher plant available K (Mulders et al., 2021) and that in part of the potato production fields farmers' K application rates were lower than K uptake rates of the potato crop, leading to a negative K balance (Vos and Van Der Putten, 2000). This hypothesis is not new as already in the 1980's there were doubts about the advised K fertilisation rates for potatoes for similar reasons, i.e., potato K uptake rates were higher than K application rates (Alblas, 1984). Relatively low K application rates were justified for young clayey soils in the Netherlands in polders that were created in the second half of the 20th century as until recently no yield response to K application was found on such soils (Janssen, 2017). However, according to the agronomists within the potato industry, adequate K fertilisation has been neglected in part of the commercial production fields for too long, resulting in lower potato yields.

Increased P and K fertilisation – if current application rates are inadequate – is expected to not only affect yield, but also yield quality. Increased P fertiliser application can lead to an increased tuber number per plant and a reduced average tuber size (Prummel, 1969; Rosen and Bierman, 2008). In other experiments increased K application led to reduced underwater weight levels (Alblas, 1984; Ehlert and Versluis, 1990) or specific gravity (Panique et al., 1997). Increased K application rates were also shown to have led to a larger proportion of large tubers (Ehlert and Versluis, 1990; Panique et al., 1997), which is favourable for processing potatoes, and to lower bruising rates (Alblas, 1984; Ehlert and Versluis, 1990). However, these responses were site dependent and often greater at relatively low soil P and K status.

In the past, many studies have been conducted to determine optimal fertiliser application rates for potatoes, including for P and K (e.g., Alblas, 1984; Chapman et al., 1992; Ehlert and Versluis, 1990; Maier et al., 1994; Mohr and Tomasiewicz, 2011; Mokrani et al., 2018; Nyiraneza et al., 2017; Prummel, 1969). These experiments were generally carried out on single or only a few experimental farms or fields, while in particular optimum P and K rates are highly context specific because of past management and soil legacy effects (Jernigan et al., 2020; Rui et al., 2020). To translate findings from experimental farms to commercial fields, it is essential to do also on-farm experiments to understand what the effect of different management practices means in practice (Cassman and Grassini, 2020; Silva et al., 2017). This need for on-farm experiments is supported by the results of the earlier mentioned studies in which yield response to P and K fertiliser application differed among sites (Alblas, 1984; Chapman et al., 1992; Maier et al., 1994), years (Mohr and Tomasiewicz, 2011) and varieties (Chapman et al., 1992; Nyiraneza et al., 2017). Note that most experiments in the Netherlands were carried out before the 1990s (e.g., the earlier mentioned studies (Alblas, 1984; Ehlert and Versluis, 1990; Prummel, 1969)), mostly with the variety Bintje, while in the meantime potato varieties have changed.

In this study, we investigated the two stakeholder-driven hypotheses and tested whether increasing P and K application in farmers' fields would increase potato yield and yield quality. To do this, we set up an unconventional fertiliser response trial in which we added additional P and K fertilisers to farmers' default fertiliser application rates (as control) on 46 commercial potato fields. By doing so, we aimed to investigate whether increasing current fertiliser application rates could increase potato yields and yield quality and therefore narrow the yield gap, while accounting for the farm-specific contexts. In addition, we analysed whether there were any associations between yield or yield response to P and K and soil conditions.

4.2 Materials and methods

4.2.1 Study Area

We investigated the effects of increased P and K fertiliser application rates on potato yield in 46 commercial potato fields across the Netherlands in 2019 and in 2020 (Fig. 4.1). In 2019, we included 22 fields in this study and in 2020 24 fields. Each year, half of the studied fields were located on sandy soils where growers cultivated the variety Fontane and half of the studied fields were located on clayey soils where growers cultivated the variety Innovator. These varieties were chosen as they are the most commonly cultivated cultivars on the respective soil types. In 2019, farms were selected based on established contacts from earlier research and through contacts from the potato industry. In 2020, mostly the same farms were selected as in 2019. In addition, participating farms from 2019 proposed neighbouring farms to participate. From each farm, 1 to 3 fields cultivated with potatoes were selected for this study, representing a large range in soil conditions and nutrient management (Table 4.1).

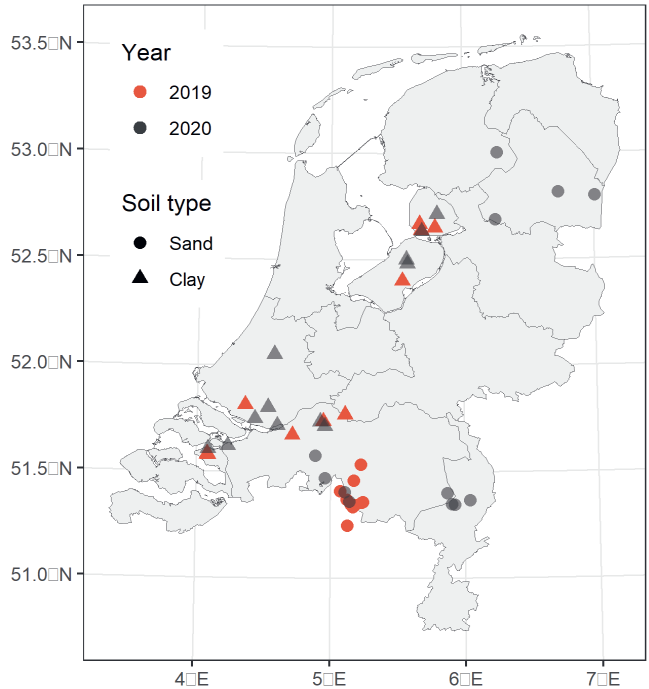


Figure 4.1. Map of the Netherlands with locations of experimental sites.

The years 2019 and 2020 were both characterised as relatively dry, although there was a large spatial variation throughout the studied region. Cumulative precipitation during the growing seasons varied between 153 and 387 mm per growing season (from April 1 – October 1), compared to 416 mm as long-term average (Fig. 4.2A) (KNMI, 2022a). The precipitation deficit averaged over all weather station in the Netherlands was 160 mm in 2019 and 209 mm in 2020, which is considerably higher compared to the long-term median precipitation deficit of 80 mm (KNMI, 2022b). In both years, monthly temperatures were mostly higher than the long-term average (Fig. 4.2B); particularly the summer period was very warm. In both years, a heat wave occurred with temperatures up to and beyond 40 °C, which was never measured before in the Netherlands. On the other hand, in 2019 May was colder than average with several days with night frost.

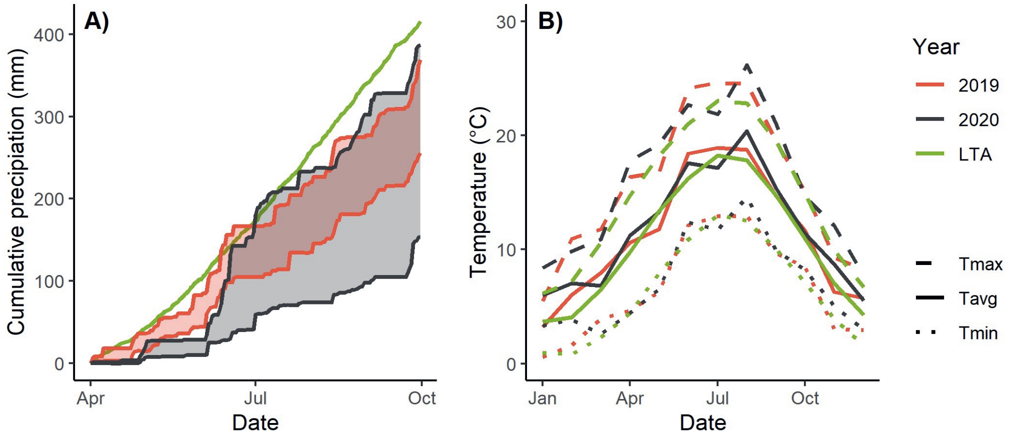


Figure 4.2. Cumulative precipitation (in mm) (A) and average monthly mean, minimum and maximum temperature (in °C) (B) in the Netherlands. Plotted areas in figure A indicate regional variability in the respective years. LTA refers to the long-term average precipitation and temperatures over the past 30 years (KNMI, 2022b, 2022a).

Fields included in the study varied in soil conditions reflecting differences that are observed among farmers (Table 4.1). Soil organic matter (SOM) was, on average, 3.6% on clayey soils for both years, 3.5% on sandy soils in 2019 and 5.0% on sandy soils in 2020. The reason for this difference between years is that in 2020 other regions with naturally higher SOM were included in the study. Considering all individual fields of both years, SOM ranged over two years from 2.3 to 5.9% on clayey soils and from 2.0 to 9.5% on sandy soils. Soil pH was, on average, 7.5 on clayey soils and 5.4 on sandy soils. Average plant available P was 2.2 mg P kg^{-1} on clayey soils (range 0.3 – 6.7 mg P kg^{-1}) and 5.3 mg P kg^{-1} on sandy soils (range 0.6 – 15.2 mg P kg^{-1}). Plant available K was larger on clayey soils than on sandy soils, with an average available K of 117 mg K kg^{-1} on clayey soils (range 55 – 268 mg K kg^{-1}) and 83 mg K kg^{-1} on sandy soils (range 29 – 214 mg K kg^{-1}). Nutrient application rates (mineral + organic) of the farmers (controls) were highly variable among fields with N application rates between 69 and 440 kg N ha^{-1}, P application rates between 5 and 121 kg P ha^{-1} and K application rates between 85 and 664 kg K ha^{-1} (Table 4.1, see Appendix C.1 for detailed information per field). Details on the soil measurements can be found in Section 4.2.4 and details on the nutrient application rates calculations can be found in Section 4.2.5.

Table 4.1. Soil properties and fertiliser application rates of the farmers on the 46 fields (controls). Indicated for each parameter are the mean, standard deviation, minimum value and maximum value.

		2019				2020			
Variable	Soil type	Mean	SD	Min	Max	Mean	SD	Min	Max
SOM (%)	Clay	3.6	0.9	2.3	5.8	3.6	1.1	2.6	5.9
	Sand	3.5	1.0	2.0	4.8	5.0	2.1	3.0	9.5
pH (-)	Clay	7.2	0.5	5.9	7.6	7.7	0.1	7.5	7.9
	Sand	5.3	0.3	4.7	5.7	5.5	0.5	4.8	6.2
Plant available N	Clay	151	32	88	185	97	49	12	170
(mg kg^{-1})	Sand	70	21	44	111	64	57	16	201
Plant available	Clay	2.8	2.0	1.1	6.7	1.7	1.8	0.3	5.7
P (mg kg^{-1})	Sand	4.7	4.4	1.1	15.2	5.8	4.8	0.6	15.2
Plant available	Clay	132	62	66	268	102	54	55	196
K (mg kg^{-1})	Sand	82	55	41	214	83	50	29	178
N applied (kg ha^{-1})	Clay	311	70	186	414	344	63	255	440
	Sand	237	46	170	329	235	70	88	322
P applied (kg ha^{-1})	Clay	63	33	18	177	63	33	20	122
	Sand	39	21	22	79	30	19	11	73
K applied (kg ha^{-1})	Clay	379	134	217	664	356	165	178	614
	Sand	248	56	152	339	283	107	85	431

4

4.2.2 Experimental design

To study the effect of increased P and K fertilisation on potato yield, we set up an experiment comparing farmers' nutrient management practices (control) with practices with increased P or K fertiliser application rates. The control treatment was fertilised by the farmer according to the farmer's management (referred to as 'farmer applied P' or 'farmer applied K'), which was farm specific (Table 4.1). The P and K treatments were also fertilised according to the farmer's management but received on top of the farmer's nutrient application, an additional 30 kg P ha^{-1} (69 kg P_2O_5 ha^{-1}; P treatment) or an additional 80 kg K ha^{-1} (96 kg K_2O ha^{-1}; K treatment). P fertiliser was applied manually in the form of TSP (triple super phosphate) at the start of the growing season through band application. K fertiliser was applied manually in the form of muriate of potash. In 2019, K fertiliser application was applied in a split application with 70% applied at the start of the growing season through band application and 30% applied around the end of June through broadcast application. In 2020, all extra the K fertiliser was given at the start of the growing season through band application.

The experiment was laid out slightly differently in 2020 than in 2019. In 2019, three replicates of each treatment were laid out in a randomised complete block design. We divided the farmers' fields into a raster of pixels of approximately 50 x 50 m (excluding headlands and field borders). We then used the R package ‘agricolae’ to randomly select three blocks in the field where the experimental plots would be located. In every block, the three treatment plots (control, P and K treatments) were randomly located within a block. The size of each plot was in 2019 6 x 7 m. We repeated this procedure for each of the 22 commercial potato fields. The 2019 field design proved physically too demanding for the available labour as it required long distance walking with measurement equipment and harvested potatoes in the (sometimes very large) fields. Therefore the design was slightly adapted in 2020 in such a way that it could be combined with another experiment done in the same fields. In 2020, we laid out all plots in a single block with four control treatments and three P and three K treatments, approximating a completely randomised design. Four control treatments, instead of three, were used as the experiment on P and K fertilisation took place simultaneously with another experiment – and for the other experiment four repetitions were required. The control plots were always located in the middle of the experiment, and the P and K treatments were randomly located around the control plots. We considered this layout to be sufficiently randomised because we repeated this experiment in 2020 in 24 fields with different spatial soil conditions in each field. In 2020, the size of each plot was 3 x 5 m. See appendix C.2 for an example on the field layouts in 2019 and 2020.

4.2.3 Crop management

As this experiment was set up in commercial potato fields, all crop management was done by the farmer. There was a large variability in the management practices reflecting a wide variety of Dutch potato cultivation practices. Planting dates ranged from March 31 till May 6. Irrigation was applied by most of the farmers and ranged, if applied, from 20 mm to 150 mm per growing season. Haulms were killed in most of the fields and haulm killing took place from August 30 till October 5. In the other fields, the crop senesced naturally or was harvested while the haulms had not fully senesced. All farmers applied herbicides, pesticides and fungicides to control weeds, pests and diseases. The type of crop production products and frequency of spraying was managed by the farmer to his or her own insight. See Appendix C.1 for detailed information on crop NPK-management, soil parameters, planting dates and harvesting dates of each field.

4.2.4 Data collection

In each field, one composite soil sample was taken from the experimental plots at the beginning of the growing season. Soil organic matter (SOM) was measured using the loss on ignition method by placing the sample in a furnace at 550 ^{o}C for 3 hours. SOM was corrected for clay content using Hoogsteen et al. (2015). pH was measured in water in a 1:2.5 soil:water ratio. Available N and P were measured spectrophotometrically with a Skalar san++ system from a 0.01 M $CaCl_2$ extraction. Available K was measured with a Varian

AA240FS fast sequential atomic absorption spectrometer from the same extracts. All soil samples were analysed at a laboratory of Wageningen University.

At the end of the growing season final yield was measured from a three m^2 area in each plot. For 2019, this was only a small part of the total plot size as the rest of the plot was used for measurements taken during the growing season. These measurements were not repeated in 2020 and therefore no results on these measurements are presented in this manuscript as they were not repeated over multiple years. Yield sampling took place after haulm killing or natural senescence, or just before harvesting by the farmer in case haulms had not senesced. From each plot, a 6 kg subsample was taken to measure underwater weight, number of tubers, and tuber size distribution, which were used as parameters to assess yield quality. Crop management information was reported by the farmer.

4.2.5 Data analysis

Measured yield data were used to calculate gross yield and marketable yield. Gross yield refers to the gross yield ha^{-1} of all harvested tubers after cleaning. Marketable yield was calculated as the yield ha^{-1} of tubers larger than 40 mm and excluding any tubers that were green or were severely misshaped.

Collected farm management data was used to calculate N, P and K application rates per field. Nutrient input was considered as the sum of fall and spring fertiliser applications. Fall application refers to fertilisers applied after the harvest of the main crop in the previous growing season. Spring application refers to nutrients applied in the same year as the potatoes were cultivated. For calculating N application rates, we included 22 kg N ha^{-1} of nitrogen deposition (CLO, 2022). Effective N application was calculated from organic fertilisers (mostly manure) considering nitrogen fertiliser replacement values as used by the Dutch government (RVO, 2018).

For each field, the P and K yield response was calculated as the difference between the average P or K treatment yield and the average control treatment yield. P and K balance were calculated for the control treatments as the total P or K applied by the farmer minus the P or K taken up by the tubers. Nutrient content was based on average P and K contents of Innovator and Fontane tubers measured in another trial (ten Den et al., 2022).

For statistical analysis, three fields were completely or partly excluded from the analysis. In 2019, one K treatment plot from one of the fields was excluded, because of incorrect top dressing of K fertiliser. In 2020, one field was discarded because of emergence problems in the field, which was inconsistent across plots and would therefore affect the analysis. From another field in 2020, two K treatment plots were excluded from the analysis, as the farmer drove through the treatment plots and the plants were severely damaged.

Analysis of variance (ANOVA) was used to analyse treatment effects on potato yield and quality parameters. A Tukey's HSD test was used as a post-hoc test to assess significant differences between treatments. Field nested with block was added to the statistical model as random effect. Hence, for the data of 2020 only one block was considered. Analysis was done in R version 4.0.2 using packages '*nlme*' and '*emmeans*'.

Multiple linear regression was used to analyse relationships between yield or yield response and soil parameters and fertiliser application rates. Data was analysed separately for soil types. Year was always included in the statistical model, also if there was no significant year effect. This was done to make sure that a relation was an actual correlation between yield response and the studied factor and did not indirectly reflect a difference between years.

4.3 Results

4.3.1 Yield differences between treatments

Average gross yield of the control treatment was 65 t ha^{-1} in 2019 and 60 t ha^{-1} in 2020 for clayey soils (cv. Innovator). On sandy soils (cv. Fontane), average gross yields of the control treatment were 64 t ha^{-1} in both years. ANOVA showed that there was a significant interaction between treatment, year and soil type ($p = 0.023$), and between treatment and year ($p = 0.035$). This is reflected in the significant difference between the P and K treatment on sandy soils for 2020 ($p = 0.020$) (Fig. 4.3). Furthermore, there were no significant differences in gross yield among treatments for the different year and soil type combinations. The marketable yield was on average 1.7 t ha^{-1} lower than the gross yield on the clayey soils (cv. Innovator) and 4.6 t ha^{-1} lower on the sandy soils (cv. Fontane). ANOVA of the marketable yield showed a similar pattern as for the gross yield with no significantly higher yields for the P and K treatments compared to the control treatment. Furthermore, no significant differences were observed between the control and P or K treatments for dry matter yield (Appendix C.3).

Yield quality was affected by the treatments to a limited extent. Under water weight was significantly lower for the K treatment (373 g) compared to the control (382 g) on sandy soils in 2019. This effect was not significant for 2020 or for clayey soils. Yield of tubers larger than 50 mm was significantly higher for the K treatment on sandy soils in 2020. In 2019 this difference was not observed. Neither was this observed for clayey soils (see figures in Appendix C.3)

4.3.2 Yield and yield response in relation to soil parameters

No significant relationships were observed between gross yield or yield response and available P or K (Fig. 4.4). This was irrespective of the year and soil types with the respective cultivars. SOM, pH and available N neither showed a relationship with yield or yield

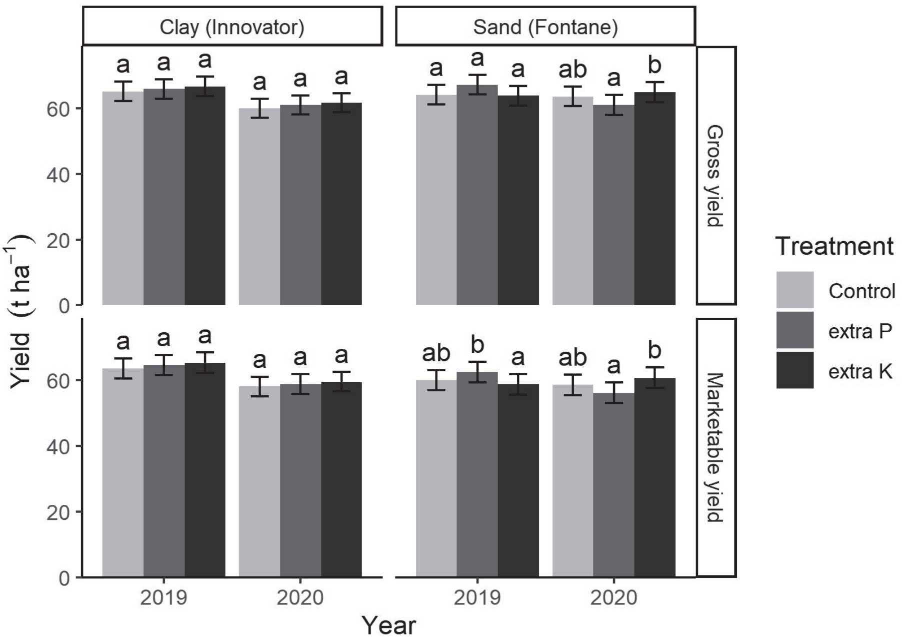


Figure 4.3. Gross yield (top row) and marketable yield (bottom row) (in t ha^{-1}) of the different treatments for 2019 and 2020 for fields on sandy and clayey soils. Significant differences between treatments within year and soil type group are indicated by different letters.

response (Appendix C.4). Significant relationships between tuber quality parameters and soil parameters were neither observed (results not shown).

4.3.3 Yield and yield response in relation to fertiliser application

No relationship was observed between yield of the control treatment and farmer applied P (control) on both soil types (Fig. 4.5A). Also, no relationship was observed between yield response from the P treatment and farmer applied P (Fig. 4.5B). Similarly, on clayey soils (cv. Innovator) no relationship was found between yield of the control treatment or yield response from the K treatment and farmer applied K (Fig. 4.5C – D). On sandy soils (cv. Fontane), no relationship was found between yield of the control treatment and total K applied by the farmer (control) (Fig. 4.5C), but a significant negative relationship ($p = 0.018$) was observed between yield response to the K treatment and farmer applied K for both years (Fig. 4.5D). This indicates that a positive yield response to extra K application was observed at relatively low levels of farmer applied K and not at higher farmer applied K. Yet, the R^2 of this correlation was 0.13, indicating that only very little of the variation in yield response could be explained by farmer applied K. Appendix C.5 shows the absence of relationships between yields or yield responses and farmer nitrogen application. Significant relationships between tuber quality and farmer applied nutrients were not found (results not shown).

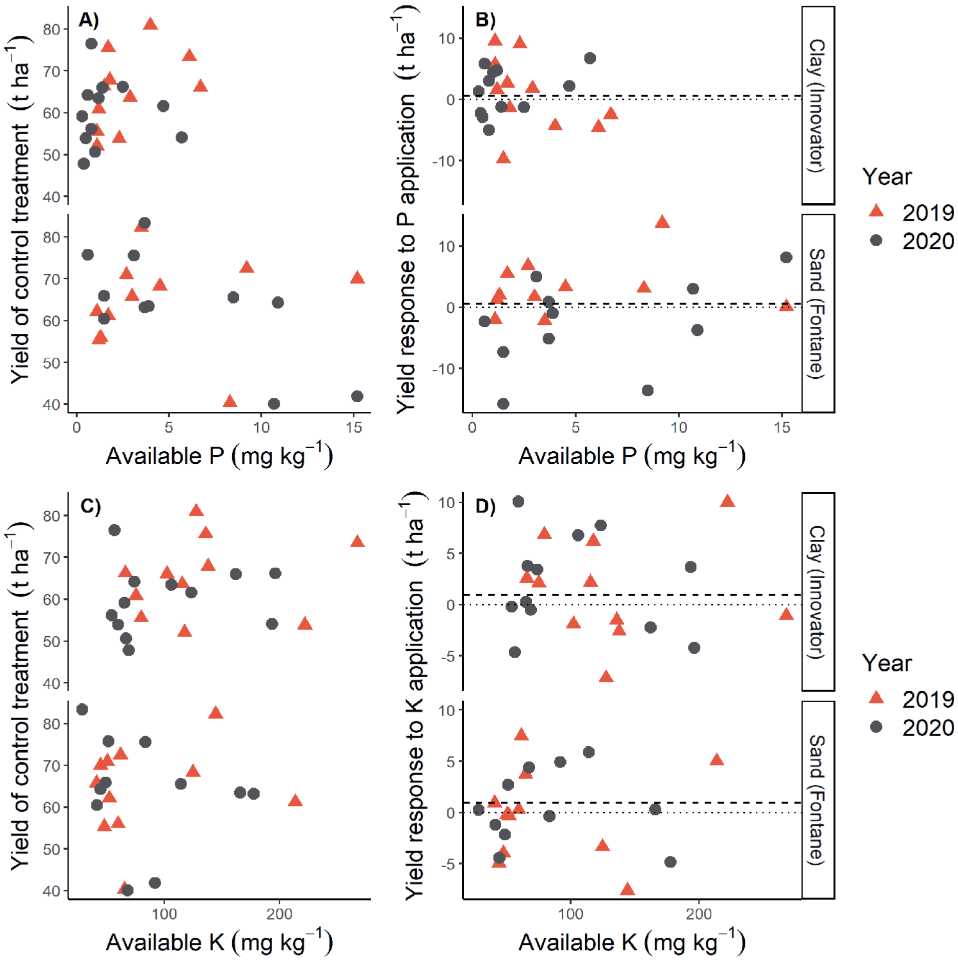


Figure 4.4. Gross yield of the control treatment (in t ha^{-1}) (A, C)), yield response to P application (in t ha^{-1}) (B) and yield response to K application (in t ha^{-1}) (D) against available P (in mg kg^{-1}) (A, B) or available K (in mg kg^{-1}) (C, D) separated for soil type and the respective cultivar. The dotted horizontal line (B, D) indicates no response of the crop to the P or K treatment. The dashed horizontal line (B, D) indicates the average response to the P or K treatment.

Statistical models that tested the effect of an interaction between soil parameters and farmer applied P or K revealed no significant effects on yield of the control treatment nor on yield response to P or K application (results not shown).

4.3.4 Yield response in relation to yield of control treatment

Lastly, we analysed whether a positive yield response to P or K treatments was correlated to different yield levels of the control. A significant negative correlation (*$p < 0.001$*) was found between yield response to extra K and yield of the control treatments on clayey soils for both years (Fig. 4.6B). This means that at low yield levels of the control treatment there

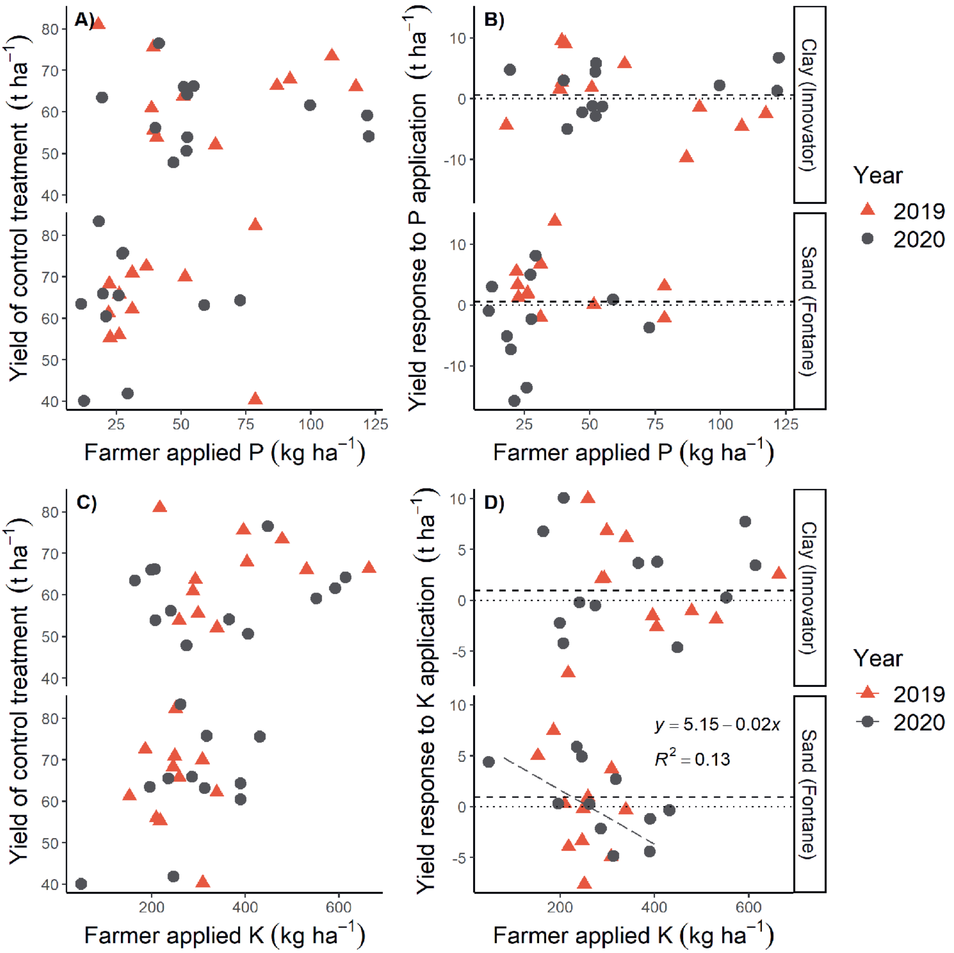


Figure 4.5. Yield of the control treatment (in t ha⁻¹) (A, C), yield response to the P treatment (in t ha⁻¹) (B) and yield response to the K treatment (in t ha⁻¹) (D) against farmer applied P (in kg ha⁻¹) (A, B) or farmer applied K (in kg ha⁻¹) (C, D) separated for soil type and the respective cultivar. The dotted horizontal line (B, D) indicates no response of the crop to the P or K treatment. The dashed horizontal line (B, D) indicates the average response to the P or K treatment.

was, on average, a positive yield response to K application. Such negative correlation between yield response to extra K and yield of the control treatment was not observed on sandy soils (cv. Fontane) (Fig. 4.6B). Neither was such a correlation observed between yield response to extra P and yield of the control treatment on both soil types (Fig. 4.6A).

4.3.5 Phosphorus and potassium balance of the control treatments

The P balance (P input – P output, see Section 4.2.5) of the studied commercial potato fields showed that, on average, there was a positive balance of 39 kg P ha^{-1} in clayey soils and 11

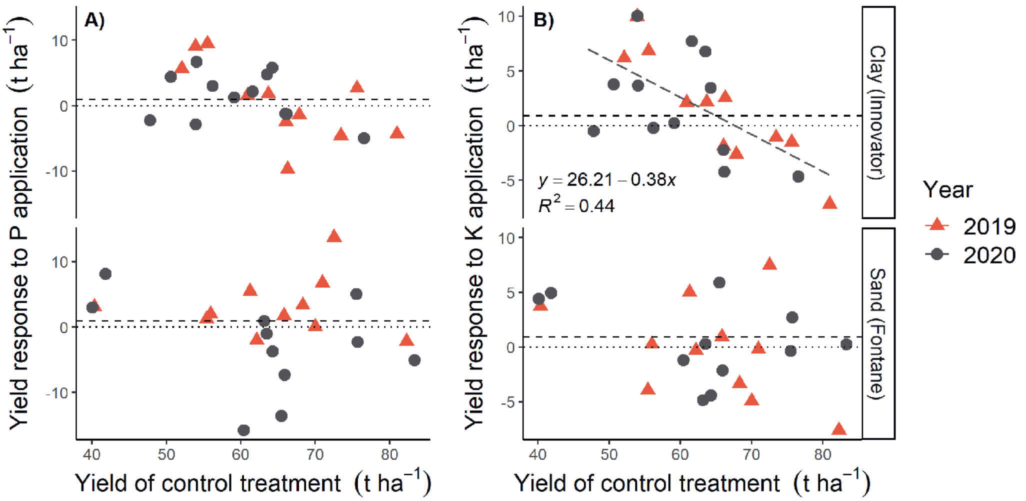


Figure 4.6. Yield response to P application (in t ha^{-1}) (A) and yield response to K application (in t ha^{-1}) (B) against yield of the control treatment (in t ha^{-1}) separated for soil type and the respective cultivar. The dotted horizontal line indicates no response of the crop to the P or K treatment. The dashed horizontal line indicates the average response to the P or K treatment.

kg P ha^{-1} in sandy soils (Fig. 4.7). Only in a limited number of fields more P was taken up by the crop than was applied by the farmer. The average K balance on clayey soils was also positive (125 kg K ha^{-1}), and only in four fields more K was taken up by the crop than applied by the farmer. On the other hand, on sandy soils there was a negative K balance in 79% of the studied fields. On average, this resulted in a negative K balance of -17 kg K ha^{-1} on sandy soils.

4.4 Discussion

In this study we analysed if increasing P and K fertiliser application rates could narrow the potato yield gap in commercial potato fields in the Netherlands. We found that, on average across the 46 fields studied, there was no significant effect of increased P and K fertiliser application rates on potato yield compared to farmers' fertiliser application strategies (Fig. 4.3). For P we did not observe any relationship between yield response to increased P fertiliser application rates and the measured soil parameters or farmer applied P. For K an association was found with farmer applied K and yield of the control treatment, but the effect varied per soil type and was small. On sandy soils (cv. Fontane), a positive response to increased K application was observed in fields with relatively low farmer applied K (Fig. 4.5D). On clayey soils (cv. Innovator), increased K application rates led to slightly higher average potato yields at low yield levels of the control treatment (Fig. 4.6B). There were only small effects of increased K fertilisation on yield quality. Increased K application rates led to a slightly lower underwater weight on sandy soils in 2019 and to a slightly higher yield

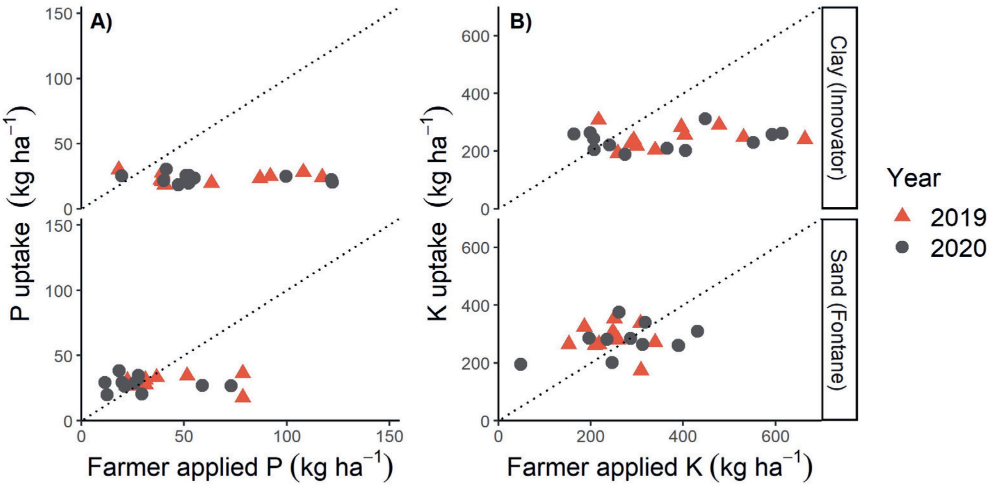


Figure 4.7. P balance with P uptake (in kg ha^{-1}) against farmer applied P (in kg ha^{-1}) (A) and K balance with K uptake (in kg ha^{-1}) against farmer applied K (in kg ha^{-1}) (B) separated for soil type and the respective cultivars. The dotted line shows the 1:1 line representing a P or K balance of 0 kg ha^{-1}.

of the large tuber size on sandy soils in 2020. However, the effects were small and not consistent over the years. Overall, we conclude there seems to be limited scope to narrow the potato yield gap or to increase potato tuber quality by increasing P and K application rates.

Given a long history of high P and K input rates in The Netherlands, the P and K balances also suggest limited scope for narrowing the potato yield gap by increasing P and K fertiliser application rates. On average, there was a net P input into the fields on both soil types (Fig. 4.7A), implying that a P deficit in the soil is not to be expected. For K, it was observed that there was a net K input on clayey soils (balance: 125 kg ha^{-1}) and a small net K output on sandy soils (balance: -17 kg K ha^{-1}) (Fig. 4.7B). This negative K balance on sandy soils could potentially explain why a positive yield response to K application was found on sandy soils at low K application rates (Fig. 4.5D). However, it is important to note that the presented P and K balances are based on a single cropping season. To fully evaluate the nutrient balance, it will be essential to perform an analysis on a whole crop rotation considering historic fertiliser application rates and soil P and K stocks (Deike et al., 2008; Łukowiak et al., 2016; Sattari et al., 2012). Especially on clayey soils, P and K fertilisers are not applied every year, but more often before a potato crop as that is the cash crop for farmers in the Netherlands (Goffart et al., 2022). To perform a P and K balance calculation of entire crop rotations, not only historical fertiliser input is required, but also historical yield data. This is often lacking for farmers' fields, as was the case in our trial.

For evaluating the effect of fertiliser application on narrowing the yield gap, not only fertiliser application rates are relevant, but also soil P and K status should be considered. In the studied fields, plant available P ranged from 0.3 till 15.2 g P kg^{-1} and plant available K ranged from 28.7 till 267.6 g K kg^{-1}, indicating a large range in soil P and K status. A direct comparison from our study with the scientific literature that analysed P or K responses (Alblas, 1984; Chapman et al., 1992; Ehlert and Versluis, 1990; Panique et al., 1997; Prummel, 1969) is difficult as different methods were used to test soil P and K status, or the research was performed in a different area. However, given the very large variability in soil fertility we assume that at low plant available P or K fertiliser responses could have been observed if there was a lack of P or K fertilisation.

Water is another factor that can influence fertiliser response in potato production. Bélanger et al. (2000) showed a greater fertiliser recovery of nitrogen by the potato crop with irrigation compared with no irrigation. Liu et al. (2015) showed that the potato crop had a higher P uptake under full irrigation than under deficit irrigation. In our study both 2019 and 2020 were relatively dry years (Fig. 4.2). Farmers did irrigate, but the amount of water applied was not always enough to meet the crop water requirements. Hence, fertiliser recovery in the studied fields might have been limited by drought stress water limitation; with water-limited yields, a lower potential nutrient uptake is to be expected. Particularly, this could have played a role in the K recovery in sandy soils as there was a negative K balance in these fields and because sandy soils are generally more prone to drought stress.

Other studies aiming at explaining potato yield variability in the Netherlands also analysed the effect of P and K soil status and fertiliser application on potato yield. Silva et al. (2020) did not find any correlation between P or K input and yield. Mulders et al. (2021) did not find an effect of P and K fertiliser application on crop growth either. However, in that study it was shown that plant available K positively affected tuber growth at a large scale farm in the south of the Netherlands, where potatoes are cultivated on sandy soils (Mulders et al., 2021). Overall, the results of these studies are largely consistent with our findings, suggesting no effect of soil P status and P fertilisation on potato yield in the Netherlands and mixed, but generally small effects of soil K status and K fertilisation on potato yield.

Although there was a slight positive effect of increased K fertiliser application rates in some fields, the yield increases were only a small portion of the potato yield gap levels currently observed in the Netherlands (Silva et al., 2017). The average current yield gap of ware potatoes was assessed at 20 t ha^{-1} (approximately 30% of potential production). However, the average yield gain of extra potassium application was only up to ca. 5 t ha^{-1}, and was observed in just a few fields (Fig. 4.5D). Hence, there is a need to further investigate which yield limiting (water, interactions between nutrients, other nutrients) or reducing factors (pests and diseases) are major contributors to the prevailing potato yield gap and yield gap variability in the Netherlands. Earlier determined drivers of actual yield variability in the Netherlands were the region (in the Netherlands), year, cultivar earliness, sowing date, harvesting date, precipitation, applied irrigation and field size (Silva et al., 2020). Many of these factors are yield defining factors (van Ittersum et al., 2013) and thus explain why potential yields differ among fields, but not necessarily why the yield gap is different among fields. Silva et al. (2017) suggested interaction effects of nutrients and crop protection products. However, they, used secondary farm survey data which provide little detail on farm management, and hence on-farm experiments and direct interactions with farmers are needed to better understand yield gap variability.

This study aimed at obtaining higher possible potato yields by increasing P and K fertiliser application rates. Although it is a relevant question to assess if a lack of P and K fertilisation contributes to the existing yield gap, it does not necessarily reflect European and national policy targets to increase nutrient use efficiencies (Gil et al., 2019), nor does it accord with a new paradigm on plant nutrition (Dobermann et al., 2022). The aim of this paradigm is to tailor fertiliser application in such a way that it serves multiple societal objectives, such as environmental ones which are high on the agenda, but also lower utility of finite resources as P. This requires utilising nutrients with high efficiency. In our study, we increased P fertiliser application rates by 30 kg ha^{-1} and K fertiliser application rates by 80 kg ha^{-1}. With no yield response to P application and an observed yield response of up to 5 t ha^{-1} to K application in a limited number of fields, fertiliser recovery of the additional applied nutrients would range from 0% to maximum 30%, which is low. From an environmental (and economic) perspective, increasing P and K application in potato production fields in the Netherlands is thus not recommended.

4.5 Conclusion

In this study we analysed whether increasing phosphorus or potassium application rates in farmers' fields could increase yield levels and improve yield quality in the Netherlands. We showed that, on average, across 46 commercial potato production fields, increased P and K fertiliser application did not increase yield in farmers' fields. Only for K a small positive yield response to increased K fertiliser application was found on sandy soils when farmers' K application rates were low, or on clayey soils when yields of the control were low. However, the found relationships could explain only small portions of the yield variability. In terms of yield quality, increased K fertiliser application slightly reduced the underwater weight and increased the yield of the large tubers on sandy soils, although this effect was observed in only one of the two studied years. Overall, we conclude that there is limited scope to narrow the yield gap or increase yield quality by increasing P and K fertiliser application rates in the Netherlands. In addition, we argue that increasing P and K fertiliser application rates for potato production is not desirable from an environmental (and economic) perspective as in most of the commercial fields fertiliser recovery of the additionally added nutrients would be absent or low, decreasing overall nutrient use efficiency. In this study, we were unable to identify causes of the existing potato yield variability in the Netherlands. Hence, to answer this question, future research should further investigate which other yield limiting or reducing factors are able to explain the existing (ca. 30%) potato yield gap.

4.6 Acknowledgements

We are very grateful to all farmers who participated in this study and allowed us access to their fields. In addition, we thank all people who contributed to the field work that was required for this study. This research is part of the project Potato Gap NL (project number 16891) of the research programme Holland Innovative Potato which is (partly) financed by the Dutch Research Council (NWO).

4

Chapter 5: Effects of planting date and field type on yield outweigh effect of seed potato origin

This chapter will be submitted as:

Ravensbergen, A. P. P., Zou, C., Struik, P.C., Reidsma, P., Kempenaar, C. & van Ittersum, M.K. Effects of planting date and field type on yield outweigh effect of seed potato origin.

Abstract

Potato yields in the Netherlands are highly variable. Although variability in yield has previously been attributed to several crop management factors, part of the yield variability remains unaccounted for. It is hypothesised that part of this unexplained yield variability is influenced by seed potato origin, encompassing where and under what conditions seed potatoes have been cultivated. In this study, we investigated the effect of seed potato origin on crop characteristics and tuber yield in interaction with and in comparison to planting date and field type in a two-year on-farm experiment on a large-scale potato farm. We evaluated three different ware potato origins of the variety Fontane, three different planting dates (early, intermediate, late) and two different field types (rainfed wet and dry irrigated). Origin significantly affected the number of stems per plant and number of tubers per stem in both years. This resulted in a significant effect of origin on number of tubers per plant in the first year. In that year, the origin with the lowest number of tubers per plant also produced the highest yield of tubers larger than 50 mm. Despite these (small) effects of seed potato origin on crop characteristics, origin did not significantly affect gross and marketable yield. Moreover, there was no interaction between origin and planting date and/or field type. However, there was a significant main effect of planting date and field type on yield. Yield in the wet rainfed field was up to 17 t ha^{-1} higher than in the dry irrigated field and late planting resulted in a yield reduction up to 10 t ha^{-1}. We conclude that for maximizing ware potato yield of the variety Fontane in the Netherlands, effects of planting date and field type outweighed the effect of seed tuber origin.

Keywords

Solanum tuberosum | physiological age | analysis of variance | on-farm trial | seed potatoes

5.1 Introduction

Potato yields in the Netherlands are highly variable, with reported yield ranges from 30 to 80 t ha^{-1} at farm level (Silva et al., 2017) and from 30 to 90 t ha^{-1} at field level (Mulders et al., 2021a; Silva et al., 2020a; Chapter 2). Part of the yield variability has previously been attributed to differences in sowing and harvesting dates, irrigation use, cultivated varieties, fungicide use and preceding crops (Mulders et al., 2021a; Silva et al., 2020a, 2017a; Chapter 3). Analyses in these studies were largely based on comparing yield of a large number of fields or farms, using farmer reported or measured data. These data are useful to explore the effect of crop management and field type on crop characteristics and yield for a wide range of conditions. However, the data are less suitable to understand the effect of factors that are not well reported or require testing under the same conditions to rule out the effect of confounding factors. An example of such a factor is seed potato origin. It is hypothesised that seed potato origin can explain part of the yield variability among farms and fields, as it was previously found that seed potato origin can influence crop growth (Mulders et al., 2021; van der Zaag and van Loon, 1987).

Seed potato origin encompasses where and under what conditions seeds were produced in the field and stored at the farm and thereby determines the physiological quality of the seed tubers (Struik and Wiersema, 1999). Seed potatoes that have been cultivated on different sites or with different management practices, but stored under similar conditions, can differ in their dormancy period (van Ittersum, 1992a, 1992b) and ware potato yield production (Johansen et al., 2008; Wiersema and Booth, 1985; Wurr, 1979). Seed potatoes stored under different temperature regimes, but cultivated under similar conditions, differ in their sprouting capacities (Susnoschi, 1981), ware potato yield production (Krijthe, 1958; Rykaczewska, 2010; Struik and Wiersema, 1999), number of stems per plant and number of tubers per stem and per plant (Nepal et al., 2016).

An important aspect of seed potato origin is its influence on physiological age. Struik and Wiersema (1999) described physiological age as the stage of tuber development, which is modified progressively by increasing chronological age, depending on growth history and storage conditions. Physiological age influences emergence, number of stems per plant and number of tubers per stem and tuber yield (Nepal et al., 2016; O'Brien et al., 1983; Struik and Wiersema, 1999; van der Zaag and van Loon, 1987; van Ittersum, 1992b). Optimal production of the ware crop requires an ideal physiological age of the seed tubers. If the seed tubers are too young, tubers will not sprout timely and produce a late and low-yielding crop. If the seed tubers are too old, growth vigour will be reduced, and when very old no sprouts may form, but so-called little potatoes (Bodlaender and Marinus, 1987). Generally, it is agreed that relatively older seed tubers will give the highest yield when the growing season is short (e.g., for seed tuber production or under organic production when an early crop is needed to escape disease infections), whilst relatively younger seeds will give the highest yields when the growing season is long (Asiedu et al., 2003; Bean and Allen, 1980; Caldiz, 2009; Vakis, 1986; van der Zaag and van Loon, 1987).

In addition to seed potato origin, planting date and field type (including water holding capacity as affected by soil texture, rootable depth and landscape topography) are crucial factors to consider when establishing a potato crop. Early planting can prolong the growing season, potentially resulting in higher yields (Johnson et al., 1996; Silva et al., 2020), whilst late planting can shorten the growing season, leading to lower yields. In dry years, fields with lower soil water holding capacity tend to have shorter crop cycles and lower yield compared to fields with high water holding capacity that sustain longer growing seasons and higher yields. Evidently, these factors may interact with seed tuber origin, yet there is limited knowledge how seed potato origin effects yield compared to and in interaction with planting date and field type.

In this study, we investigated the effect of seed potato origin on crop characteristics and tuber yield in interaction with planting date and field type in a two-year on-farm experiment. Furthermore, we compared the effect of seed potato origin on yield to the effect of planting date and field type. The farm where the experiment was performed is intensively managed and located on sandy soils in the south of the Netherlands. Previously, a five-year on-farm experiment was conducted on the same farm to evaluate the effect of seed potato origin on yield (Bartelen, 2016; Waverijn, 2020). However, in these experiments potatoes were harvested prematurely, constraining the ability to formulate final conclusions. In this study, we optimised the design of the earlier experiments.

5.2 Materials and Methods

5.2.1 Study site

The experiment was performed at the farm ‘van den Borne Aardappelen’ (51°19'09.5"N 5°10'29.5"E), a large-scale commercial farm located on sandy soil in the south of the Netherlands, on which each year approximately 600 ha are cropped to potato (Mulders et al., 2021). For an optimal establishment of the crop at the start of the growing season, the farmer has to consider three main factors: (1) different field types, (2) a wide planting window and (3) different seed potato origins. Two main field types are distinguished: dry irrigated fields and wet rainfed fields. Dry irrigated fields have a shallower topsoil layer, are located on top of slightly rolling slopes and therefore have less soil moisture available throughout the growing season. These fields are irrigated to compensate for the lower water availability. Wet rainfed fields have a deeper topsoil layer, are located in depressions in the landscape and therefore generally have more soil moisture available throughout the growing season. These types of fields are generally not irrigated. The planting window of

Table 5.1. Origin (O), Planting date, tuber initiation date, haulm killing date, harvesting date, mean storage temperature till early planting, temperature sum, and approximate location of the seed tuber field (year before planting the ware crop). Temperature sum (using a base temperature of 0 ˚C) of the stored seed tubers was calculated from harvesting of the seed tuber field until early, intermediate, and late planting.

Year	O	Planting date (seed tuber field)	Tuber initiation date*	Haulm killing date	Harvesting date	Mean storage temperature till early planting (°C)	Temperature sum (degree-days, between harvesting and planting)			Approximate location
							Early planting	Inter-mediate planting	Late planting	
2021	A	23/4/2020	19/6/2020	6/8/2020	16/9/2020	7.3	1457	1563	1690	52°38'09.9"N 5°50'05.8"E
	B	19/4/2020	12/6/2020	19/8/2020	7/9/2020	8.6	1818	1924	2051	52°24'54.4"N 5°30'05.8"E
	C	21/4/2020	4/6/2020	29/7/2020	30/8/2020	7.2	1564	1670	1729	53°20'31.3"N 6°20'11.2"E
2022	A	30/4/2021	18/6/2021	25/8/2021	8/10/2021	7.9	1575	1670	1760	52°38'09.9"N 5°50'05.8"E
	B	29/4/2021	18/6/2021	13/8/2021	15/9/2021	8.6	1774	1869	1959	52°24'54.4"N 5°30'05.8"E
	C	27/4/2021	18/6/2021	14/8/2021	23/9/2021	7.8	1562	1657	1747	53°20'31.3"N 6°20'11.2"E

** Tuber initiation date was estimated based on weekly visits to the seed potato fields. We assumed that tuber initiation took place, when at least three tubers with a diameter of 1 cm were formed. In 2022, tuber initiation took place in the same week on the three farms, but the exact dates might have been slightly different.*

the farm is year dependent but spans more than one month. In a year with favourable (dry) weather conditions during spring, planting is started around the first week of April and finished around the second week of May. The majority of the fields are planted with the variety Fontane, a key cultivar for the potato processing industry. Planted seed tubers (of the cultivar Fontane) originate each year from the same three seed potato growers from the northern part of the Netherlands. These growers cultivate and store their seed tubers according to their own management practices. Table 5.1 provides information on important management dates in the seed tuber fields and storage temperature sums.

In both years, the experiments were laid out in two commercial fields of the farm, where one field was characterised as a dry irrigated field and the other field was characterised as a wet rainfed field, similar to the field types on the farm as described earlier. The trial fields were managed and fertilised alongside with the management of the rest of the commercial fields (Table 5.2 provides an overview of fertiliser application and irrigation rates of the trial fields). Nutrient application rates were calculated as the sum of applied nutrients from January till the end of the growing season. Effective nitrogen was calculated using nitrogen fertiliser replacement values prescribed by the Dutch government (RVO, 2018). Application rates excluded nitrogen deposition and mineralisation from the soil.

Table 5.2. Fertiliser application rates and irrigation of the trial fields.

	2021		2022	
	Dry irrigated field	Wet rainfed field	Dry irrigated field	Wet rainfed field
N applied (kg ha^{-1})	480	380	445	336
Effective N applied (kg ha^{-1})	324	314	373	235
P applied (kg ha^{-1})	75	63	108	37
K applied (kg ha^{-1})	374	376	523	340
Number of irrigation events (#)	1	0	4	0
Total irrigation water applied (mm ha^{-1})	30	0	100	0

In terms of weather, 2021 and 2022 were contrasting years (Fig. 5.1). A nearby weather station (approximately 20 km away from the fields) reported 420 mm of rainfall during the growing season in 2021 and 320 mm in 2022. Whereas rainfall distribution from April 1 until September 30 was fairly homogeneous in 2021, 2022 came with a very dry July and August with only a few mm of rainfall. The cumulative precipitation deficit during the growing season was 70 mm in 2021 and 225 mm in 2022 (KNMI, 2023). Global radiation was similar to the long-term average in 2021 and above average in 2022. In terms of temperature, spring was relatively cold in 2021 and summer was relatively warm in 2022 with a heat wave in August.

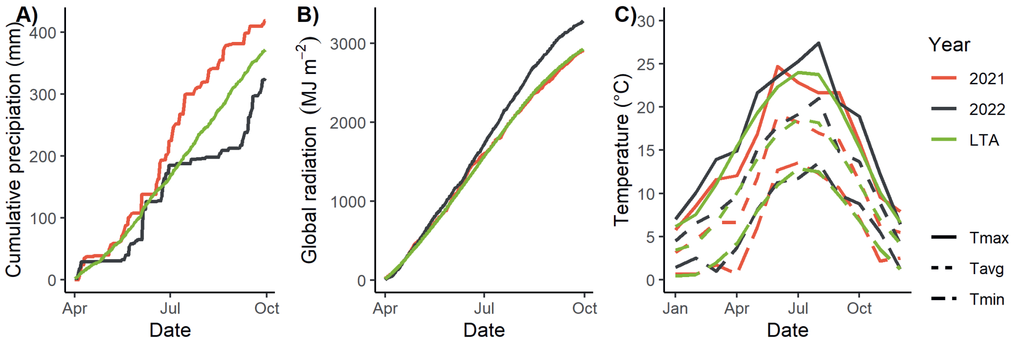


Figure 5.1. Cumulative precipitation (in mm) (A), cumulative global radiation (in MJ m^{-2}) (B), and monthly average temperature (in °C) (C) over time. Different colours indicate different years. LTA = long-term average (period 1992 – 2022).

5.2.2 Experimental design

An experiment was laid out with seed potato origin and planting date as treatments within each of the two field types, following a randomised complete block design with four replicates. The design and measurements were optimised based on a similar experiment running from 2015 – 2019 (Bartelen, 2016; Waverijn, 2020). Just before the first planting date, seed potatoes sized 40 – 50 mm were collected from the three different seed potato growers that supply seed tubers to van den Borne Aardappelen. Seed potatoes were collected from a single 1 m^3 storage box to make sure tubers from a single origin were stored under similar conditions. In the weeks between collecting the seed tubers and the second and third planting date, all seeds were stored in the same storage facility at the ware potato farm until planting. Hence, differences in storage were only created until the first planting date.

Planting dates were consistent with early, intermediate, and late planting at the farm. In 2021, seed tubers were planted on April 8, April 22, and May 6. In 2022, seed tubers were planted on April 12, April 26, and May 10. Seed potatoes were planted at 75 cm between rows and 33 cm within rows. Small hills were built manually directly after early and intermediate planting. After the final planting date, hilling was done on the whole trial field with a machine, resulting in a planting depth of 16 cm. In 2022, hilling was done incorrectly in six plots in the wet rainfed field, therefore these plots were discarded from the analysis.

5.2.3 Crop measurements

Two intermediate harvests were taken from a 2 m^2 plot (8 plants) in the third week of July and August and final harvest was taken from a 5 m^2 plot (20 plants) at the end of the growing after crop senescence in both years. The number of stems per plot were counted during both intermediate harvests. The average of the two measurements was used for further calculations. Tuber weight and underwater weight were measured, and the number tubers were counted at each harvest using a (semi-)automatic grading machine. Among tuber quality aspects, tuber size and dry matter content are important quality aspects for the potato processing industry. Tubers larger than 40 mm are marketable. Large tubers can give farmers a premium price. Because these different size classes are relevant for farmers, we assessed at each harvest total tuber yield (all tubers), marketable yield (tubers > 40 mm) and large-tuber yield (tubers > 50 mm). Underwater weight was recalculated to dry matter concentration using the equation established by Ludwig (1972). For frying potatoes, a dry matter content of at least 19.7% (underwater weight 360 g) is required. This was achieved in all plots (data not shown) and therefore not further considered.

5.2.4 Statistical analysis

Analysis of variance (ANOVA) was used to analyse treatment effects on potato yield and other crop characteristics. A Tukey's HSD test was used as a post-hoc test to assess significant differences between treatments, with the blocks added as random effects. Analysis was done in R version 4.2.2 using packages '*nlme*' and '*emmeans*'.

5.3 Results

5.3.1 Effect of seed potato origin on crop characteristics and yield

The number of stems per plant was significantly affected by seed potato origin in both years (Table 5.3). In addition, in 2021 an interaction was observed between origin and planting date. Origin A had significantly fewer stems per plant compared to the other two origins at all planting dates (Fig. 5.2). Origin C had significantly more stems per plant when planted late (5.7 stems plant^{-1}) than when planted early (4.7 stems plant^{-1}) ($p = 0.001$). In 2022, a three-way interaction was observed between origin, planting date and field type, and a two-way interaction between origin and field type (Table 5.3). On the wet rainfed field, no significant differences were observed in number of stems per plant (Fig. 5.2). On the dry irrigated field, origin B had significantly more stems per plant when planted late (6.3 stems plant^{-1}) than when planted early (5.0 stems plant^{-1}) ($p = 0.040$) and origin C had significantly more stems per plant when planted late (6.8 stems plant^{-1}) than when planted at the early (4.9 stems plant^{-1}) ($p = 0.009$) or intermediate planting date (5.2 stems plant^{-1}) ($p = 0.018$). In addition, origin C (6.8 stems plant^{-1}) had significantly more stems per plant than origin A at the late planting date (5.2 stems plant^{-1}) ($p = 0.005$).

Table 5.3. ANOVA table with p-values of main effects and interactions (at final harvest) for number of stems per plant, number of tubers per stem, number of tubers per plant, number of marketable tubers per plant, dry matter content, gross yield (all tubers), marketable yield (tubers > 40 mm) and large-tuber yield (tubers > 50mm). Bold values indicate statistical significance ($p < 0.05$).

Year	Fixed terms	Number of stems (# plant^{-1})	Number of tubers per stem (# stem^{-1})	Number of tubers (# plant^{-1})	Number of marketable tubers (# plant^{-1})	Dry matter content (%)	Gross yield (t ha^{-1})	Marketable yield (t ha^{-1})	Large-tuber yield (t ha^{-1})
2021	Origin (O)	**<0.001**	**<0.001**	**<0.001**	0.077	0.051	0.353	0.108	**0.003**
	Planting date (P)	**0.012**	**0.010**	0.095	**0.022**	0.166	**0.033**	0.076	0.180
	Field (F)	0.093	0.775	0.227	0.882	**0.004**	**<0.001**	**<0.001**	**<0.001**
	O x P	**<0.001**	**<0.001**	**0.015**	0.876	0.063	0.769	0.635	0.244
	O x F	0.742	0.214	0.428	0.529	0.339	0.741	0.508	0.157
	P x F	0.162	**0.002**	**<0.001**	0.559	0.138	0.984	0.784	0.287
	O x P x F	0.419	0.818	0.087	0.141	0.291	0.623	0.839	0.962
2022	Origin	**0.045**	0.436	0.608	0.129	0.263	0.127	0.064	0.138
	Planting date	**<0.001**	**<0.001**	**<0.001**	**<0.001**	**0.001**	**<0.001**	**0.002**	**0.020**
	Field	**0.003**	**0.016**	**0.046**	**0.005**	0.258	**<0.001**	**<0.001**	**<0.001**
	O x P	0.125	0.053	0.753	0.124	0.078	0.419	0.152	0.260
	O x F	**0.019**	**0.018**	0.196	0.560	0.505	0.846	0.995	0.704
	P x F	**0.037**	0.459	0.255	0.476	**0.012**	0.121	0.202	0.185
	O x P x F	**0.015**	0.146	0.349	0.147	0.171	0.061	0.088	0.191

5

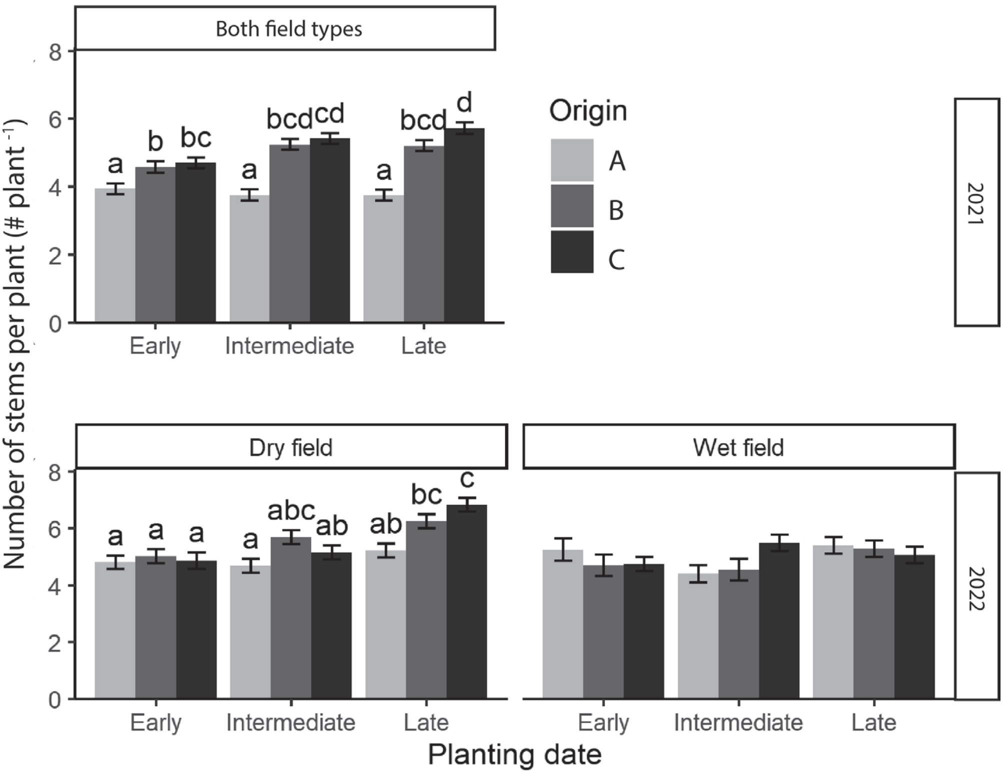


Figure 5.2. Number of stems per plant. Different shades of grey indicate different origins. No overlap in letters indicate significant differences between combinations of planting date and seed tuber origin. For the wet rainfed field there were no significant differences between planting dates and origins.

The number of tubers per stem was significantly different among origins in 2021, but not in 2022 (Table 5.3). In 2022, a significant interaction between origin and planting date was observed as well. At intermediate and late planting, origin B (3.3 and 3.4 tubers stem^{-1} respectively) and C (3.2 and 3.0 tubers stem^{-1} respectively) had significantly fewer tubers per stem than origin A (4.1 and 4.6 tubers stem^{-1} respectively), and compared to planting early (B: 3.9, and C: 4.1 tubers per stem^{-1}) (Fig. 5.3). In 2022, a significant interaction effect was observed between origin and field type (Table 5.3). Origin B had significantly more tubers per stem on the wet rainfed field (3.6 tubers stem^{-1}) than on the dry irrigated field (2.8 tubers stem^{-1}) ($p = 0.017$). This effect was not observed for the other origins.

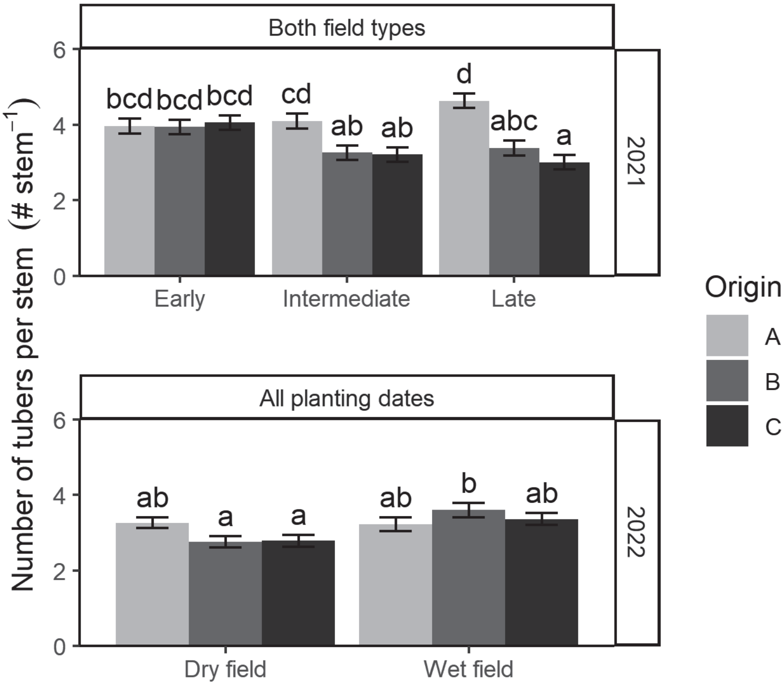


Figure 5.3. Number of tubers per stem for different origins and planting dates in 2021 and for different origins and field types in 2022. Different shades of grey indicate different origins. No overlap in letters indicate significant differences between combinations of planting date and seed tuber origin in 2021 and field type and seed tuber origin in 2022.

There was a significant interaction between origin and planting date on the number of tubers per plant in 2021 (Table 5.3). Comparing at final harvest, origin A produced significantly fewer tubers per plant (15.5 tubers plant^{-1}) than origin B (18.0 tubers plant^{-1}) (*p = 0.001*) and C (19.0 tubers plant^{-1}) (*p = <0.001*) when planted early (Fig. 5.4). When planted at the intermediate planting date, origin A produced significantly fewer tubers per plant (15.6 tubers plant^{-1}) than origin C (17.4 tubers plant^{-1}) (*p = 0.04*), but not than origin B (17.0 tubers plant^{-1}) (*p = 0.11*). There was no difference among origins in number of tubers per plant at final harvest for the late planting date. In 2022, there seemed to be a small difference in number of tubers per plant at final harvest when planted early (Fig. 5.4). However, there was no significant interaction between planting date and origin, nor was there a significant main effect of origin at final harvest (Table 5.3).

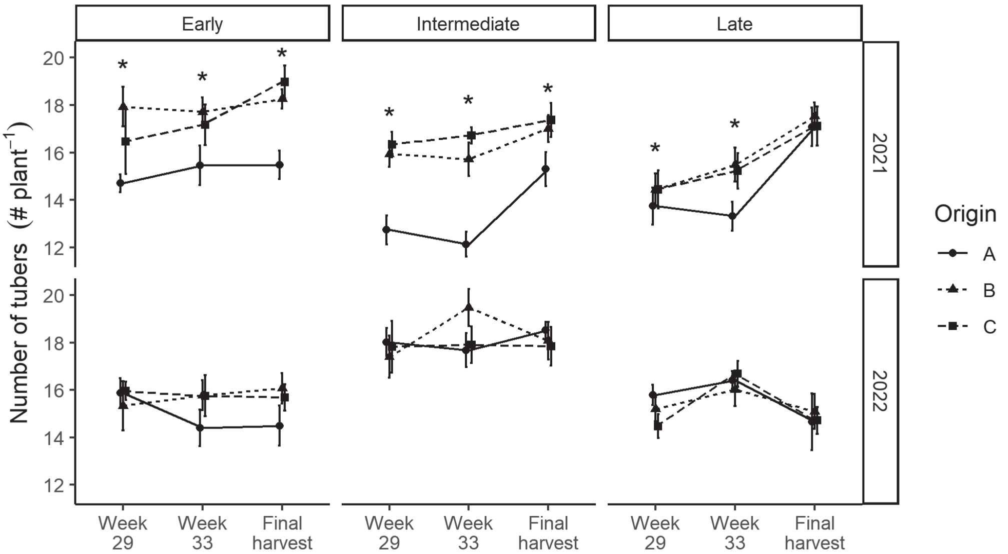


Figure 5.4. Number of tubers per plant at three different harvest moments for three different planting dates (Early, Intermediate, Late) and two different years. An asterisk indicates significant differences among origins.

There were no significant interaction effects between origin and planting date or field type on number of marketable tubers per plant or dry matter content (Table 5.3). Nor was there a significant main effect of origin on number of marketable tubers per plant or dry matter content.

Although crop characteristics were affected by seed potato origin, gross and marketable yield were not significantly different among origins in both years (Table 5.3, Fig. 5.5). Nor were any significant interactions found with field type and/or planting date. However, in 2021 there was a significant main effect of seed potato origin on large-tuber yield (tubers > 50 mm) (Table 5.3). Final large-tuber yield of origin A (54 t ha^{-1}) was significantly higher than that of origin B (46 t ha^{-1}) ($p = 0.003$) and C (48 t ha^{-1}) ($p = 0.029$) (Fig. 5.5). This effect seemed to be larger in the dry irrigated field than in the wet rainfed field (Fig. 5.5B), but the interaction was not significant. In 2022, no significant interaction or main effect of origin on large-tuber yield was found (Table 5.3).

5.3.2 Effect of seed potato origin on yield compared to planting date and field type

In both years, marketable yield was most strongly affected by the field type (Fig. 5.6A). Marketable yield was 16 t ha^{-1} higher in the wet rainfed field than in the dry irrigated field in 2021 and 17 t ha^{-1} higher in 2022. Planting date had the second largest effect on

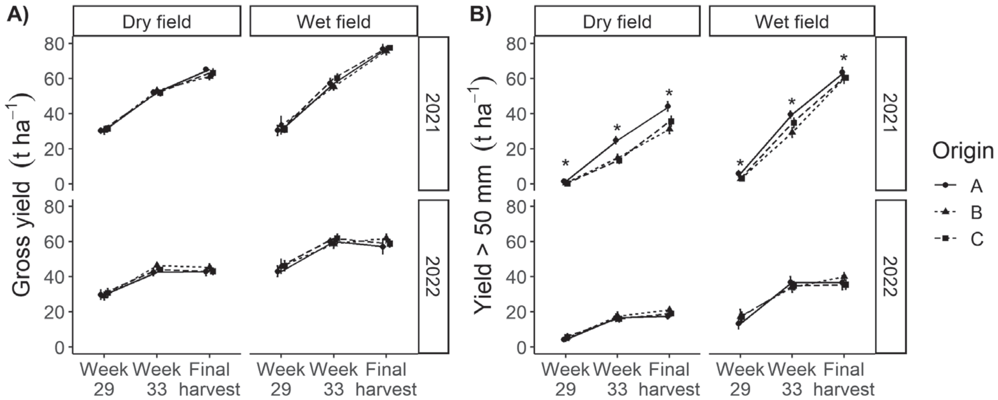


Figure 5.5. Gross yield (in t ha^{-1}) (A) and yield of tubers larger than 50 mm (in t ha^{-1}) (B) over time. An asterisk indicates significant differences among origins.

marketable yield: maximum marketable yield differences among planting dates were 5 t ha^{-1} in 2021 and 10 t ha^{-1} in 2022, with highest yield obtained at the early and intermediate planting dates. Seed potato origin did not affect marketable yield and was thus least important compared to field type and planting date.

The effect of field type and planting date on large-tuber yield were similar to the effect on marketable yield. In addition, in 2021 the effect of planting date on large-tuber yield was similar to the effect of origin, although only significant for the latter (Fig. 5.6B). In 2022, the effect of planting date on large-tuber yield was larger than the effect of origin. Overall, highest yield was obtained by planting on the wet rainfed fields and by avoiding late planting.

5.4 Discussion

5.4.1 Effect of seed potato origin on yield and plant characteristics

Our study revealed a small effect of seed potato origin on crop characteristics. Origin affected the number of stems per plant and the number of tubers per stem and per plant in both years, as a main effect and/or in interaction with planting date or field type. In 2021, this resulted in fewer tubers per plant for origin A compared to the other origins (Fig. 5.4). Because origin A produced relatively fewer tubers per plant, large-tuber yield for this origin was 6 – 8 t ha^{-1} higher compared to the other two origins. This result is consistent with earlier findings that, generally, a lower number of tubers per plant results in larger tubers (Haverkort et al., 1990; Mackerron et al., 1988; Ozgen and Palta, 2005). Nevertheless, origin did not significantly affect gross and marketable yield production. Neither did the effect of origin on gross or marketable yield interact with planting date or field type.

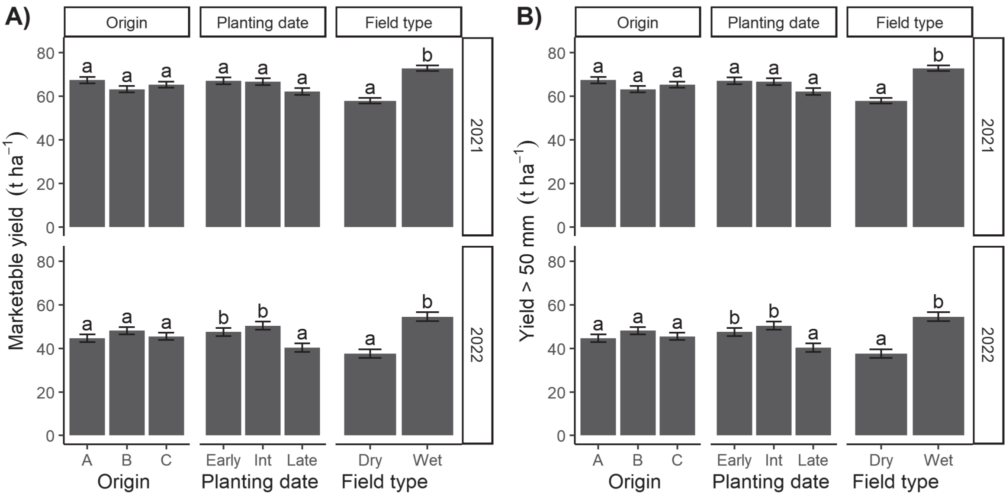


Figure 5.6. Main effect of origin, planting date, and field type on marketable (A) and large-tuber yield (B) (in t ha^{-1}). Different letters within the same factor indicate significant differences among treatments. Int stands for the intermediate plating date.

The result of this experiment is in line with earlier studies exploring yield variability on the same farm. Mulders et al. (2021) found that seed potato origin affected stem length of the ware potato crop, but this effect did not result in significant yield differences among origins. Bartelen (2016) and Waverijn (2020) conducted experiments on the same farm to evaluate the effect of seed potato origin on crop characteristics and yield. These studies found a significant effect of origin on number of stems and tubers. In addition, sometimes a higher large-size tuber yield was observed. Yet, there were no significant differences in gross yield among origins, despite the differences in crop characteristics. A limitation of these two studies was that the tubers were harvested prematurely. With our experiment we can confirm and conclude that for the variety Fontane physiological characteristics of seed origin is not a main yield influencing factor on this farm. We consider it likely that this conclusion can be extended to other farms in the Netherlands considering some conditions. All seed potatoes in the Netherlands are managed well, and, moreover, the seed producers for this farm were carefully selected, and may hence produce seed potatoes of above average quality. Seed tubers of lower quality, either from a phytosanitary point of view or from a physiological age point of view may well translate in lower performance (Crosslin et al., 2006; Motyka-Pomagruk et al., 2021). Also, effects of physiological age and seed origin may only reveal under extreme environmental conditions, such as very late planting or very cold conditions after planting.

Other studies in different contexts found yield differences when planting seed tubers with different physiological ages because of differences in storage temperature (O'Brien et al., 1983; Rykaczewska, 2010; Vakis, 1986; Van Loon, 1987) or production locations (Johansen et al., 2008; Wiersema and Booth, 1985; Wurr, 1979). However, these studies were done under controlled conditions, with larger extremes in terms of storage temperature. For instance, Rykaczewska (2010) compared storage temperatures of 4 °C to storage temperatures of 18 °C, while in our case storage temperatures varied throughout the storage season between 4 °C and 10 °C (after temperatures were slowly lowered at the start of the storage season). Differences in production locations in cited references were mostly related to difference in altitude of the seed production field. Such experimental situations are useful to get to distinct differences in physiological status of the seed potatoes. However, they do not reflect variability in storage and production conditions of seed tubers in a farming setting, and certainly not in a homogenous (in terms of climate and management) country such as the Netherlands.

5.4.2 Effect of planting date and field type on yield in comparison with seed potato origin

Large ware potato yield variability among production fields in the Netherlands has been found consistently (Mulders et al., 2021a; Silva et al., 2020a; Chapter 2). Previous studies have shown that part of the ware potato yield variability was attributed to differences in management factors such as sowing and harvesting dates, irrigation use, cultivated varieties, fungicide use and preceding crops (Mulders et al., 2021a; Silva et al., 2020a, 2017a; Chapter 3). We considered three factors to evaluate differences in yield: field type, planting date and seed potato origin. We showed that highest yield was obtained by planting on the wet rainfed field, and by avoiding late planting. In both years of investigation, marketable yield on the wet rainfed field was more than 15 t ha^{-1} higher than on the dry irrigated field (Fig. 5.6). This shows that the applied irrigation could not compensate entirely the impact of water limitation. Late planting resulted in a 5 t ha^{-1} yield penalty in 2021 and 10 t ha^{-1} in 2022, although only significant in the second year (Fig. 5.6). The beneficial effect of early planting on yield is well known (e.g., Johnson et al. 1996; Silva et al. 2020). However, our result nuances the conclusion that early planting always leads to the highest yields. In the second year, highest yield was obtained with the intermediate planting date, although the effect was not significant (Fig. 5.6).

As already concluded, we found no effect of seed potato origin on marketable yield and no interaction effect between origin, planting date and field type. Hence, within the variation of seed origins and conditions of our experiment, it does not pay off to design an optimal planting strategy that maximises marketable yield at farm level with these three factors. However, in 2021 large-tuber yield was higher for the origin with fewer tubers and stems per plant. Furthermore, data suggest a larger positive effect of seed origin on large-tuber yield on the dry irrigated field than on the wet rainfed field (Fig. 5.5B), although the interaction between origin and field type was not significant. This suggests that in 2021 origin A, which produced fewer tubers per plant, could have been planted best on dry irrigated fields to obtain the highest large-tuber yield at farm level.

Our analysis uses knowledge on the performance of seed tubers in hindsight of the growing season. However, to adjust planting as a farmer it is essential to know potential differences among origins ahead of the growing season. If indeed origins that produce fewer tubers per plant perform best on the dry irrigated field, it is essential to have a diagnostic tool that can assess differences in physiological age and associated expected physiological properties of the seed potatoes (Struik, 2007). Chronological age or the physiological age index as proposed by (Caldiz et al., 2001) are insufficient as a tool to compare seed potatoes of different origins (Struik et al., 2006), as it does not capture differences in production location and field type of the seed crop that also constituted differences among origin in this study.

5.5 Conclusion

We found a significant effect of seed origin on number of stems and number of tubers per stem in both years. This resulted in a significant effect of origin on total number of tubers in the first year. In that year, the origin with the lowest number of tubers also produced the highest yield of tubers larger than 50 mm. Despite this small effect of seed potato origin on crop characteristics, origin did not significantly affect gross and marketable yield production. Furthermore, there was no interaction with planting date and/or field conditions of the ware potato crop. In two distinct years, the highest yield was obtained on the wet rainfed field and by avoiding late planting. Hence, we conclude that for maximizing ware potato yield of the variety Fontane in the Netherlands, effects of planting date and field type outweighed the effect of seed tuber origin.

5.6 Acknowledgements

We are very grateful to van den Borne Aardappelen for managing the field trial. In addition, we thank all colleagues, students and other volunteers who contributed to the field work that was required for this study. This research is part of the project Potato Gap NL (project number 16891) of the research programme Holland Innovative Potato which was (partly) financed by the Dutch Research Council (NWO).

5

Chapter 6: Field monitoring shows scope for reducing environmental impact of ware potato cultivation in the Netherlands without compromising yield

This chapter will be submitted as:

Ravensbergen, A. P. P., van Ittersum, M.K., Hijbeek, R., Kempenaar, C., & Reidsma, P. Field monitoring shows scope for reducing environmental impact of ware potato cultivation in the Netherlands without compromising yield.

Abstract

Arable farming in Northwest Europe is highly intensive. In the region, high yields are obtained, but simultaneously there is considerable variation in nutrient, crop protection product en water use and use efficiency. Inefficient use has contributed to several environmental problems, such as nitrate leaching and emissions of crop protection products. There is a need to reduce environmental emissions which contributes to a more circular and sustainable agriculture in Northwest Europe. Here, we take ware potato production in the Netherlands as an example cropping system to assess if there is scope to reduce input levels and environmental impact without compromising yield. We determined variability in yield, use and use efficiency of nitrogen (N), phosphorus (P), potassium (K) and pesticides as well as water productivity (WP) based on on-farm observations of 96 ware potato fields in the Netherlands, cultivated on clay and sandy soils. In addition, we assessed if relatively high performance could be achieved on multiple environmental indicators simultaneously. Average N surplus was 265 kg N ha^{-1} on clay soils and 139 kg N ha^{-1} on sandy soils and varied among fields by a factor three. Phosphorus and K input exceeded P and K output on clay soils by 33 and 105 kg ha^{-1}, respectively, while on sandy soils P and K balances were close to zero. Mean WP was 43 kg dry matter (DM) mm^{-1} ha^{-1} and ranged from 30 to 60 kg DM mm^{-1} ha^{-1} for both soil types. In terms of crop protection product use, lowest and highest use differed by a factor four. Surprisingly, across the on-farm data, no relationship was found between outputs and input rates. Consequently, input rates were the most important drivers to explain variability in resource use efficiency and environmental impacts. At the same time, a comparison across multiple indicators simultaneously showed that it was possible to achieve relatively high yields with relatively low N surplus, high WP, and low crop protection product use. Yet, in the best performing fields N surplus and crop protection product use did not meet environmental targets. Hence, this means that further reductions (beyond current best practice) in input use will be needed to meet environmental targets for N surplus or crop protection product use reduction.

Keywords

Solanum tuberosum | on-farm observations | yield response | environmental impact | resource use efficiency

6.1 Introduction

Sustainability assessments of food production systems require not only an evaluation of yield, but also of environmental indicators. In Northwest Europe, crop productivity is high, but it is also coupled with high input rates and high emissions and environmental impact (van Grinsven et al., 2019). One reason for relatively high input rates is farmers' perception that recommended rates are insufficient to reach maximum yield (Rajsic and Weersink, 2008). Another reason is that the cost of overapplication is lower compared to the cost of underapplication (i.e., when it results in yield reduction) (Meyer-Aurich and Karatay, 2019). However, lowering input rates and thereby increasing resource use efficiency and reducing emissions to the environment is essential to move towards a more circular and sustainable agriculture (Schröder et al., 2011; Spiertz, 2010). The need for a more sustainable production has been expressed by the European Commission though its Farm to Fork strategy, which aims to reduce chemical pesticide use by 50% and reduce nutrient losses by 50%, which should be accompanied by a reduction in artificial fertiliser use of at least 20% (European Commission, 2020).

Arable farming in the Netherlands is among the most intensive in Northwest Europe (van Grinsven et al., 2019) and contributes to several environmental problems (Ros et al., 2023). Nitrate leaching poses a threat to groundwater quality, particularly below sandy soils (de Vries et al., 2021; Oenema et al., 2005). The use of crop protection products is high, putting pressure on the groundwater and surface water quality and organisms (Schipper et al., 2008). Recent drought events resulted in yield reduction (van Oort et al., 2023) and lower nutrient utilisation (Ros et al., 2023). Use of heavy machinery under unfavourable (wet) conditions, poses a threat to soil compaction (Alakukku et al., 2003; van den Akker and Hoogland, 2011). Lastly, high concentrations of Phosphorus in soils are a cause of lower surface water quality (Chardon and Schoumans, 2007).

Ware potato is an important crop in the Netherlands, as it is cultivated on 14% of the arable land and on 50% of the arable farms (CBS, 2022). It serves as a key cash crop for farmers (Devaux et al., 2021; Goffart et al., 2022). Its yield is on average around 70% of potential yield (Silva et al., 2020, 2017), the theoretical maximum yield determined by radiation, cultivar, and CO_2 concentration (van Ittersum et al., 2013). Compared to other important arable crops in the Netherlands, nitrogen surplus is among the highest (Silva et al., 2021). In addition, crop protection product use in ware potato exceeds the use in other crops such as sugar beet and winter wheat by more than 50% (CBS, 2022). On the other hand, potato uses water very efficiently as water productivity is at least 50% higher than that for spring onion and cereals (Silva et al., 2020).

Despite high average ware potato yields, large yield variability has been observed among fields, farms, and regions (Mulders et al., 2021; Silva et al., 2020, 2017). At the same time, there is also considerable variation in nutrient, crop protection product and water use (De Jong and De Snoo, 2002; Silva et al., 2021, 2020). Yet, this large variability in resource use comes with very low responses to the input rates (Mulders et al., 2021; Silva et al., 2021, 2017). This suggests that current resource use may exceed the required input rates to achieve current yield levels and that there may be scope to reduce input levels and environmental impact without reducing yield. However, previous studies were either local (Mulders et al., 2021), assessed on single indicators or used secondary data (Silva et al., 2021, 2017), which lacked detail for accurate field level assessments. Given the multiple environmental challenges it is important to assess if multiple resources (water, nutrients, crop protection products) can be used more efficiently simultaneously or whether trade-offs in achieving targets occur.

In this study, a detailed assessment is conducted of resource use, use efficiency and environmental impact of ware potato production at field level in the Netherlands for multiple indicators. We used on-farm observations of 96 fields across the Netherlands. The aims were twofold: (1) to quantify and explain variability in resource use, use efficiency and environmental impact in potato production in the Netherlands and (2) to assess the feasibility of reducing multiple environmental impacts simultaneously.

6.2 Materials and Methods

6.2.1 Indicators

In this study, we assessed the environmental performance of ware potato production at field level across the Netherlands. Indicators that were assessed included crop yield, nutrient (nitrogen (N), phosphorus (P), potassium (K)) use efficiency, nutrient (N, P, K) surplus, (irrigation) water productivity and crop protection product use (active ingredients and environmental impact points).

Crop yield

Yield represents the harvested product per land unit and was expressed in t fresh tubers ha^{-1}.

Nutrient use

We quantified N use efficiency (NUE) and N surplus in line with the guidelines of the EU Nitrogen Expert Panel (EUNEP) framework (EUNEP, 2015; Quemada et al., 2020). NUE was calculated as N output divided by N input (Eq. 6.3) and expresses how efficiently N is used, but was not corrected for soil N supply. This calculation method is most suitable for analysing farmers' data (compared to field experiments) as for farmers no information on the soil N supply (yields without any N fertiliser) is available. Nitrogen surplus (Eq. 6.4) was calculated as N input minus N output and indicates the potential losses to the environment.

$$N\ output\ (kg\ N\ ha^{-1}) = yield * DM\% * N_{concentration} \qquad \text{Eq. 6.1}$$

$$N\ input\ (kg\ N\ ha^{-1}) = N_{appl} + N_{depo} \qquad \text{Eq. 6.2}$$

$$NUE\ (kg\ N\ kg\ N^{-1}) = \frac{N\ output}{N\ input} \qquad \text{Eq. 6.3}$$

$$N\ surplus\ (kg\ N\ ha^{-1}) = N\ input - N\ output \qquad \text{Eq. 6.4}$$

where $yield$ is the yield obtained in a field (t fresh tubers ha^{-1}), $DM\%$ is the dry matter percentage of the harvested tubers, $N_{concentration}$ is the nitrogen concentration in the tubers (g N kg DM^{-1}), N_{appl} is the amount of N applied by the farmer (kg N ha^{-1}) and N_{depo} is the yearly atmospheric N deposition (kg N ha^{-1}). In this study, we expressed N application in two manners: as total N and as effective N input. The first considers all applied N, whilst the latter only considers the N that was expected to become available in the year of N application. For mineral fertilisers, first year availability was set at 100% whilst for organic fertiliser, N application was multiplied with N fertiliser replacement values (RVO, 2018; see Section 6.2.3) which are well below 100%.

The EUNEP framework provided provisional reference values for NUE between 50 and 90% (EUNEP, 2015). It assumes that below 50%, N is used inefficiently, whilst above 90% there is a risk of nutrient depletion of the soil. In this study, we considered 50% NUE as a minimum desirable NUE. However, we ignored the upper level of 90%. Although there might be a negative N balance within a single cropping season, crop rotations in the Netherlands are well fertilised and therefore we do not expect major soil N depletion over a whole crop rotation.

Initially, the EUNEP framework set a provisional reference for N surplus at 80 kg ha^{-1} as a maximum allowable N surplus (EUNEP, 2015). However, they also noted that reference values could or should be adapted to the local context. In this study, we used therefore – besides the EUNEP reference - also a national reference value. For the national threshold value, we considered N surplus to be too high when NO_3^- concentration in the groundwater could be expected to become higher than 50 mg NO_3^- L^{-1}, as stated in the EU Nitrates Directive (EC, 1991). Ros et al. (2023) identified an N surplus threshold of 50 kg N ha^{-1} on sandy soils and 125 kg N ha^{-1} on clay soils, which we used in this study.

For P and K, we assessed nutrient use efficiency and nutrient surplus in a similar way to that for N. Previously, it was found that current P and K fertiliser application rates are not limiting ware potato production in the Netherlands (Chapter 4). Hence, from a resource use efficiency perspective, we considered a neutral nutrient balance as desirable. In the

Netherlands, there is a long history of high P application rates with soil P accumulation and high soil P fertility, which have resulted in agricultural P losses to the environment, lowering surface water quality. With such high soil P stocks, it could be argued that crop P uptake does not need to be compensated fully by P application to the soil (Janssen, 2017). However, as this study focusses on single season fertilisation strategies, this is not considered in this study. Potassium losses from agricultural fields are not an environmental concern.

Water productivity

Water productivity (WP) determines how much yield is obtained per mm of seasonal water available (Eq. 6.7), which was calculated similar to Silva et al. (2020).

$$SM(mm) = Z * \theta_{planting} - Z * \theta_{harvest} \quad \text{Eq. 6.5}$$

$$TSWA\ (mm) = SM + P + I + CR - DP \quad \text{Eq. 6.6}$$

$$WP\ (kg\ DM\ mm^{-1}) = \frac{yield * DM\%}{TSWA} * 1000 \quad \text{Eq. 6.7}$$

Where SM is the soil moisture available during the growing season (mm), Z is the maximum rooting depth of the crop (mm), $\theta_{planting}$ is the soil moisture concentration at planting ($mm^3\ mm^{-3}$), $\theta_{harvest}$ is the soil moisture concentration at harvest ($mm^3\ mm^{-3}$), TSWA is the total seasonal water available (mm), *P* is the effective precipitation during the growing season (mm), *I* is the effective applied irrigation by the farmer (mm), *CR* is the water that became available through capillary rise (mm) and *DP* is the water that was lost from the soil profile due to deep percolation (mm).

Irrigation water productivity (IWP) determines how much yield is obtained per mm of irrigation water applied. We considered actual (Eq. 6.8) and potential (Eq. 6.9) IWP.

$$IWP_a(kg\ DM\ mm^{-1}) = \frac{(yield * DM\%) - Yw_{rf}}{I} * 1000 \quad \text{Eq. 6.8}$$

$$IWP_p(kg\ DM\ mm^{-1}) = \frac{Yw_{irr} - Yw_{rf}}{I} * 1000 \quad \text{Eq. 6.9}$$

Where Yw_{rf} is the simulated water-limited potential yield under rainfed conditions (in t DM ha^{-1}), and Yw_{irr} is the simulated water-limited potential yield under (partially) irrigated conditions applied by the farmer (in t DM ha^{-1}). Irrigation water productivity was only calculated on sandy soils as these are more prone to drought stress and as these are more frequently irrigated.

Crop protection product use

In Dutch potato cultivation, crop protection products are used to protect the crop against weeds, pests, and diseases and to kill immature haulms of the potato crop before harvesting. We determined total crop protection product use by calculating the total amount of applied active ingredients. In addition, we used the Environmental Yardstick tool for pesticides to calculate the Environmental Impact Points (EIP) ha^{-1}, which is calculated using Eq. 6.10 (Reus and Leendertse, 2000). The tool combines information on the quantity and harmfulness of the applied product to calculate the environmental impact of the applied crop protection products on three environmental compartments: groundwater, surface water and soil. The EIP are calculated for each of the three indicators separately. To get a total score, we summed the environmental impact points of the three compartments into a single indicator. Environmental impact points are calculated for a standard dose of 1 kg or L ha^{-1} and multiplied with the applied dose to get the actual EIP.

$$EIP = \sum_i {}^{PEC_i}/_{MPC_i} * 100 * dose \qquad \text{Eq. 6.10}$$

Where i indicates the environmental compartment, *PEC* is the predicted environmental concentration, *MPC* is the maximum permissible concentration set by the Dutch government and *dose* refers to by the applied amount in the field (in kg or L ha^{-1}).

6

Crop protection product use efficiency was expressed as the yield divided by the total amount of EIP.

6.2.2 Study area

This study uses data collected previously for another objective (*i.e.,* a yield gap analysis). Here, we will give the main elements of the data and data collection, relevant for our research objective. For further details the reader is referred to Chapter 3.

In 2020 and 2021, 96 farmers' fields were selected in six important potato growing regions in the Netherlands: Tholen/West-Brabant (1), Zuid-Holland (2), Flevoland (3), Noord-Brabant (4), Limburg (5) and Drenthe (6) (Fig. 6.1). Soils in the first three regions are characterised as clay soils and in the latter three regions as sandy soils. In regions with clay soils, we selected fields with the variety Innovator. In regions with sandy soils, we selected fields with the variety Fontane. Both varieties are among the main cultivated varieties on the respective soil types. We selected eight potato fields per region per year. Hence, we collected data from a total of 48 fields for each soil type and for each year. Over the two years, in total 55 different farmers participated in this research; from each farmer, 1 to 2 fields per year were selected. Overall, the selected fields represented a broad range in soil conditions (Table 6.1).

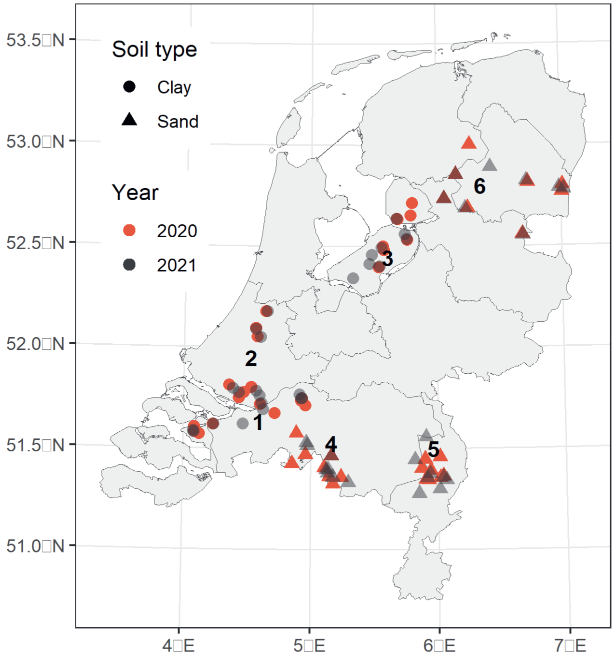


Figure 6.1. Map of the Netherlands with field locations. Different colours indicate different years. Different symbols indicate different soil types. Different numbers indicate different potato growing regions in the Netherlands.

The years 2020 and 2021 were distinct in terms of weather conditions. The first year can be characterised as dry to average in terms of rainfall, with cumulative precipitation over the growing season ranging from 153 to 387 mm (long-term average 416 mm) (Fig. 6.2A) (KNMI, 2022a). The second year of the experiments can be characterised as an average year, with cumulative precipitation over the growing season ranging from 317 – 461 mm. The cumulative precipitation deficit was on average 200 mm in 2020 and 70 mm in 2021 (KNMI, 2022b). Cumulative global radiation was 15% higher in 2020 and 3% higher in 2021 than the long-term average (Fig. 6.2B). Lastly, temperatures in 2020 were higher than those in 2021. In 2020, the summer was relatively hot with a heat wave in August, while in 2021 spring was relatively cold (Fig. 6.2C).

6.2.3 Data collection

Crop and field measurements

Crop yield was measured from four three m^2 plots after haulm killing or natural haulm senescence, or just before harvesting by the farmer in case haulms had not senesced. A six kg subsample was taken per plot to measure underwater weight, which was then recalculated to dry matter concentration (Ludwig, 1972). A pooled one kg subsample was

***Table 6.1. Soil properties of the 96 fields (2020 and 2021). Indicated for each parameter are the mean, standard deviation, minimum value, and maximum value. For more details on the measurements the reader is referred to Appendix D.1 or* Chapter 3.**

		2020				2021			
Variable	Soil type	Mean	SD	Min	Max	Mean	SD	Min	Max
SOM (%)	Clay	3.9	1.4	2.4	8.2	4.1	0.7	2.7	5.4
	Sand	5.0	2.2	2.5	9.5	4.9	3	2.7	17.4
pH (-)	Clay	7.6	0.2	7.3	7.9	7.5	0.2	6.7	7.7
	Sand	5.5	0.4	4.7	6.2	5.3	0.5	4.2	6.1
Plant available N	Clay	116	60	12	238	91	46	14.5	167
(mg kg^{-1})	Sand	60	50	16	202	60	53	11.4	227
Plant available P	Clay	2.1	2.1	0.3	6.9	1.6	1.2	0.5	4.9
(mg kg^{-1})	Sand	5.8	3.9	0.6	15.2	5.8	5.1	0.3	16.4
Plant available K	Clay	132	94	39	459	157	71	82	305
(mg kg^{-1})	Sand	95	62	27	265	133	72	37	341
Total N (in the	Clay	1.8	0.7	1.0	3.7	1.8	0.4	1.0	2.6
soil) (g kg^{-1})	Sand	1.6	0.5	0.8	2.7	1.6	0.7	1.0	4.1
Total P (g kg $^{-1}$)	Clay	0.9	0.1	0.7	1.2	0.9	0.1	0.8	1.2
	Sand	0.7	0.2	0.3	1.3	0.9	0.3	0.4	1.5

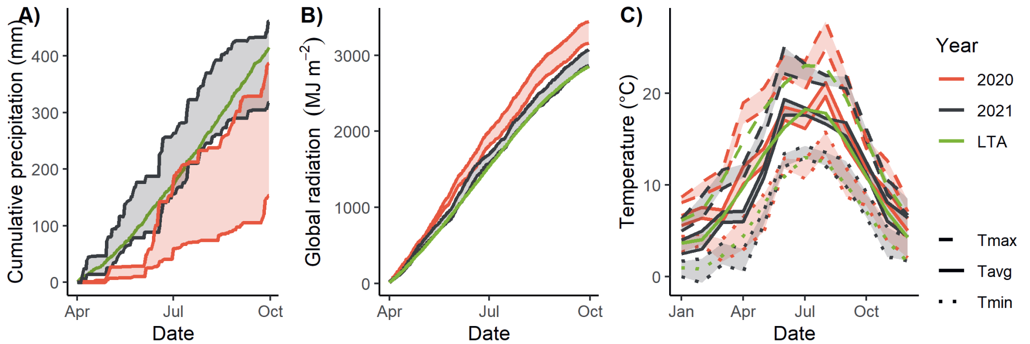


Figure 6.2. Cumulative precipitation (in mm) (A), Cumulative global radiation (in MJ m^{-2}) (B) and Temperature (in °C) (C) over time. Different colours indicate different years. Shaded areas present the spread in variables observed across the six regions. LTA = long-term average (period 1991-2021).

oven dried for nutrient concentration measurements. Dried samples were digested with a mixture of H_2SO_4-Se and salicylic acid (Novozamsky et al., 1983). In these digests, total N and P were measured with a Skalar san++ system and total K was measured with a Varian AA240FS fast sequential atomic absorption. Soil penetration resistance was measured using a penetrologger (Royal Eijkelkamp, 2022) at the beginning of the growing season when it could be assumed that the soil moisture content was at field capacity (van de Steeg and van Diepen, 1997). The measurements were repeated on three locations per plot. Rooting depth was estimated as the average depth at which the measured soil penetration resistance was larger than two MPa. Maximum rooting depth was set at 50 cm, which is where the majority of the potato roots are, although they can go deeper (van Woerden and Cevaal, 1976). To explain variability in resource use efficiency and nutrient surplus (Section 6.2.4), additional crop and soil measurements were used. See Appendix D.1 for a full overview of the crop and soil measurements.

Crop management information

Farmers were asked to report their crop management information for each field. Farmers informed us when they applied irrigation and how much they applied per event. Type, timing and quantity of the applied fertilisers and crop protection products were also recorded. We processed the information on applied fertilisers to calculate the N, P and K application rates. When nutrient concentrations of organic manures were not measured, we used governmental default values to calculate the amount of nutrients in organic fertilisers (RVO, 2023a). The amounts were calculated as the sum of farmer applied nutrients starting from the harvest of the previous crop till the end of the potato growing season and excluded mineralisation. We calculated effective N input in the same way, but used N fertiliser replacement values from the Dutch government to correct for the non-readily available nitrogen (RVO, 2018). N deposition was taken from Atlas Natuurlijk Kapitaal (2023) and averaged per region. From two fields, the crop management information was incomplete, and these fields were excluded in analyses that required crop management details.

Soil water balance

The crop growth model WOFOST (ten Den et al., 2022) was coupled with the soil hydrological model SWAP (Kroes et al., 2017) to simulate a daily soil water balance. For model simulations, it was assumed that there was an interaction between soil moisture and groundwater on clay soils (i.e., groundwater levels are shallow) and that there was a free drainage situation on sandy soils (i.e., groundwater levels are deep). Groundwater levels were collected from the 'Landelijk Hydrologisch Model' (NHI, 2023). Rainfall data was taken from the farmers' weather station when available, or otherwise from the nearest KNMI-weather station. Soil type and profile were taken from the BOFEK soil map (Heinen et al., 2022). Model output provided information on capillary rise, deep percolation, and soil moisture content. In addition, SWAP-WOFOST was used to estimate water-limited potential yield under partially irrigated conditions (Yw_{irr}), water-limited potential yield under rainfed conditions (Yw_{rf}), and transpiration reduction due to drought and/or oxygen stress. The latter variable was used in regression analyses (see Section 6.2.4). For more detailed information on this modelling, the reader is referred to Chapter 3.

6.2.4 Data analysis

Linear regression was used to test the relationship between nutrient surplus or water productivity and explanatory variables (see Appendix D.1 which explanatory variables were included). To avoid the risk of overfitting, a selection had to be made of variables to be included in the statistical models. First, a full model was made using a dependent variable and all measured variables as explanatory variables. Then, we used the dredge function from the MuMIn package (Barton and Barton, 2015) to run all possible combinations of reduced models, using R version 4.2.2. We added a restriction to the function that only one to a maximum of four explanatory variables could be included in the reduced linear models. Furthermore, we excluded all combinations of variables that were correlated to each other (Pearson correlation test > 0.5). After running all models, the top-ranking models were selected based on the AICc criterium, where all models with ΔAICc < 3 were considered to be top-ranking ones. Finally, a model was tested with all explanatory variables that were included in one or more of the top-ranking linear models. However, if explanatory variables were correlated to each other, we included only the variable that was used in the majority of the top-ranking models. If explanatory variables were correlated to each other and were used in an equal share of top-ranking models, multiple models were tested and the model with the lowest AICc was chosen as the final statistical model. We included variety and year as an explanatory variable in all linear models. The final model was not constrained to a maximum number of variables. Nutrient use and crop protection product use efficiency followed an exponential relationship with inputs. Hence, for explaining variability of these parameters, non-linear regression was used.

The environmental performance was assessed across the indicators yield, N surplus (considering total N), WP and EIP. Each field received a ranking score for each indicator based on its relative performance compared to other fields (considering all 94 fields). A high rank was given to a high yield, high WP, low N surplus or low EIP (1 is high, 94 is low). After scoring each field on the four indicators, the average rank was calculated across the three impact indicators (N surplus, WP and EIP). Finally, the rank of each individual indicator was plotted against the mean rank of the three impact indicators and linear regression was used to test if a high performance of one indicator was correlated to a high average performance across the impact indicators. When there was a (positive) correlation, we concluded that multiple objectives can be achieved at the same time. When there was no correlation, we concluded that performance for one indicator was unrelated to performance the other indicators. In addition, for each cultivar, the 12 best performing fields (based on mean rank of the three impact indicators) were compared to the 12 worst performing fields. We assessed whether there was a significant difference between the two groups for each of the indicators. A student t-test was used for normally distributed data and a Mann-Whitney U test was used for non-normally distributed data. Normality was assessed using a Shapiro-Wilk test.

6.3 Results

6.3.1 Crop yield

Average gross yield of the variety Innovator cultivated on clay soils was 63 t ha^{-1} in 2020 and 54 t ha^{-1} in 2021 (Fig. 6.3). Average gross yield of the variety Fontane cultivated on sandy soils was 62 t ha^{-1} and 64 t ha^{-1} in 2021. Among fields, large variability in potato yields was observed with Innovator yields ranging from 48 t ha^{-1} to 77 t h^{-1} in 2020 and from 34 to 61 t ha^{-1} in 2021, and Fontane yields ranging from 40 t ha^{-1} to 83 t ha^{-1} in 2020 and from 53 t ha^{-1} to 81 t ha $^{-1}$ in 2021.

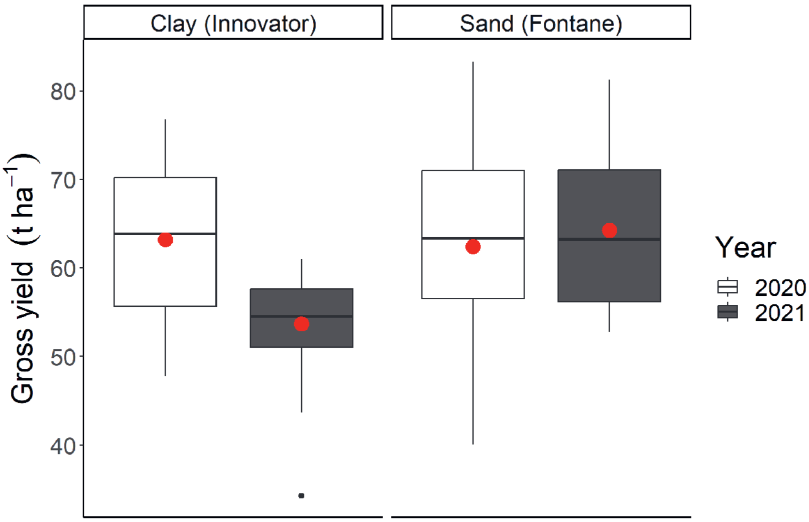


Figure 6.3. Gross yield (in t ha^{-1}) for two different years and cultivars (and respective soil types). The red dots indicate the mean yield for each cultivar (and soil type) and year combination. The boxplots indicate the minima, 1st quantiles, medians, 3rd quantiles and maxima.

6.3.2 Nutrient use

On clay soils (with the potato variety Innovator), average total N input was 448 kg N ha^{-1} which equalled 365 kg effective N ha^{-1} (Fig. 6.4). Variability in N input rates was large, ranging from 271 kg N ha^{-1} to 978 kg N ha^{-1} for total N input and from 256 kg N ha^{-1} to 568 kg N ha^{-1} for effective N input. N output values were much lower than N input with an average N output of 183 kg N ha^{-1}, ranging from 119 to 237 kg N ha^{-1}. Average NUE on clay soils was 44% for total N input and 52% for effective N input (Table 6.2). Average N surplus was 265 kg N ha^{-1} for total N input and 182 kg N ha^{-1} for effective N input. Variability in terms of NUE and N surplus was large, and only in part of the fields the environmental thresholds were met. Considering total N input, NUE was above 50% (the EUNEP reference value for minimum N use efficiency) in only 32% of the potato fields. The national and EU thresholds for N surplus were met in only 4% of the fields with clay soils. Considering effective N input, NUE was above 50% in 49% of the potato fields. The EU threshold for N surplus was met in only 6% of the fields and the national threshold was met in 21% of the fields.

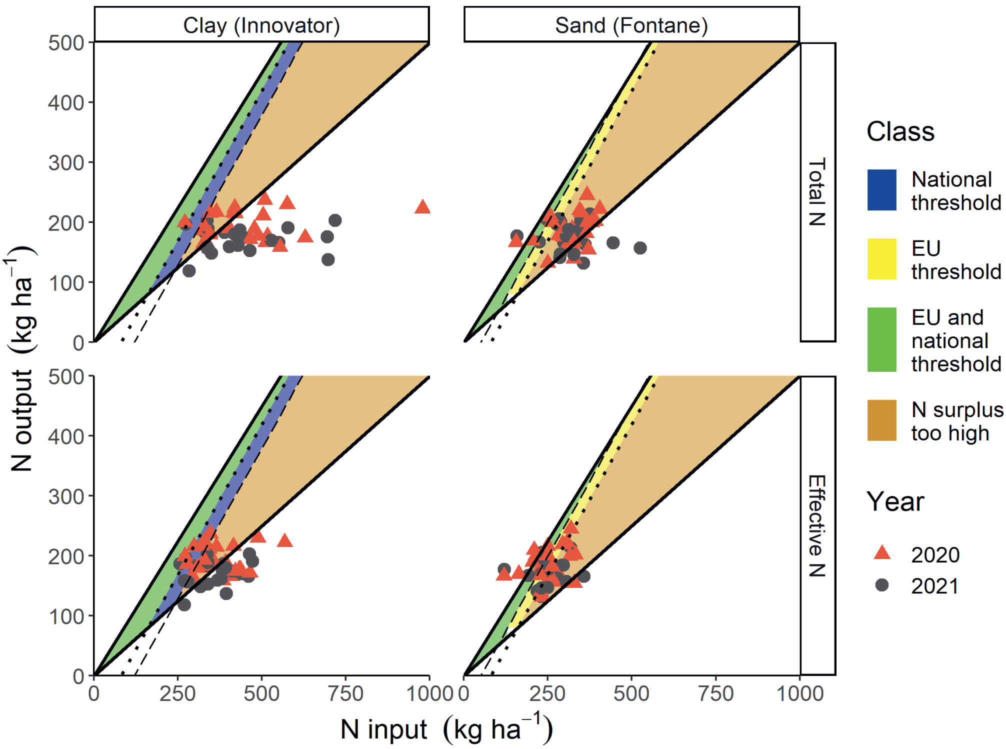


Figure 6.4. N output (in kg N ha^{-1}) against N input (in kg N ha^{-1}) for two different years and soil types (and respective cultivars). N input is expressed as total N input or as effective N input. Different colours and shapes of symbols indicate different years. The upper solid line indicates an NUE of 90% and the lower solid line an NUE of 50%. The dotted line indicates an N surplus of 80 kg ha^{-1}, in line with the EUNEP framework (EUNEP, 2015). The dashed line indicates the critical N surplus ha^{-1} above which NO_3^- concentrations in the ground water is likely to exceed 50 mg l^{-1}. For clayey soils, this N surplus value is 125 kg ha^{-1} and for sandy soils 50 kg ha^{-1}. The brown area indicates when NUE is within the desired range, but N surplus is too high. The green colour indicates when NUE is within the desired range and when critical N surplus meets the EU and national threshold. The blue and yellow colours indicates when NUE is within the desired range and when critical N surplus meets only the national threshold (blue) or the EU (yellow) threshold.

On sandy soils (with the potato variety Fontane), average total N input was 319 kg N ha^{-1} which equalled 250 kg effective N ha^{-1} (Fig. 6.4). Variability in N input rates was large ranging from 155 kg N ha^{-1} to 525 kg N ha^{-1} for total N input and from 120 kg N ha^{-1} to 357 kg N ha^{-1} for effective N. N output values were much lower than N input with an average N output

Table 6.2. Mean NUE and N surplus considering total N input or effective N input and % of fields that meet the threshold for NUE, N surplus according to the EU threshold and N surplus according to the national threshold.

	Total N input		Effective N input	
	NUE		NUE	
	Average (%)	% of fields that meet threshold	Average (%)	% of fields that meet threshold
Clay (Innovator)	44	32	52	49
Sand (Fontane)	59	59	75	75

	N surplus		N surplus	
	Average (kg N ha^{-1})	% of fields that meet threshold (EU/national)	Average (kg N ha^{-1})	% of fields that meet threshold (EU/national)
Clay (Innovator)	265	4 / 4	182	6 / 21
Sand (Fontane)	139	19 / 11	70	57 / 32

of 180 kg ha^{-1} and ranging from 132 to 245 kg ha^{-1}. Average NUE on sandy soils was 59% for total N input and 75% for effective N (Table 6.2). Average N surplus was 139 kg N ha^{-1} for total N input and 70 kg N ha^{-1} for effective N. Variability in terms of NUE and N surplus was large and only in some of the fields the environmental thresholds were met. Considering total N input, NUE was above 50% in 59% of the potato fields on sandy soils. The EU threshold for N surplus was met in 19% of the fields and the national threshold for N surplus in 11% of the fields. Considering effective N input, NUE was above 50% in 75% of the potato fields. The EU threshold for N surplus was met in 57% of the fields and the national threshold was met in only 32% of the fields with sandy soils.

Regression analysis showed that N surplus significantly increased with higher total N input rates ($p < 0.001$), which was an almost 1:1 relationship (Fig. 6.5). On average, for every 50 kg N extra applied, N surplus increased by 49 kg N ha^{-1}, indicating that very little of the extra N was taken up by the crop. Between the two years, mean N surplus was 24 kg ha^{-1} higher in 2021 than in 2020 ($p < 0.001$). N surplus was also significantly higher under water-limited conditions ($p = 0.007$; $R^2 = 0.97$). N surplus increased by 15 kg N ha^{-1} for every 50 mm increase in drought and/or oxygen stress.

The observed relation between N surplus and N input and drought and/or oxygen stress also held for effective N input (Appendix D.2). No relationship was found between N surplus and plant available N, P or K, neither when using total N input nor when using effective N input. For NUE, a similar strong (but negative) exponential relation was found between NUE

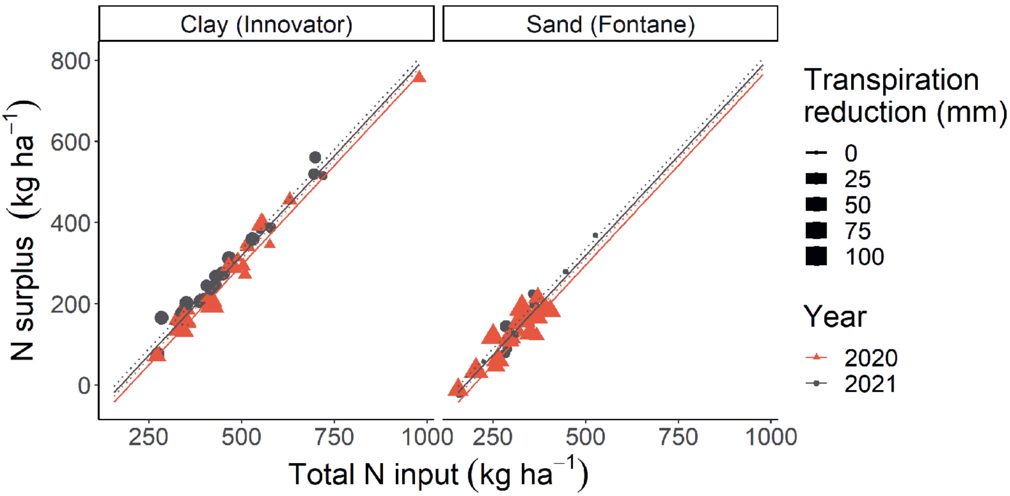


Figure 6.5. N surplus (in kg ha^{-1}) against total N input (in kg ha^{-1}) for two different years and soil types (and respective cultivars). The solid lines indicate the regression lines without any transpiration reduction due to drought and/or oxygen stress. The dotted lines indicate the regression lines with 100 mm transpiration reduction due to drought and/or oxygen stress. Different colours and shapes of symbols indicate different years. Different symbol sizes indicate differences in transpiration reduction due to drought and/or oxygen stress.

and total N input (or effective N input) (Appendix D.2), only no significant effect of transpiration reduction due to drought and/or oxygen stress was found. As for N surplus, no relationships were found between NUE and plant available nutrients. 6

On clay soils (Innovator), P and K applied were much higher than P and K output (Fig. 6.6). On average, P input was 56.4 kg ha^{-1} and P output was 23.2 kg ha^{-1}, which translated into a positive P balance of 33.2 kg ha^{-1}. Among fields, the P balance ranged from a negative balance of -31.5 kg P ha^{-1} to a positive one of 118.0 kg P ha^{-1}. Average K input was 336 kg ha^{-1} and K output 231 kg ha^{-1}, which translated into an average positive K balance of 105 kg ha^{-1}. Among fields, the K balance ranged from a negative balance of -123 K ha $^{-1}$ to a positive balance of 409 kg ha^{-1}.

On sandy soils (Fontane), P and K applied were in the same range as P and K output (Fig. 6.6). On average, P input was 30.4 kg ha^{-1} and P output was 31.1 kg ha^{-1}, with translated in a P balance of -0.6 kg ha^{-1}. Among fields, the P balance ranged from a negative balance of -39.7 kg P ha^{-1} to a positive balance of 61.3 kg P ha^{-1}. Average K input was 279 kg ha^{-1} and K output 278 kg ha^{-1}, which translated in an average positive K balance of 1 kg ha^{-1}. Among fields, the K balance ranged from a negative balance of -228 K ha^{-1} to a positive one of 292 kg ha^{-1}. Different allocation strategies of nutrients within a rotation and within the farm explain why balances are more positive on clay soils than on sandy soils; on clay soils, relatively more nutrients are applied to the ware potato crop.

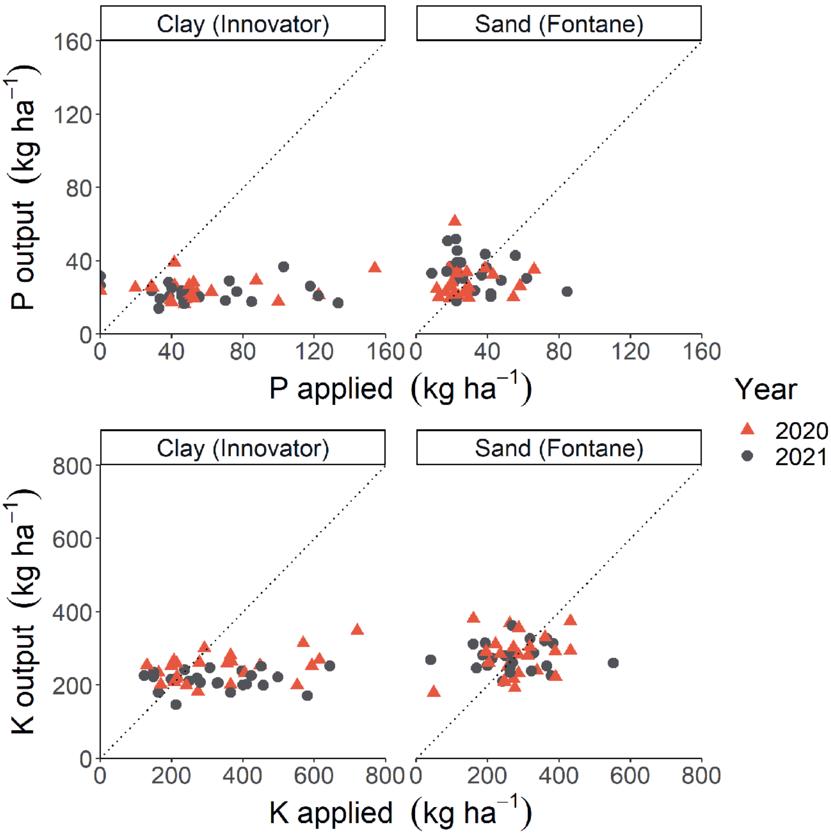


Figure 6.6. P output against P applied and K output against K applied (in kg ha-1) for two different years and soil types (and respective cultivars). Different colours and symbols indicate different years. The dotted lines indicate 1:1 lines where nutrient input equals nutrient output.

Phosphorus and K output were not correlated to P and K input. For both soil types (and respective varieties), variability in P and K use efficiency was driven by P and K input rates. For P, P use efficiency was also related to transpiration reduction due to drought and/or oxygen stress (Appendix D.2).

6.3.3 Water productivity

Average WP was 42.3 kg DM mm^{-1} ha^{-1} for Innovator on clay soils and 43.5 kg DM mm^{-1} ha^{-1} for Fontane on sandy soils (Fig. 6.7). When used as a single explanatory variable, seasonal available water was significantly negatively related to WP. However, using the best model selection method, seasonal available water was not considered an explanatory variable (this relation is therefore not presented in Fig. 6.7). Instead, variability in WP was explained by four other variables, where WP increased with higher emergence rate, later planting date, larger water stress and higher crop protection product use (Table 6.3). The explained variability in water productivity using all four variables together was relatively low (R^2 = 0.22).

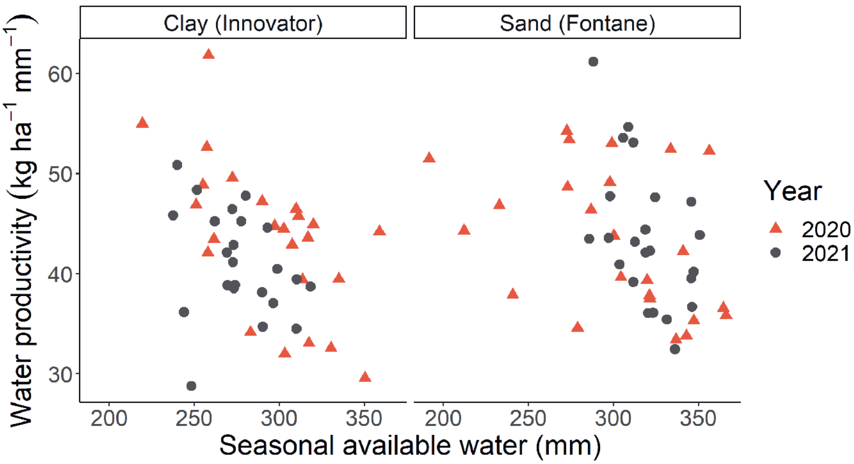


Figure 6.7. Water productivity (in kg DM mm^{-1} ha^{1}) against seasonal available water (in mm) for two different years and soil types (and respective cultivars). Different colours and symbols indicate different years. Water productivity is calculated according to Eq. 6.7.

Table 6.3. Linear regression model results for explaining variability in WP.

	Water productivity (all fields)
Intercept (mean Innovator, 2020)	-27.94
Variety (Fontane vs Innovator)	-0.30
Year (2021 vs 2020)	-0.25
Emergence rate (%)	0.37*
Planting date (doy)	0.27***
Total water stress (mm)	0.074*
Environmental impact points (EIP ha^{-1})	0.002*
R^2-adjusted	0.22

*** p < 0.05 ** p < 0.01 *** p < 0.001**

Irrigation water use was highly variable among years and fields on sandy soils (Fontane). In 2020, 19 out of 24 fields were irrigated, whilst in 2021 nine out of 23 fields were irrigated. On the irrigated fields, on average 89 mm was applied in 2020 and 45 mm in 2021. Both IWPa (considering actual yield) and IWPp (considering simulated water-limited yield) were significantly higher in 2020 compared to 2021 (both p = 0.002). Irrigation water productivity was not related to the amount of irrigation applied. Hence, for 2020 this implies that irrigation water was on average used effectively, as the yield gain did not decrease or increase with more irrigation water applied (Fig. 6.8). In 2021, IWPp was around zero and IWPa negative, suggesting that irrigation water use was redundant. Actual irrigation water productivity could be negative because actual yields were lower than simulated rainfed water-limited yields. This is due to negative yield effects of pests and diseases.

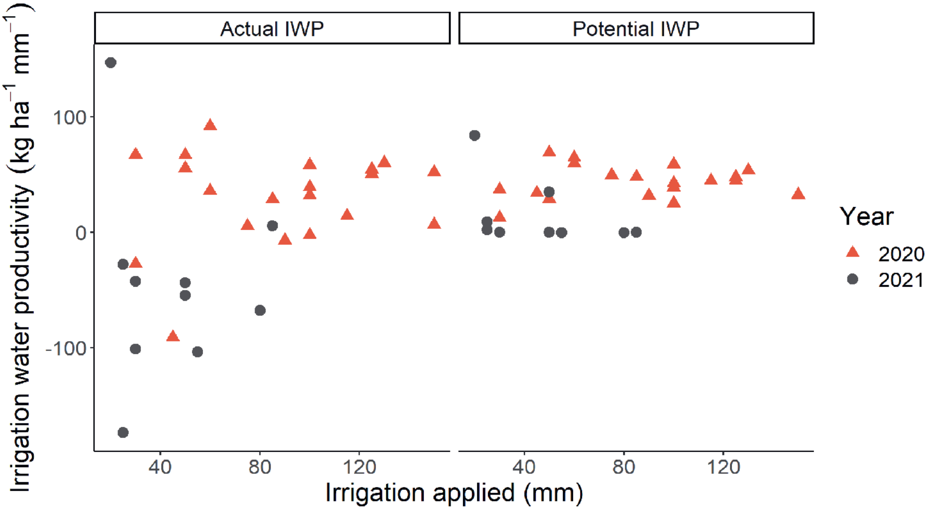


Figure 6.8. Actual and potential irrigation water productivity (IWP) on sandy soils (Fontane). Actual irrigation water productivity is calculated with measured actual yield minus simulated rainfed water-limited potential yield (Eq. 6.8) and potential irrigation water productivity is calculated with simulated (partially) irrigated water-limited potential yield minus simulated rainfed water-limited potential yield (Eq. 6.9). Red triangles are data from 2020. Different colours and symbols indicate different years.

6.3.4 Crop protection product use

Crop protection product use was highly variable among fields for both Innovator (clay) and Fontane (sand) (Fig. 6.9A). The number of EIP ranged from 979 to 4038 for Innovator in 2020, from 464 to 3062 for Innovator in 2021, from 1782 to 4384 for Fontane in in 2020, and from 1485 to 5131 for Fontane in 2021. On average, 60% of the EIP was attributed to the application of fungicides, 35% to herbicides and 5% to other crop protection products. Of the fungicides, 56% of the EIP originated from crop protection products against late blight, 36% from products against early blight and 7% from products against both early and late blight. Total EIP was 36% higher for Fontane on sandy soils than for Innovator on clay soils, which was mostly attributed to the higher application rates of fungicides. Of the environmental compartments, aquatic organisms were most affected by application of crop protection products. On the other hand, on clay soils (Innovator) soil organisms were least affected by application of crop protection products and on sandy soils (Fontane) groundwater was least affected (Fig. 6.9B). Previous analysis showed a significant relation between EIP use and yield, but the explained variability was extremely low (R^2 0.01) (Chapter 3). Variability in crop protection product use efficiency was driven by crop protection product input rates (Appendix D.3).

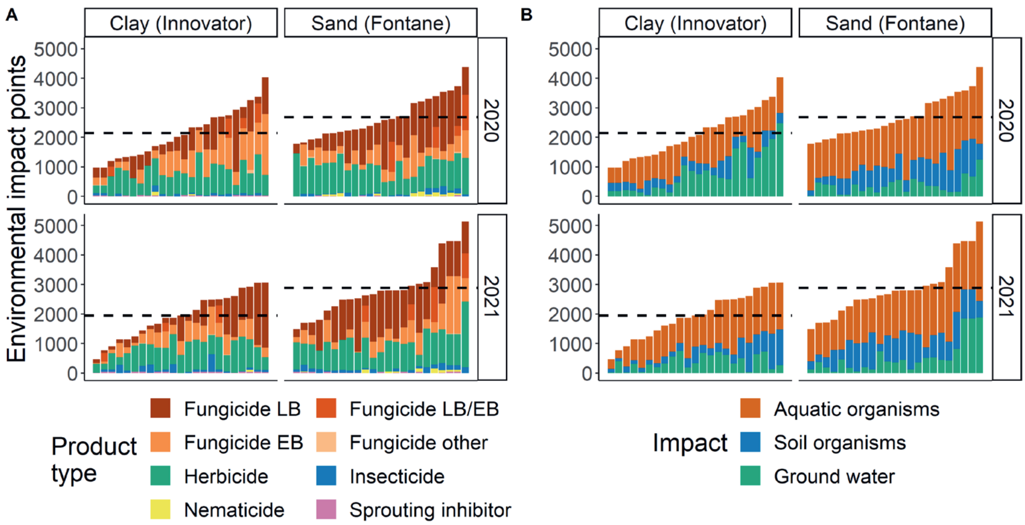


Figure 6.9. Environmental impact points from crop protection product application for two different years and soil types (and respective cultivars). Different colours in panel A indicate environmental impact points per product type. Different shades of orange indicate fungicides. Different colours in panel B indicate how the environment is impacted. Fungicide LB and/or EB refer to fungicides that protect the crop against late and/or early blight. Fungicide other refers to fungicides that are used against other fungi. Horizontal dashed lines show average EIP.

6.3.5 Performance across multiple indicators

A positive correlation was observed between the mean rank (comparing all 94 fields) of the three impact indicators (N surplus, WP and EIP) and yield, N surplus, WP and EIP (Fig. 6.10). Hence, this shows that it was possible to perform relatively well on all four indicators simultaneously. To provide an example, it means that in farmers' fields with a relatively high yield, on average a relatively low N surplus, high WP and low EIP were obtained as well.

A comparison of the 12 best performing fields with the 12 lowest performing fields showed that the division among groups based on the mean rank across the three impact indicators (N surplus, WP, and EIP) still held for the individual indicators: both Innovator (clay) and Fontane (sand) had a significantly lower N surplus, higher WP, and lower EIP in the best performing group (Fig. 6.11). In addition, for Fontane yield was significantly higher in the best performing group as well. For Innovator, yield was not significantly different between groups. However, when the one field with high yield in the low performance group was omitted, a significant difference ($p = 0.008$) between the Innovator groups was observed as well.

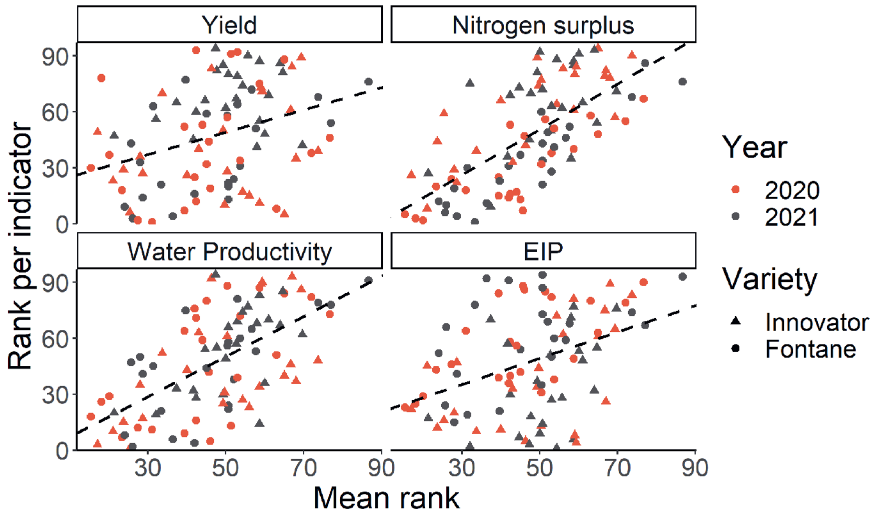


Figure 6.10. Rank for each indicator against the mean rank across three input indicators (N surplus, WP and WIP). A low (high) number indicates a high (low) performance on the indicator. Different colours indicate different years. Different symbol shapes indicate different varieties (and the respective soil types). The dashed lines indicate significant regression lines.

A comparison of the two groups of fields revealed that 42% of the fields in the low performing group were affected by yield reducing factors, whereas none of the fields in the high performing group were affected by yield reducing factors. Hence, overall it shows that it was possible to achieve relatively high yield, with relatively low N surplus, high WP and low EIP simultaneously and that reducing factors partly influenced the performance of the fields across different indicators.

6.4 Discussion

In this study, we used detailed data obtained through frequent on-farm monitoring to quantify and explain variability in resource use, use efficiency and environmental impacts. The results showed that large variability exists among farmers' fields. Differences between highest and lowest N surplus were a factor three (Fig. 6.5), between highest and lowest water productivity (WP) a factor two (Fig. 6.7) and between highest and lowest crop protection product use a factor four (Fig. 6.9). Overall, input rate was the most important driver to explain variability in resource use efficiency and environmental impact (Fig. 6.5, Appendix D.2 Fig. D.12-16). Other studies have also found no or limited yield response to inputs in the Netherlands (Mulders et al., 2021; Silva et al., 2020, 2017), which strongly suggests that current input rates exceed the required amounts to obtain actual yield levels and that input rates can be reduced while yields are maintained. Although N and P input rates of particular individual fields were above the reference application rates (RVO, 2023b),

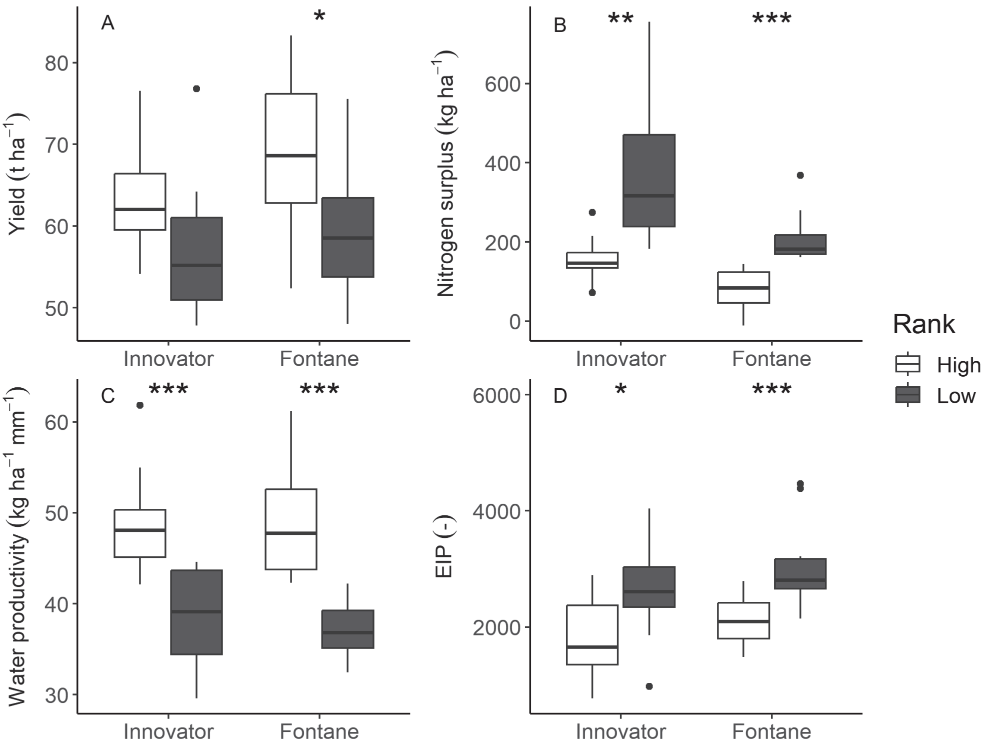


Figure 6.11. Performance on four indicators (A) yield (in t ha^{-1}), (B) nitrogen surplus (in kg ha^{-1}), (C) water productivity (in kg ha^{-1} mm^{-1}) and (D) environmental impact points (EIP) (-) for fields with a high average rank on the three impact indicators (N surplus (considering total N), WP and EIP) compared to performance of fields with a low average rank on the three impact indicators. A different shade of grey of the boxplots indicates different groups of mean performance across the three impact indicators. An asterisk indicates a significant difference between high and low: * $p < 0.05$ ** $p < 0.01$ *** $p < 0.001$.

we have no reason to assume that farmers are not operating within the current legislation space, which normally applies to the entire farm, rather than to individual crops or fields.

6.4.1 Nutrient management

Nitrate leaching is one of the main environmental concerns in the Netherlands and is caused by a too large N surplus at field level (de Vries et al., 2021; Oenema et al., 2005). Considering effective N input, average N surplus was 62 kg N ha^{-1} above the national environmental threshold on clay soils and 20 kg N ha^{-1} on sandy soils. However, effective N input was calculated using a N fertiliser replacement value that is based on short-term nutrient uptake responses. In the Netherlands, organic inputs are often applied over multiple cropping seasons and total N input is high, resulting in expected higher N fertiliser replacement values than the values we used and are considered by the Dutch government (Hijbeek et al., 2018; Schröder, 2005). When considering total N input, average N surplus was 145 kg N ha^{-1} above the national environmental threshold on clay soils and 89 kg N ha^{-1} on sandy soils, which is higher than previously reported (Silva et al., 2021). To comply with environmental thresholds, there will be a need to reduce N surplus. Our results show that the N surplus of only a limited number of fields remained within the environmental thresholds.

Variability in N surplus was explained, in decreasing order of importance, by N input rates, year and transpiration reduction due to drought and/or oxygen stress (Fig. 6.5). Hence, N surplus can be reduced by irrigating crops and/or draining fields more adequately and by lowering N input rates; the effect of the latter is much larger than the former. The correlation between N input rate and N surplus was almost 1:1 and reducing N input by 50 kg ha^{-1} resulted in an average N surplus reduction of 49 kg ha^{-1} (Fig. 6.5). Reducing drought stress by 50 mm could reduce N surplus by 15 kg ha^{-1}. It is striking that no relationships were found between N surplus and nutrient availability in the soil. This, in combination with a lack of yield response to input rates larger than 200-250 kg effective N ha^{-1}, suggest that N inputs can be reduced till 200-250 kg effective N ha^{-1} without compromising yield, provided that N is applied at the right time, right place and in the right form (Fixen, 2020). This is confirmed in a recent study with different N treatments on sandy soils with the variety Fontane. No significant yield differences were found between the high N treatment (245-275 kg effective N ha^{-1}) and the low N treatment (185-215 kg effective N ha^{-1}) (van Geel et al., 2023). Prikaziuk et al. (2022) found no significant yield differences for the same varieties and soil types comparing N rates of 75-85 kg N ha^{-1} to 320-375 kg N ha^{-1}. Hence, there is a need to further investigate by how much N input can be reduced without affecting crop yield.

Phosphorus and K balances were positive on clay soils and neutral on sandy soils, which is in agreement with earlier findings in Chapter 4. Historical high P application rates have caused a high P status in Dutch soils (Oenema and Roest, 1998; Steén, 1997). Associated P losses from these rich soils, have led to eutrophication of surface water bodies. However, our results showed that P fertilisation was balanced on sandy soils. Therefore, extra leaching due to fertilisation of potatoes is not expected. On clay soils, there was a large positive P balance. However, it should be acknowledged that on these soils fertilisation is often applied to a crop rotation rather than to an individual crop. Since potato is a cash crop, farmers tend to apply relatively more fertilisers before the potato crop. Hence, although there was a positive balance for a single growing season, the P balance should be evaluated over a crop rotation to assess the risk for increased P leaching. In the used dataset, information on fertilisation over a whole crop rotation was unavailable. With regards to K there are no negative environmental effects. Its nutrient balance followed a similar pattern as for P, with a neutral balance on sandy soils and a positive balance on clay soils.

6.4.2 Water and irrigation water productivity

As for the other inputs investigated, water productivity was highly variable among farmers' fields. In our study, WP increased with higher emergence rate of the crop, a later planting date, reduced drought and oxygen stress and larger pesticide application rates (Table 6.2). Hence, water productivity increased with a better crop coverage, through improved water utilisation. Water was also used more efficiently under water limited conditions. Previously, using the same dataset it was found that yield of Innovator (clay soil) was partly explained by crop protection product use, although this correlation was very weak (Chapter 3). Perhaps, this could also explain the improved water utilisation with large pesticide application rates.

In addition to water productivity, irrigation water productivity is a relevant indicator as irrigation water is extracted from existing water reserves which can impact water availability in dry years when availability is limited. In average or wet years, ware potato needs relatively little irrigation and generally sufficient water is available in the Netherlands. On the other hand, in dry years, water could become limiting and restrictions on irrigation could be imposed. In such conditions, it is important to use irrigation water more efficiently, particularly on sandy soils in the south of the Netherlands, which are more vulnerable to drought stress and where less water is available (Diogo et al., 2017). In this study, a dry year (2020) and a wet year (2021) were included. Average irrigation water use in sandy soils (Fontane) was higher in 2020 than in 2021 (Fig. 6.8). Variability in irrigation water productivity was found, but could only be explained by year and not by any of the explanatory variables. It showed that in 2020 irrigation water was used effectively, regardless of the application rate, whereas in 2021 irrigation was mostly redundant. An important note is that the outcome was partly based on model results (as the yield without irrigation was modelled instead of measured). To assess actual irrigation water productivity under existing field conditions, on-farm experimentation including treatments with and without irrigation will be needed.

6.4.3 Crop protection product use

Variability in crop protection product use (as expressed in EIP) varied by a factor four across the different potato fields. The most frequently sprayed type of crop protection product in potato was fungicides (Fig. 6.9). Fungicides are sprayed mostly preventive against early and late blight. However, adverse weather conditions or limited availability of machinery or labour due to the scale of the farm can prevent farmers from spraying at the optimal timing. As a result, when late blight infection is expected or detected, farmers have to apply curative fungicides against late blight instead of preventive fungicides. The former have a larger environmental impact than the latter, which partly explains the variability in EIP among fields.

Even though there was large variability in crop protection product use, it may be too easy to conclude that the use of crop protection products can be reduced in all fields. It is important to acknowledge the financial risk of (severe) yield reduction due to a late blight infection, which could completely devastate a crop (Haverkort et al., 2009). Decision support systems aid in understanding under what conditions crop protection product use can be reduced, which results in a lower usage than when farmers apply at regular and fixed intervals (Cooke et al., 2011; Small et al., 2015). It is estimated that 36% of Dutch ware potato growers use a decision support system for late blight control (Cooke et al., 2011). Hence, its use could be more widely applied. Furthermore, introducing late blight resistant varieties in combination with low-input fungicide application has the potential to largely reduce fungicide application, although its use cannot be reduced to zero (Haverkort et al., 2008; Kessel et al., 2018).

6.4.3 Performance across indicators

Given the multiple environmental challenges in the Netherlands, it is important to not only consider one indicator at a time, but to evaluate fields across multiple indicators simultaneously. A comparative analysis across indicators showed that the individual scores of yield, N surplus, WP and EIP were correlated to the mean rank of the three impact indicators jointly (N surplus, WP and EIP) (Fig. 6.10). Hence, it showed that relatively high yields, low N surplus, high WP and low EIP could be obtained simultaneously. This was further confirmed by the pairwise comparisons of the high performing groups compared to the lowest performing groups. On average, the 12 best performing fields had a significantly lower N surplus, higher WP and lower EIP than the 12 worst performing fields (Fig. 6.10). In addition, it was found that the highest performing fields had a higher yield, although for Innovator (clay soil) this was only significant when the high yielding field in the low performance group was excluded. Low performance was partly caused by reducing factors such as pest and diseases. These results suggest that it is possible to achieve high yields while reducing environmental impact of potato cultivation and that to do so controlling the negative effects of pest and diseases on crop yield is a relevant management factor.

Despite the reduced environmental impact in the best performing group of fields, an important note is that the average total N surplus among the twelve best performing fields was still above the environmental threshold (Fig. 6.4 & 6.11), both for Innovator on clay soils and Fontane on sandy soils. Also, the average crop protection product use of the 12 best performing fields would not meet the 50% reduction (as targeted in the Farm to Fork strategy (European Commission, 2020)) compared to the average pesticide use of all fields. Hence, this means that current best practice is insufficient to meet environmental targets for N surplus or crop protection product use reduction, if applied to the 96 potato fields.

Further research should focus on assessing the effects of these targets on ware potato production over a whole crop rotation.

6.5 Conclusions

This study revealed large variability among ware potato fields in resource use, use efficiency and environmental impact in the Netherlands. Differences between fields with highest and lowest N surplus were a factor three, between highest and lowest water productivity a factor two and between highest and lowest crop protection product use a factor four. Also, P and K balances were highly variable among fields. For all indicators, variability in resource use efficiency was driven by variability in input rates and relationships between outputs and input rates were not found. Average performance across the three impact indicators, N surplus, WP, and crop protection product use, showed that it was possible to achieve high yields combined with relatively low N surplus, high water productivity and low crop protection product use. Hence, we conclude that there is scope to reduce input use and environmental impact, without compromising yield. However, in the best performing fields average total N surplus was still above the desired national and EU environmental thresholds. In addition, average crop protection product use among the best performing fields would not meet the target reduction of 50% compared to average use among all fields, as targeted by the European Farm to Fork strategy. Hence, this means that further reduction in input use, beyond current best practice, will be needed to meet environmental targets for N surplus or crop protection product use reduction. Further research should evaluate such effects on crop production over the entire crop rotation.

6.6 Acknowledgements

We are very grateful to all farmers who participated in this study and allowed us access to their fields. In addition, we thank all colleagues, students and other volunteers who contributed to the extensive field work campaign that was required for this study. Furthermore, we would like to thank Katerina Mouka for processing part of the data and doing initial analyses. This research is part of the project Potato Gap NL (project number 16891) of the research programme Holland Innovative Potato which was (partly) financed by the Dutch Research Council (NWO).

Chapter 7: General discussion

7.1 General findings

The overall aim of this thesis was to quantify and explain variability in yield, yield gaps, resource (water, nutrients and crop protection products) use efficiency and environmental impact of ware potato production in the Netherlands. The analysis was done in three steps, focusing on (1) quantifying spatiotemporal yield variability, (2) quantifying production levels and explaining yield (gap) variability and (3) quantifying and explaining variability in resource use, use efficiency and environmental impact of ware potato production (Fig. 7.1). Chapter 2 revealed that spatial yield variability was largest among and within fields, smaller among farms and smallest among regions. Temporal yield variability was equally or more important than spatial yield variability at all spatial scales. In Chapter 3, we estimated the average potential yield (Yp) at 16.4 t DM ha^{-1} for Innovator on clayey soils and 17.5 t DM ha^{-1} for Fontane on sandy soils. Modelling showed that Yp could be increased by planting earlier and/or harvesting later. Average water-limited potential yield (Yw) was estimated at 12.6 t DM ha^{-1} for Innovator and 15.4 t DM ha^{-1} for Fontane. Average actual yield (Ya) was 12.0 t DM ha^{-1} for Innovator on clayey soils and 13.4 t DM ha^{-1} for Fontane on sandy soils. On clayey soils, yield limitation was mostly attributed to oxygen stress as a result of water excess in both years. On sandy soils, drought stress was the most important yield gap influencing factor in the dry year 2020, and yield reducing factors the most important in the wet year 2021. Frequent field monitoring revealed that a wide variety of reducing factors were affecting actual crop yields. Yield reduction was partly related to pest and diseases, and partly to poor agronomic practices, such as planting cut seed potatoes. We did not find evidence that nutrient input rates and chemical soil quality are relevant factors to explain yield (gap) variability. In Chapter 3, no associations were found between yield and nutrient input or chemical soil quality. This was confirmed in Chapter 4, where we found that increasing P and K application rates did not lead to a higher yield. Furthermore, in Chapter 5 we demonstrated that physiological aspects of seed potato origin had a small effect on certain crop characteristics (number of stems and tubers per plant, tuber size distribution), but that yield was not influenced by it. Chapter 6 revealed that ware potato production in the Netherlands is characterised by high input rates of nutrients and crop protection products while yield responses are nearly absent. Variability in resource use efficiency and environmental impact was mostly determined by variability in nutrient and crop protection product input rates and yield limiting and reducing factors.

In the introduction of this thesis, I wrote that outcomes of this research can be used to provide recommendations on how to increase yields, improve resource use efficiency and reduce the environmental impact of ware potato production. However, to better understand this scope it is essential to provide additional context to the setting in which farmers operate and to the methodologies used to come to the conclusions. In this

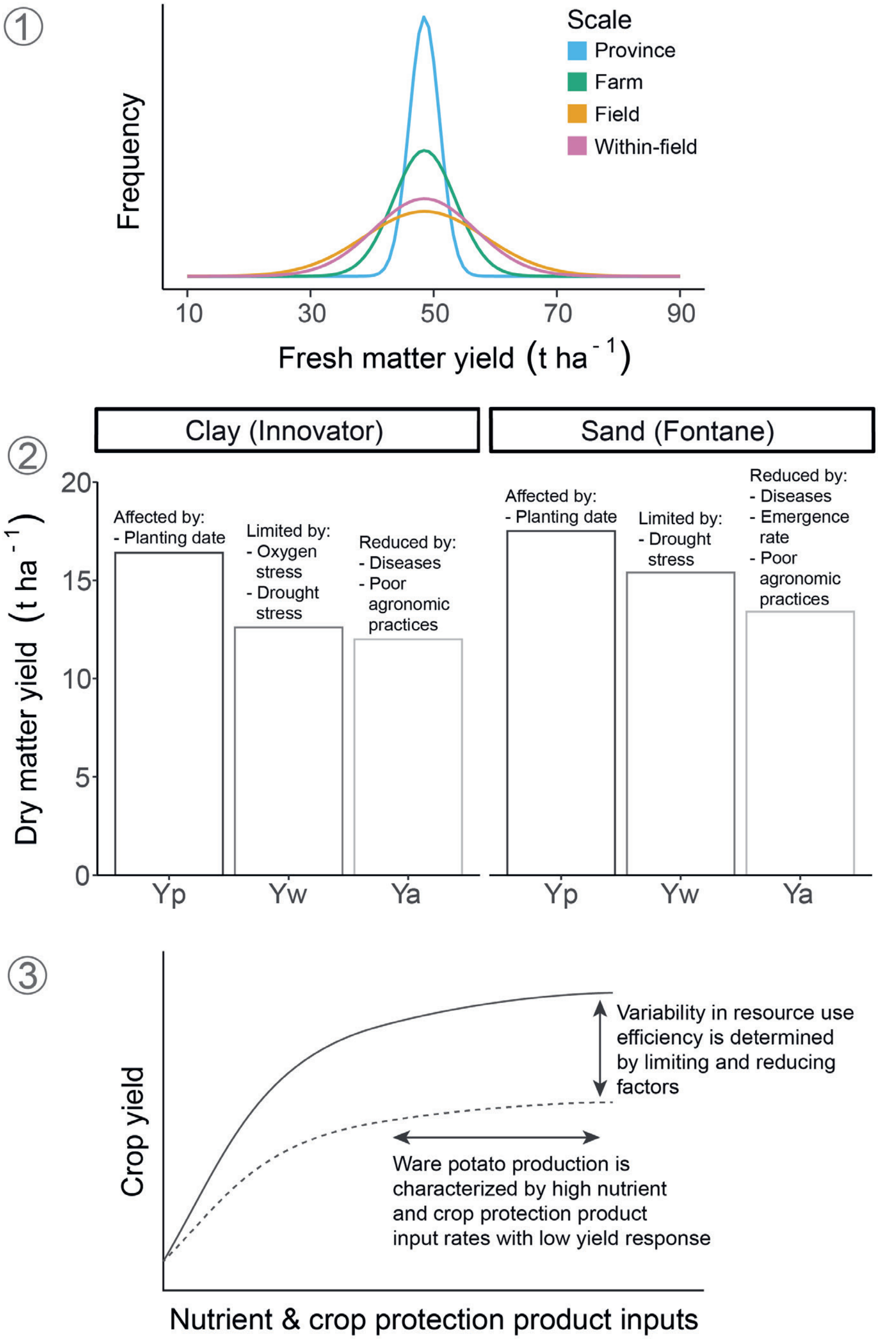


Figure 7.1. Summary of the main findings of this thesis following the three steps introduced in Chapter 1. Different colours in step 1 indicate different spatial scales. Yp in step 2 refers to potential yield, Yw to water-limited potential yield, and Ya to actual yield. Different curves in step 3 indicate different levels of resource constraints, for which in the dotted curve crop yield is constrained by limiting and reducing factors.

discussion, I first assess to what extent this thesis contributed to gaining an improved understanding of variability in yield and yield gaps (Section 7.2). In Section 7.3, I elaborate on additional factors that could potentially play a role in explaining variability in yield and yield gaps as well, but that were not included in the analyses in this thesis. In Section 7.4, I evaluate to what extent farmers' perceptions on yield gap explaining factors are in agreement with measurements in the field. In addition, in this section I dive further into management and socio-economic constraints at farm level that could contribute to the yield gap at field level. In Section 7.5, I evaluate resource use, use efficiency and environmental impact of ware potato production in the Netherlands and try to seek an explanation for high input rates through a simple economic analysis of input costs. In addition, I assess alternative ways of improved sustainability of ware potato production. In Section 7.6, I assess the benefit of using detailed field monitoring in yield gap studies and address limitations of the methods used. I finish this general discussion with the lessons we can distil from this thesis and a prospect towards the future (Section 7.7).

7.2 Understanding variability in yield and yield gaps for ware potato production in the Netherlands at field level

Ware potato farming in the Netherlands is highly productive. This thesis identified an average productivity at 73% of potential yield for Innovator on clayey soils and at 77% of potential yield for Fontane on sandy soils (Chapter 3). The estimated ware potato yield gap in the Netherlands is similar to previously estimated yield gaps (Silva et al., 2020, 2017), although reported actual and potential yields in this study are higher than in the previous studies. Yield gap variability among fields was large with yield gaps ranging from 1 to 53% for Innovator on clayey soils and from 0 to 47% for Fontane on sandy soils (Chapter 3), and shows similar large yield variability among fields compared to other studies (Mulders et al., 2021; Silva et al., 2021, 2017).

This thesis has shown the importance of variety, soil and year effects on the yield gap and yield gap explaining factors. For Innovator on clayey soils, Yp_{max} (potential yield based on maximum growing season length) was estimated around 17 – 18 t DM ha^{-1}, while for Fontane on sandy soils it was estimated around 18 – 20 t DM ha^{-1}. The (Yp_{max} – Ya) yield gap (i.e., potential yield with longest possible growing season minus actual yield) of Innovator (clayey soils) was for 59% attributed to oxygen stress, for 12 – 22% explained by radiation limitation, for 8 – 18% by drought stress, and for 1 – 21% by nutrient limitation and/or reducing factors (Chapter 3). For Fontane (sandy soils), the (Yp_{max} – Ya) yield gap was for 9 – 52% determined by drought stress, 29 – 31% by radiation limitation, 18 – 59% by nutrient limitation and/or reducing factors (mostly diseases) and less than 1% by oxygen stress. The relative contribution of the yield gap explaining factors for Fontane (sandy soils) varied for the two studied years. The effect of reducing factors on the yield gap was much larger in the year with average climatic conditions (2021) and the effect of drought stress was more pronounced in the relatively dry year (2020).

We attributed a considerable proportion of the yield gap to oxygen and drought stress. However, it cannot simply be concluded that the yield gap will be narrowed to the same extent if these water related stresses are taken away. It was shown that in fields with low drought and/or oxygen stress levels, the (Yw_{irr} – Ya) yield gap (i.e., water-limited potential yield with irrigation minus actual yield) was still relatively large (Chapter 3), meaning that pests and diseases and/or nutrient limitation were a cause of the existing yield gap when there was no drought and/or oxygen stress. This follows Liebig's law of the minimum, which implies that the most constraining factor is determining the yield level. Hence, under drought and/or oxygen stress, water deficit or excess are mostly limiting yields, but without drought and/or oxygen stress, yield reducing factors and/or nutrient limitation still prevent farmers from obtaining potential yields in (part of) their fields.

Further analysis demonstrated that reducing factors played an important role in determining actual yields, while there was a negligible effect of fertilisation on crop yield. Statistical analysis showed significant effects of emergence rate and crop health score on the yield gap for both varieties (Chapter 3). Furthermore, for Innovator, it was found that the (Yw_{irr} – Ya) yield gap was lower with increasing crop protection product use. On the other hand, plant available P, P applied, and K applied showed no or counterintuitive effects on the yield gap of both varieties, where larger nutrient availability or nutrient application led to larger yield gaps. These results are in line with other findings on ware potato production in the Netherlands that showed limited, contradicting, or counterintuitive effects of soil fertility and fertilisation rates on the yield gap (Mulders et al., 2021; Silva et al., 2020; Vonk et al., 2020). The effect of reducing factors on actual potato yields in the Netherlands has been less well studied, but has been acknowledged to contribute to current ware potato yield variability (Wustman, 2005). Yield reduction due to diseases may even worsen under future climate change (Schaap et al., 2013). Reducing factors were also an important yield gap explaining factor for sugar beet yield variability in the Netherlands (Hanse et al., 2011) and for ware potato yield variability in other high input cropping systems (Sinton et al., 2022).

The statistical analyses were useful to determine the overall effect of reducing and or nutrient limiting factors on the yield gap, but could not be used to identify specific problems at individual fields. Using qualitative field observations throughout the growing season, we could establish that the reducing factors that impacted crop growth were diverse (Chapter 3). A large part of the reducing factors was related to using diseased planting material, such as *Pectobacterium* spp. infected tubers. In other fields, there were problems with airborne diseases including early (*Alternaria solani*) and late blight (*Phytophthora infestans*).

Damaging levels of potato cyst nematodes (*Globodera* spp.) were explaining the yield gap in two fields. Poor agronomic practices were also part of yield gap explaining factors in a few fields. One farmer planted potatoes with a broken machine and other farmers planted cut seed tubers resulting in heterogeneous stem densities. This qualitative assessment did not provide the possibility to quantify the yield reducing effect of different factors, but it did provide an overview of the various reducing factors that influence yield at field level. This is a clear advantage to other studies where yield gaps were attributed to reducing factors, but where lack of information prevented drawing conclusions on which pests and diseases or other factors were reducing yields (Deguchi et al., 2016; Silva et al., 2017).

7.3 Additional yield gap explaining variables

Although many aspects of ware potato production are touched upon in this thesis, inevitably not all factors that determine ware potato productivity could be taken into account. In this section, I discuss four additional factors that can potentially play a role in limiting or reducing yields, but that were included in the analysis only to a limited extend: soil compaction, flooding, crop rotation and long-term fertilisation effects.

Soil compaction is a physical form of soil degradation that alters soil structure, limits water and air infiltration and reduces root penetration in the soil (Nawaz et al., 2013). It is reported that soil compaction in potato fields can delay emergence, slow down ground cover development, reduce rate of leaf expansion and reduce rooting density and maximum rooting depth (Huntenburg et al., 2021; Stalham et al., 2007). Ultimately, this will lead to lower yields; indeed yields were found to be reduced by 11 – 18% in fields with traffic compared to fields without traffic (Chamen et al., 1992; Vermeulen and Klooster, 1992). Another study reported a yield loss of 13% as a result of a compacted soil and 33% yield loss as result of a plough pan (Bouma and Van Lanen, 1989). Marketable yield can also be affected by soil compaction resulting in more small sized tubers (Edrris et al., 2020). Irrigation can alleviate the effect of compaction (Stalham et al., 2007), although a dry uncompacted soil can yield similar to an irrigated compacted soil (Bouma and Van Lanen, 1989), which requires thus additional inputs to maintain yields in the compacted soil.

In this thesis, soil compaction was considered in terms of soil penetration resistance, and was used to assess rooting depth. This way, we assessed the total available water using SWAP-WOFOST (Chapter 3). However, a compacted soil also has a lower water holding capacity or reduced aeration (Johansen et al., 2015; Stalham et al., 2007). This aspect of soil compaction was not taken into account. Better porosity can alleviate both drought and oxygen stress while lower porosity can aggravate stress. A survey of 602 farms in the UK showed that two thirds of the fields had a penetration resistance that is expected to be limiting for potato root growth within the top 55 cm of soils (Stalham et al., 2007). For the

Netherlands, it is estimated that 43% of the subsoils is overcompacted and thus affecting ware potato yields as well (Brus and Van Den Akker, 2018).

Model outcomes on water-limited yield (Chapter 3) suggested that lower ware potato yields could be attributed to oxygen stress as a result of excess water in the field. Although too much water plays a role when oxygen stress occurs, it is not necessarily equal to flooding in the field, as flooding can destroy a whole crop. When potatoes have been submerged in standing water for a prolonged period, tubers will start to rot, potentially leading to a complete yield loss. A pot experiment showed that after 2 days of flooding, yield was reduced by 71%, and that flooding is detrimental to yield irrespective of the development stage of the plant (Jovović et al., 2021). We did not encounter prolonged flooding in our measurement areas, but flooding is surely a factor that affect ware potato production in the Netherlands and can occur both on sandy and clayey soils (Mulders, 2023; Wustman, 2005). Often flooding does not happen on the whole farm, but on a particular part of a farm and field and can for instance result in lower emergence (Fig. 7.2) or a smaller area harvested.

Figure 7.2. A potato field in Limburg was flooded during a heavy rain shower in 2021, leading to poor emergence in part of the field (source: Paul Ravensbergen, 15/06/2021).

It is well known that crop rotation has several advantages compared to continuous cropping, for instance because of disease suppression and improved nutrient cycling. Narrower rotations with potato were often found to have higher abundance of pathogens (Carter and Sanderson, 2001; Qin et al., 2022; Wang et al., 2022) and nematodes (Bélair et al., 2006; Whitehead et al., 1991), which negatively affects yield. In the past, it was found that rotations with potato once every three, four or six years had respectively 21, 16 and

7% lower yields compared to plots on which potato was grown for the first time (Hoekstra, 1989). More studies found that yields were reduced in relatively narrow rotations compared to relatively wide rotations (Qin et al., 2022; Scholte and Jacob, 1990; Vos, 1996; Whitehead et al., 1991). In this thesis, we found that a decreasing crop health score negatively affected yields. However, it was not attributed to what extent crop rotations contributed to this yield reduction. On 84% of the studied fields on clayey soils and 51% on sandy soils, potatoes were cultivated on that particular field four or fewer years ago (Fig. 7.3). Hence, existing crop rotations are likely to be an important yield reducing factor and contributor to the disease pressure.

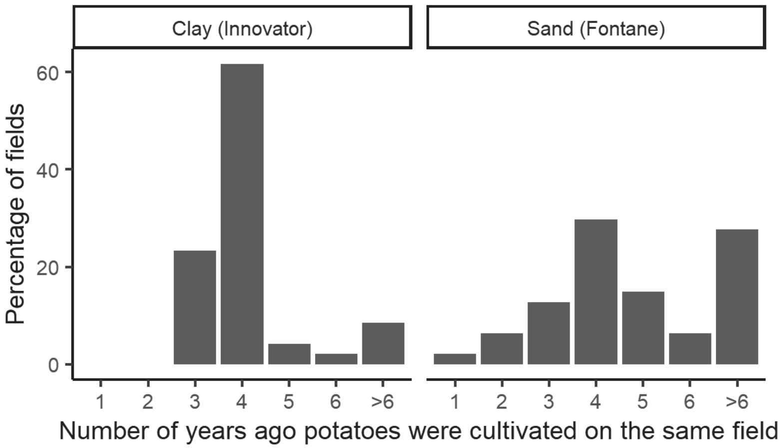


Figure 7.3. Frequency of potato cultivation in the crop rotation. Percentages refer to each soil type (and cultivar). Figure is based on observations from 94 fields (Chapter 3, 6).

Crop rotations can also positively influence ware potato yield, for instance through extra N supply after grass or a leguminous crop. Such potential benefits of crop rotations have not been assessed, but can be relevant in determining yield, although Silva et al. (2017) concluded that such beneficial rotational effects tend to disappear in high input systems. Yet, they are relevant to consider for nutrient management, as legacy N can reduce N input demands. Sustainable management will require adequately accounting for the additional N supply to the potato crop (Azimi et al., 2022). Hence, rotational effects can therefore also explain variability in nutrient input rates and use efficiency.

In this thesis, we considered the effect of nutrient application on yield and resource use efficiency in several ways. We found that additional P and K fertiliser application did not result in higher actual yields (Chapter 4), that N, P and K application rates and soil properties were not or counterintuitively related to yield (Chapter 3) and that variability in resource use efficiency was mostly driven by variability in nutrient application rates (Chapter 6). For all of these conclusions, we considered nutrient application for the studied growing season and neglected historic fertiliser application. Because of the lack of responses and the large N surplus, we concluded in Chapter 6 that current N application rates could be reduced to increase NUE and decrease N surplus. This is confirmed in long-term trials on experimental stations where N application rates above crop demand did not increase yield and increased N leaching (Constantin et al., 2010; Goulding et al., 2000; Janssen, 2017). Similarly, we observed a large positive P and K balance in clayey soils based on single season nutrient application rates, which also suggests that inputs to the potato crop can be reduced. However, farmers farm under a wide variation of conditions caused by differences in soil, climate, crop choice, management and other factors. Reducing nutrient input could also have side effects, such as that the potato crop can become more susceptible to early blight under lower N fertilisation conditions (Abuley et al., 2019). There is a need to evaluate the effects of reducing inputs in the long term and for the entire crop rotation under a wider variety of conditions, to understand under which conditions reducing nutrient inputs without compromising yield is possible and what the potential trade-offs are.

7.4 Addressing yield gaps at farm level

7.4.1 Comparing farmers' perception with field observations

As part of the analysis, we asked farmers to estimate the yield gap and yield gap explaining factors at their farm (Chapter 2). Farmers indicated a yield gap for ware potato in the Netherlands of 13 – 18 t fresh matter ha^{-1}, corresponding to 20 – 24% of potential yield. In Chapter 3, we estimated the yield gap at 23 – 27% of potential yield which shows that the farmer estimated yield gap was similar to the estimated yield gap based on measured data. Nevertheless, farmers' estimates of potential yield were highly variable and ranged between 50 and 90 t ha^{-1}. Hence, this shows that part of the farmers underestimated potential yield (compared to model simulations of roughly 75 – 95 t ha^{-1}). A potential explanation is that farmers may have a different interpretation of potential yield than researchers. As the highest farmers' yield is generally lower than the potential yield and only reached by few farms (Silva et al., 2017), this may be a reason why farmers underestimate the potential yield as defined by climatic conditions and with optimal crop management (van Ittersum et al., 2013).

In terms of yield gap explaining factors, there were similarities and striking differences between farmers' perceptions and measurements in the field. Water deficit and water excess were indicated by farmers as major biophysical factors explaining the yield gap. Water deficit was considered most important in 2020 and water excess was most important in 2021. This is largely in agreement with model simulations done in Chapter 3. However, a difference is that farmers on sandy soils also indicated water excess as a yield-limiting factor, which can likely be related to flooding in certain parts of the farm (Fig. 7.2). In terms of management factors, farmers mentioned that a lack of irrigation was one of the most important factors limiting potato yields, which corresponds with water deficit being a major yield-limiting factor according to model simulations.

Diseases were perceived as another important yield gap explaining factor for Fontane on sandy soils in 2021. The answers to the open questions in the questionnaire (Chapter 2) revealed that this was largely related to late blight (*Phytophthora infestans*) infections. Although we observed late blight infections in 2021 in some fields, most of the yield reduction was related to other diseases. For Fontane on sandy soils, this was mostly related to *Pectobacterium* (formerly Erwinia) infections resulting in black leg disease and soft rot (Chapter 3). Part of the observed diseases (and pests) in ware potato cultivation can be related to narrow rotations. Yet, in the questionnaire none of the farmers indicated that crop rotation was reducing yield at their farm (Chapter 2). From personal conversations with farmers in the field, I learned that some farmers acknowledge the negative effect of a narrow rotation on yield, but that farm economics does not allow to have a wider crop rotation. As such, farmers do not consider crop rotation a yield reducing factor as it is something that cannot be changed in the short term.

A striking difference between farmers' perception on yield gap explaining factors (Chapter 2) and assessments in this thesis (Chapter 3 and 4), is the role of nutrients in explaining the yield gap. Roughly 20% of the farmers indicated in the questionnaire that fertilisation was a yield-limiting factor at their farm. When we explicitly asked farmers about it, almost 70% indicated that a more lenient N and P legislation could lead to increased yield at farm level. Yet, we did not observe any yield response to N and P input (Chapter 3). In addition, increased P fertiliser application rates did not result in higher ware potato yield (Chapter 4). In Chapter 6, we conclude that it is likely that N input can be reduced while maintaining yields. This contradicts the view of part of the farmers. One farmer commented in the questionnaire: "Increasingly reducing nutrient inputs, especially the organic part, is perceived by us as one of the biggest threats, because we know from the past that a crop grows well and stable with sufficient slurry. We also see that plants become more susceptible to pests and diseases, because we have to restrict nutrient application. This results in higher use of crop protection products, which are also increasingly restricted. It is worrying, I expect we will have to do with lower yields if this is not changed."

7.4.2 Overcoming yield constraining factors at farm level

This thesis showed that a wide variety of yield constraining factors determine the actual yield and yield gap at field level. Also, suggestions were provided to increase actual yield, such as by planting earlier and improving irrigation. However, to actually increase yield, there is a need to understand the environmental and socio-economic context of the farm. In Chapter 2, it was identified that farmers consider economics as an important constraint to apply irrigation. Answers to the open questions revealed that low potato prices due to the COVID-19 pandemic were an important cause for this. Also, some farmers prioritise other crops such as spring onion above potato in terms of irrigation. Furthermore, a few farmers also indicated that farm size can influence the yield gap. Farmers explained that because of the size of the farm, some fields had to be harvested under unfavourable (wet) conditions in the previous year, negatively impacting soil structure.

There are many other constraints that prevent farmers from taking away yield limiting or reducing factors, but that were not apparent from the answers to the multiple-choice questions of the questionnaire. The answers to the open questions in the questionnaire (Chapter 2) provide valuable additional insight in challenges that farmers face. Some farmers indicated that farming is done over multiple seasons, and that their aim is not to maximise yield of a single crop, but over an entire rotation. Another farmer mentioned that they try to have an early crop, so that it is more likely to harvest under dry conditions. This is beneficial to soil structure and could result in a higher yield on the long term. Another farmer preferred harvesting earlier because of the higher ware potato price. Harvesting later, with a potentially higher yield, is thus financially less attractive. Farmers are also dependent on the region where they are located. Some farmers indicated that they are unable to irrigate because of brackish water or because they are in an area with seed potatoes. As a result, farmers cannot irrigate their crop to prevent disease spreading of brown and/or ring rot. Finally, a group of farmers indicated that they are not allowed to protect the ware potato crop against early blight because they are located in an area where drinking water is exploited, limiting their options of using crop protection products.

Other external factors that farmers cannot control also explain why it can be difficult to overcome yield gaps. A farmer indicated that field conditions were too wet to enter the field and that it was not possible to spray the crop with a late blight infection as a result. Another example is that when the crop demands irrigation while (heavy) thunderstorms in a few days are forecasted, farmers wait to irrigate to avoid the risk of having a flooded field. However, this could also mean that irrigation comes too late if it does not rain, with drought stress as a result. Furthermore, on rented land farmers cannot influence choices (e.g., crop rotation, fertilisation) in previous years and sometimes even in the year of cultivation. Lastly, due to dry weather conditions in spring 2020 the clayey soil became very hard. As a result, farmers needed to put more effort into planting, delaying overall planting. In conclusion, in practice farmers face a multitude of challenges and give priorities to other crops and/or goals which ultimately prevent them from obtaining potential yield. It is incredibly difficult to do everything right and thus to narrow the yield gap, but it starts by identifying the right problems. One farmer rightfully acknowledged: “In the end, a successful crop is determined by a large number of factors, partly by legislation, partly by nature, and partly by crop management. For the latter, it is important to look into the mirror and reflect on whether I as a farmer could have improved cultivation during the growing season. Other factors are often too easily used as arguments to hide."

7.5 From yield gap to efficiency gap, and beyond?

7.5.1 Pathways to increase resource use efficiency and reduce environmental impact

Given environmental challenges in the Netherlands, there is a need to move towards a more sustainable agriculture by increasing resource use efficiency and reducing the impact to the environment. There are several pathways to increase resource use efficiency and reduce environmental impact of ware potato production in the Netherlands (Fig. 7.4). Here, I take nitrogen use as an example of how improved efficiency can be achieved. One way is to increase current yield levels while maintaining the same input rates, leading to an improved resource utilisation of applied inputs (Fig. 7.4 – 1). This thesis showed that current yield levels are around 73 – 77% of potential yield and that there is space to increase actual yield. However, due to socio-economic constraints at farm level, expected yield increase is marginal and will likely only be achieved on part of the production fields. Hence, increasing yield could, on average, only marginally increase resource use efficiency and will be insufficient to stay within the environmental thresholds for nitrate concentration in the groundwater. Nonetheless, for particular individual fields with relatively large yield gaps resource use efficiency could be considerably improved by increasing yield.

A second pathway is to reduce input levels while maintaining actual yield levels (Fig. 7.4 – 2). The majority of the farmers applied roughly between 250 and 500 kg effective N ha^{-1} on clayey soils and between 200 and 350 kg effective N ha^{-1} on sandy soils. Despite the large variability in input rates, we did not find any relation between yield and N input. Based on this finding, it can be expected that average N application rates could be reduced till 250 kg effective N ha^{-1} on clayey soils and 200 kg effective N ha^{-1} on sandy soils without yield loss. However, it is still uncertain if inputs can be reduced further without compromising yield. If input reduction while maintaining current yield levels is insufficient to stay below the environmental thresholds for nitrate concentration in the groundwater, potentially a third pathway is needed where extra input reduction is necessary, accepting slightly lower yields (Fig. 7.4 – 3). Another experiment with the same varieties and soil types has shown that still relatively high yields were obtained with input rates of 75-85 kg N ha^{-1} (Prikaziuk et al., 2022).

In addition to environmental challenges, there is also a need to produce sufficient food for a growing population (UN, 2022). Hence yield and efficiency gaps should be considered simultaneously (van Noordwijk and Brussaard, 2014). Modelling can aid to assess minimum

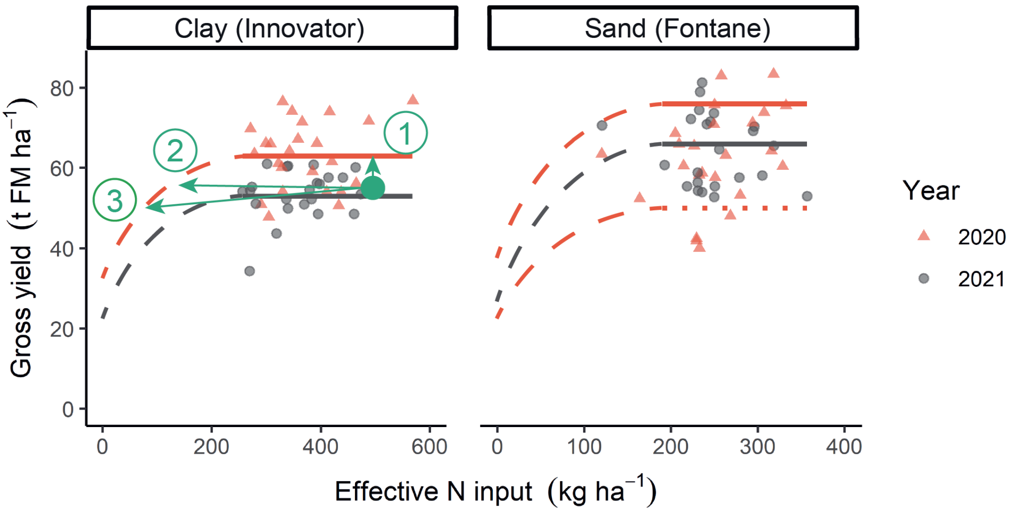


Figure 7.4. Yield response curves to effective N input in ware potato production in the Netherlands. The horizontal part of the curves indicate the (absent) average response of gross yield to N input found in this thesis. The solid red (grey) lines indicate the yield response for 2020 (2021), without water stress. The dotted red line (in the right panel) indicates the yield response for 2020 with drought stress taken into account. The dashed lines indicate hypothetical response curves at lower N application rates. The red and grey symbols refer to the actual observations in the field. The green symbol refers to a random field. Situation 1 refers to a scenario of narrowing the yield gap, situation 2 to minimizing input use while maintaining yield and situation 3 to optimizing the yield and resource use efficiency gap simultaneously.

input requirements at certain yield levels or to minimise trade-offs between yield and resource use efficiency (Kheir et al., 2022; ten Berge et al., 2019). Model outcomes should be evaluated through long-term experiments at systems level to evaluate changes in management practices for a wide variety of conditions, similar to the conditions that farmers face (e.g., Li et al., 2023).

7.5.2 Economics related to resource use efficiency

Low resource use efficiency does not only come with emissions to the environment, it also comes with economic losses to the farmer as inputs remain unutilised (Steyn et al., 2016). An often used argument to keep using large amounts of inputs, is the risk that crop productivity may decline when inputs are reduced or that the cost of overapplication is lower compared to the cost of underapplication (i.e., when it results in yield reduction) (Meyer-Aurich and Karatay, 2019; Rajsic and Weersink, 2008). In this section, I evaluate how much money can be saved on inputs compared to the revenue loss if an input is limiting yield (Table 7.1), assuming potential input use efficiency (see footnotes in Table 7.1 for details on assumptions).

First, I compare the cost savings of fertiliser reduction to the revenue loss as a result of potentially lower yield. KWIN-AGV (Quantitative information field crops and horticulture) reports that an average farmer in Flevoland applies 250 kg N ha^{-1} $year^{-1}$ to the potato crop (van der Voort, 2022). If the farmer would reduce N input by 10%, this equals an input reduction of 25 kg N ha^{-1} which saves € 23,- ha^{-1} on N fertiliser (Table 7.1). When the crop is limited by N and assuming 67% N use efficiency (Silva et al., 2021), this could result in a yield loss of 5.4 t ha^{-1}, which equals a revenue loss of € 540,- ha^{-1} to € 1080,- ha^{-1}. Hence, the potential revenue loss due to lower yield is 23 – 47 times higher than the cost savings by reducing N fertiliser input. Similar calculations can be done for P and K and indicate that revenue loss is 118 – 235 times higher than cost savings for P, and 37 – 74 times for K. Although yield (and thus revenue) losses as a result of reduced fertiliser inputs will likely not be as large as depicted in this optimistic scenario, these numbers clearly indicate that the costs of overapplication are indeed much lower than the potential losses as a result of underapplication (see also Neeteson, 1990).

For irrigation, revenue loss divided by the cost savings is much smaller than for fertilisers. When one irrigation event of 25 mm is skipped, its cost savings are 2 – 9 times lower than its potential revenue loss. This is calculated with ware potato prices of € 0.10 to € 0.20 and indicates that product price is an important determinant whether irrigation is profitable, as was also indicated by the farmers in the questionnaire (Chapter 2). When the potato prices were very low (as low as € 0.02 kg^{-1}) due to the COVID-19 pandemic, part of the farmers stopped irrigating the crop because of the low return on investments.

Crop protection products was another important input evaluated in this thesis. However, it was not possible to calculate a revenue loss due to lower application rates. Whilst fertilisers and irrigation are applied to get a yield gain, crop protection products are used to prevent a yield loss. Instead, it is possible to compare the cost savings of a lower application rate to the maximum yield loss that is required to 'break even'. On an average farm in Flevoland, € 800,- ha^{-1} is spent on crop protection products[1] (Van der Voort, 2022). Reducing crop protection product input by 10% saves € 80,- ha^{-1}. With a potato price of € 0.10 this allows for a maximum yield loss of 0.8 t FM^{-1} to break even.

The three examples for fertiliser, water, and crop protection product use indicate that the potential revenue loss due to a yield loss is much larger than costs of overapplying inputs and thus can be an explanation for the high input rates, especially when also considering the high fixed costs of land, buildings, and machinery that also need to be paid at farm level.

[1] This excludes plant growth regulators and sprout suppressants, which are used to control sprouting in storage

Table 7.1. Cost savings with decreasing input rates, potential yield loss if a particular input is limiting yield, potential revenue loss and revenue loss/cost savings.

Decrease in input	Cost savings ha^{-1} (€)	Potential yield loss if input is limiting (t FM ha^{-1})	Potential revenue loss if input is limiting (€ ha^{-1})		Revenue loss / Cost savings
			Price = € 0.10 kg^{-1} potato	Price = € 0.20 kg^{-1} potato	
25 kg N ha^{-1} [1]	23[4]	5.4[6]	540	1080	23 – 47
1.7 kg P ha^{-1} [1]	3.4[4]	4.0[7]	400	800	118 – 235
15 kg K ha^{-1} [1]	9.4[4]	3.5[7]	350	700	37 – 74
25 mm irrigation[2]	108 –239[5]	4.8[8]	480	960	2 – 9
10% less crop protection products[3]	80[4]	Not available[9]	Not available	Not available	Not available

[1] *It is assumed that fertilisers are applied in the form of calcium ammonium nitrate (N), triple super phosphate (P) and muriate of potash (K).*

[2] *This is a standard application rate for one irrigation event.*

[3] *Assuming an equal 10% decrease over all applied crop protection products.*

[4] *Source: van der Voort (2022)*

[5] *Source: van der Voort (2019), excludes labour costs.*

[6] *Assuming 67% nitrogen use efficiency (median NUE in* Silva et al. (2021)*), an N concentration in tubers of 1.49% (average of measurements in Chapter 6), and a dry matter concentration of 21%.*

[7] *Assuming equal input and output rates (100% efficiency), and thus maintaining a net zero balance (Chapter 4, 6), a P and K concentration of 0.20% and 2.05% respectively (average of measurements in Chapter 6), and a dry matter concentration of 21%.*

[8] *Assuming 80% of irrigation water evapotranspired, a 0.05 t DM yield reduction mm drought stress^{-1} ha^{-1} (Chapter 4), and a dry matter concentration of 21%.*

[9] *Crop protection products are used to prevent a yield loss and their use does not directly correlate to yield. Therefore, no estimate is provided of a potential yield loss.*

7.5.3 Beyond currently common practices

Sustainability assessments in this thesis have mostly focused on improving efficiency of the current ware potato production system. In addition to increasing efficiency, substitution and redesign have been proposed as two other stages to transition towards more sustainable production systems (Pretty, 2018). Substitution focuses on replacing current technologies or practices. In the context of ware potato production an important example is introducing late blight resistant varieties. Farmers use large amounts of fungicides to prevent late blight infections in the fields (Chapter 6). However, application comes with harmful effects to the environment. In addition, by overapplying fungicides there is a risk that *Phytophthora* becomes resistant to certain fungicides, reducing the efficacy of the product (Schepers et al., 2018). By combining highly resistant varieties with reduced application of fungicides, fungicide inputs can be reduced by 80 – 90% (Kessel et al., 2018). This way, substitution could be more effective in reducing fungicide use than by optimizing the current application strategies.

Redesign focuses on transforming current production systems and could for instance be achieved by diversifying crop choice. Current rotations are relatively narrow with potential negative effects on disease (or pest) pressure (Fig. 7.3) (e.g., Carter & Sanderson, 2001; Qin et al., 2022; Wang et al., 2022). Widening rotations is likely to reduce disease pressure, which potentially increases yield and resource use efficiency. However, farmers will need to be able to adapt to the cultivation of a larger diversity of crops. In addition to diversifying in time, diversification can take place in space, for instance through strip or pixel cropping (Ditzler et al., 2023; Juventia et al., 2022). Such spatially diverse systems can have positive effects on weed species compositions or abundance of natural enemies, but can also be a challenge to farmers in terms of crop management (Ditzler et al., 2023). Furthermore, widening rotations and/or extensifying current ware potato production systems could mean that total ware potato production goes down. There is a need to learn from different type of systems to assess how environmental impact can be reduced while productivity is maintained.

7.6 Methodological considerations

7.6.1 The added benefit of detailed field monitoring

Yield gap analyses have been done for various crops in different environments and have provided valuable insight at regional or higher aggregation levels in scoping the increases in yield or resource use efficiency (Caldiz and Struik, 1999; Dadrasi et al., 2022; Espe et al., 2016; Gobbett et al., 2017; Rattalino Edreira et al., 2017; van Loon et al., 2019; Wang et al., 2018). Also, for ware potato production in the Netherlands yield (gap) variability analyses have been done (Mulders et al., 2021; Silva et al., 2021, 2020, 2017). However, available data in previous studies have proven insufficient for a detailed understanding of yield gap variability and its explaining factors at field level and for a large number of farms. In addition, farmer reported data can contain inaccuracies, providing uncertainty about reported findings (Fraval et al., 2019; Silva et al., 2021).

In Chapter 3, we showed that with frequent field monitoring at field level we were able to get detailed understanding of yield gaps and yield gap explaining factors at individual fields. Several production levels could be quantified at field level and various causes of yield gaps have been identified with relatively high R^2 values up to 0.65. Also, in terms of resource use efficiency and environmental impact, large variability has been observed among fields. Detailed analyses at field level showed that it is likely feasible to maintain high yields with reduced resource input (Chapter 6). Our findings indicate the advantage of detailed field monitoring compared to other yield gap studies at regional or higher aggregation levels that were able to identify yield gaps and yield gap influencing factors at regional level, but could not identify variability and constraints at individual fields (e.g., Dadrasi et al., 2022; Espe et al., 2016; Gobbett et al., 2017; Rattalino Edreira et al., 2018).

Despite the improved understanding of yield gaps at field level, part of the yield gap remained unexplained. In addition, specific factors could not be evaluated in comparison of yield gaps among multiple fields. The additional performed on-farm experiments were useful to assess the effect of specific agronomic factors in a wide variety of conditions within the context of the farm. It provided an opportunity to translate findings from experimental farms to commercial fields to understand what the effect of different management practices means in practice (Cassman and Grassini, 2020; Silva et al., 2017).

To address yield gaps, it is essential to provide a wider perspective of the farming system and the context in which farmers operate. In Chapter 2, we obtained valuable insights in yield variability across multiple scales and confirmed the importance of understanding yield variability among fields, because at that level the largest yield variability was observed. Answers provided to the questionnaire presented in the same chapter provided insight in the socio-economic context at farm level, which could not be obtained from the yield gap analysis. In addition, it showed the similarities and differences between farmers perceptions on yield gaps and measurements in the field.

7.6.2 Limitations of the study

For each chapter, limitations to data and analyses remain. Several of these limitations have been discussed in the discussion sections of these chapters. However, there are a few limitations that require further elucidation, because they determine the overall outcome and conclusions of this thesis.

The yield gap assessment was done for only two years, with distinct differences in the yield gaps and yield gap explaining factors between the two years. Grassini et al. (2015) showed that for stable yield gap estimates preferably a ten-year period should be used. The same would apply to yield gap explaining factors. We experienced an average and a dry year in our study, so two different conditions with two different results. Although I expect that the same yield gap explaining factors will determine the yield gap in other years, the relative contribution of these factors can be different. Furthermore, additional yield gap explaining factors might play a role. We did for instance not record a weather extreme resulting in yield loss due to rotten tubers, which happened on a large scale in 1998 and 2016 (Gobin and Van de Vyver, 2021; van Oort et al., 2023; Wustman, 2005). Similarly, 2018 was an even drier year than 2020 (Gobin and Van de Vyver, 2021; van Oort et al., 2023), aggravating the effect of drought stress and perhaps reducing the effect of oxygen stress. If dry or wet weather extremes will occur more frequently in future (van den Hurk et al., 2014), this will impact the effect of yield limiting and/or reducing factors on the yield gap (Gobin, 2012), which could vary over the country (van Oort et al., 2012).

We did this yield gap analysis on ware potato production in the Netherlands for two important cultivars only. We showed the importance of considering different cultivars and soils in terms of its yield potential and yield gap explaining factors (Chapter 3). However, the yield gap and yield gap explaining factors could be different for other cultivars. For instance, the impact of drought stress and diseases can vary with drought sensitivity and disease tolerance of different cultivars (Sinton et al., 2022; Stark et al., 2013). Also, resource use efficiency can vary among cultivars, such as differences in nitrogen use efficiency (Cohan et al., 2018).

A considerable part of the output in this thesis is based on crop modelling. Although we used an updated model for estimating potential yield (ten Den et al., 2022), there are uncertainties about the model outcomes as well, particularly in relation to the soil hydrological modelling using SWAP. Oxygen stress was hypothesised to be a major yield limiting factor on clayey soils. The outcomes were not validated with field experiments designed to evaluate the effect of oxygen stress on tuber yield. Further experimentation in the field will be necessary to validate the outcome. In addition, the (Yw – Ya) yield gap (i.e., the yield gap between water-limited yield and actual yield) is largely determined by the estimated level of water-limited yield. Hence, a validation of oxygen stress is also necessary to evaluate the effect of nutrient limiting or reducing factors on ware potato yield.

7.7 Conclusions and towards the future

This thesis showed large variability in yield and yield gaps in ware potato production in the Netherlands. Variability was largest among and within fields, indicating the importance of understanding and addressing yield variability at low aggregation levels. On clayey soils, lower yields were mostly attributed to oxygen stress and partly to late planting, drought stress and reducing factors. On sandy soils, major yield gap influencing factors were drought stress and reducing factors (pests and diseases). Late planting contributed to lower yields on sandy soils as well. On both soil types, frequent field monitoring provided a detailed qualitative understanding of the various yield limiting and reducing factors that affect ware potato yield at field level and shows the added benefit of in-season field monitoring compared to big data analyses. The numerous factors that influence yield in combination with the already high productivity plus the socio-economic constraints identified at farm level, indicate that on average there is limited scope for narrowing the ware potato yield gap in the Netherlands. Only in particular fields a yield gain could be achievable, which would then result in decreased yield variability.

In addition to variability in yield, large variability was found in resource use, use efficiency and environmental impact of ware potato production in the Netherlands. The findings in this thesis reveal inefficient use of N and hugely variable use of crop protection products in particular. For all studied environmental indicators, variability in resource use efficiency and environmental impact was mostly related to input rates and showed an absence of yield response to inputs. Given the environmental challenges that the Netherlands is facing, there is a need to increase resource use efficiency of current production system by reducing inputs. Simultaneously, there is a need to produce sufficient food to feed a growing population. The observed variability among fields suggests that it is possible to obtain high yields while reducing the environmental impact of ware potato production. However, there will be a need to evaluate how far and under which conditions input reduction is possible without yield loss. In addition, it needs to be assessed how current ware potato production systems can be integrated with alternative cropping systems that can contribute to improved sustainability of ware potato production in the Netherlands.

References

Abuley, I.K., Nielsen, B.J., Hansen, H.H., 2019. The influence of timing the application of nitrogen fertilizer on early blight (Alternaria solani). Pest Manag Sci 75, 1150–1158. https://doi.org/10.1002/ps.5236

Adams, R.M., Mccarl, B.A., Mearns, L.O., 2003. The effects of spatial scale of climate scenarios on economic assessments: An example from US agriculture. Clim Change 60, 131–148. https://doi.org/https://doi.org/10.1023/A:1026014311149

Alakukku, L., Weisskopf, P., Chamen, W.C.T., Tijink, F.G.J., Van Der Linden, J.P., Pires, S., Sommer, C., Spoor, G., 2003. Prevention strategies for field traffic-induced subsoil compaction: A review Part 1. Machine/soil interactions. Soil Tillage Res 73, 145–160. https://doi.org/10.1016/S0167-1987(03)00107-7

Alblas, J., 1984. Kalibemesting voor aardappelen in de Brabantse Biesbosch en het Land van Altena. PAGV.

Al-Gaadi, K.A., Hassaballa, A.A., Tola, E., Kayad, A.G., Madugundu, R., Alblewi, B., Assiri, F., 2016. Prediction of potato crop yield using precision agriculture techniques. PLoS One 11. https://doi.org/10.1371/journal.pone.0162219

Allaire, S.E., Cambouris, A.N., Lafond, J.A., Lange, S.F., Pelletier, B., Dutilleul, P., 2014. Spatial variability of potato tuber yield and plant nitrogen uptake related to soil properties. Agron J 106, 851–859. https://doi.org/10.2134/agronj13.0468

Asiedu, S.K., Astatkie, T., Yiridoe, E.K., 2003. The effect of seed-tuber physiological age and cultivar on early potato production. J Agron Crop Sci 189, 176–184. https://doi.org/10.1046/j.1439-037X.2003.00032.x

Atlas Natuurlijk Kapitaal, 2023. Grootschalige stikstofdepositie Nederland [WWW Document]. URL https://www.atlasnatuurlijkkapitaal.nl/grootschalige-stikstofdepositie-nederland (accessed 11.10.23).

Azimi, M.A., Jiang, Y., Meng, F.R., Liang, K., 2022. Yield responses of four common potato cultivars to an industry standard and alternative rotation in Atlantic Canada. American Journal of Potato Research 99, 206–216. https://doi.org/10.1007/s12230-022-09873-4

Barnes, A.P., Soto, I., Eory, V., Beck, B., Balafoutis, A., Sánchez, B., Vangeyte, J., Fountas, S., van der Wal, T., Gómez-Barbero, M., 2019. Exploring the adoption of precision agricultural technologies: A cross regional study of EU farmers. Land use policy 80, 163–174. https://doi.org/10.1016/j.landusepol.2018.10.004

Bartelen, A., 2016. Analysis of the impact of seed quality and seed management practices on the yield and quality of ware potatoes. (MSc thesis). Plant Production Systems Group, Wageningen University, Wageningen.

Bartholomeus, R.P., Witte, J.P.M., van Bodegom, P.M., van Dam, J.C., Aerts, R., 2008. Critical soil conditions for oxygen stress to plant roots: Substituting the Feddes-function by a process-based model. J Hydrol (Amst) 360, 147–165. https://doi.org/10.1016/j.jhydrol.2008.07.029

Barton, K., Barton, M.K., 2015. Package ‘mumin.’ Version 1, 439.

Basso, B., Antle, J., 2020. Digital agriculture to design sustainable agricultural systems. Nat Sustain 3, 254–256. https://doi.org/10.1038/s41893-020-0510-0

Bean, J.N., Allen, E.J., 1980. Effect of physiological age and variety on growth and light interception in the potato. Potato Res 23, 256–257.

Been, T.H., Schomaker, C.H., 2000. Analytical and Theoretical Plant Pathology Development and Evaluation of Sampling Methods for Fields with Infestation Foci of Potato Cyst Nematodes (Globodera rostochiensis and G. pallida) 90, 647. https://doi.org/https://doi.org/10.1094/PHYTO.2000.90.6.647

Bélair, G., Dauphinais, N., Fournier, Y., Dangi, O.P., Ciotola, M., 2006. Effect of 3-year rotation sequences and pearl millet on population densities of Pratylenchus penetrans and subsequent potato yield. Canadian Journal of Plant Pathology 28, 230–235. https://doi.org/10.1080/07060660609507291

Bélanger, G., Walsh, J.R., Richards, J.E., Milburn, P.H., Ziadi, N., 2000. Yield response of two potato cultivars to supplemental irrigation and N fertilization in New Brunswick. American Journal of Potato Research 77, 11–21. https://doi.org/10.1007/bf02853657

Benoit, G.R., Grant, W.J., 1985. Excess and deficient water stress effects on 30 years of Aroostook County potato yields. Am Potato J 62, 49–55. https://doi.org/https://doi.org/10.1007/BF02903462

Berkhout, Petra, van der Meulen, H., Ramaekers, P., Verhoog, A.D., Berkhout, P, Bergevoet, R.H.M., Daatselaar, C.H.G., van Horne, P.L.M., Hoste, R., Janssens, S.R.M., 2022. Staat van Landbouw en Voedsel. Wageningen Economic Research.

Beza, E., Silva, J.V., Kooistra, L., Reidsma, P., 2017. Review of yield gap explaining factors and opportunities for alternative data collection approaches. European Journal of Agronomy 82, 206–222. https://doi.org/10.1016/j.eja.2016.06.016

Bodlaender, K.B.A., Marinus, J., 1987. Effect of physiological age on growth vigour of seed potatoes of two cultivars. 3. Effect on plant growth under controlled conditions. Potato Res 30, 423–440. https://doi.org/https://doi.org/10.1007/BF02361920

Boote, K.J., Jones, J.W., Pickering, N.B., 1996. Potential uses and limitations of crop models. Agron J 88, 704–716. https://doi.org/10.2134/agronj1996.00021962008800050005x

Bouma, J., Van Lanen, H.A.J., 1989. Effects of the crop rotation system on soil physical behaviour and relations with potato yield, in: Effects of Crop Rotation on Potato Production in the Temperate Zones: Proceedings of the International Conference on Effects of Crop Rotation on Potato Production in the Temperate Zones, Held August 14–19, 1988, Wageningen, The Netherlands. Springer, pp. 77–88.

Brown, I., 2013. Influence of seasonal weather and climate variability on crop yields in Scotland. Int J Biometeorol 57, 605–614. https://doi.org/10.1007/s00484-012-0588-9

Brus, D.J., Van Den Akker, J.J.H., 2018. How serious a problem is subsoil compaction in the Netherlands? A survey based on probability sampling. Soil 4, 37–45. https://doi.org/https://doi.org/10.5194/soil-4-37-2018

Bus, C.B., Bosma, K.W., de Hoop, D.W., 1983. Onderzoek naar verschillen in opbrengst en kwaliteit van consumptie-aardappelen in het zuidwesten van Nederland. PAGV.

Caldiz, D.O., 2009. Physiological age research during the second half of the twentieth century. Potato Res 52, 295–304. https://doi.org/10.1007/s11540-009-9143-4

Caldiz, D.O., Fernandez, L. V, Struik, P.C., 2001. Physiological age index: a new, simple and reliable index to assess the physiological age of seed potato tubers based on haulm killing date and length of the incubation period. Field Crops Res 69, 69–79. https://doi.org/https://doi.org/10.1016/S0378-4290(00)00134-9

Caldiz, D.O., Struik, P.C., 1999. Survey of potato production and possible yield constraints in Argentina. Potato Res 42, 51–71. https://doi.org/https://doi.org/10.1007/BF02358391

Carter, M.R., Sanderson, J.B., 2001. Influence of conservation tillage and rotation length on potato productivity, tuber disease and soil quality parameters on a fine sandy loam in eastern Canada. Soil Tillage Res. https://doi.org/https://doi.org/10.1016/S0167-1987(01)00224-0

Cassman, K.G., Grassini, P., 2020. A global perspective on sustainable intensification research. Nat Sustain 3, 262–268. https://doi.org/10.1038/s41893-020-0507-8

CBS, 2022. CBS Open data Statline [WWW Document]. URL https://opendata.cbs.nl/statline/#/CBS/nl/dataset/7100oogs/table?ts=1694443768101 (accessed 12.23.22).

Chamen, W.C.T., Vermeulen, G.D., Campbell, D.J., Sommer, C., 1992. Reduction of traffic-induced soil compaction: a synthesis. Soil Tillage Res 24, 303–318. https://doi.org/10.1016/0167-1987(92)90116-S

Chapman, K.S.R., Sparrow, L.A., Hardman, P.R., Wright, D.N., Thorp, J.R.A., 1992. Potassium nutrition of kennebec and russet burbank potatoes in tasmania: Effect of soil and fertiliser potassium on yield, petiole and tuber potassium concentrations, and tuber quality. Aust J Exp Agric 32, 521–527. https://doi.org/10.1071/EA9920521

Chardon, W.J., Schoumans, O.F., 2007. Soil texture effects on the transport of phosphorus from agricultural land in river deltas of Northern Belgium, the Netherlands and North-West Germany. Soil Use Manag 23, 16–24. https://doi.org/10.1111/j.1475-2743.2007.00108.x

CLO, 2022. stikstofdepositie [WWW Document]. URL https://www.clo.nl/indicatoren/nl0189-stikstofdepositie (accessed 6.27.22).

Cohan, J.P., Hannon, C., Houilliez, B., Gravoueille, J.M., Geille, A., Lampaert, E., Laurent, F., 2018. Effects of Potato Cultivar on the Components of Nitrogen Use Efficiency. Potato Res 61, 231–246. https://doi.org/10.1007/s11540-018-9371-6

Constantin, J., Mary, B., Laurent, F., Aubrion, G., Fontaine, A., Kerveillant, P., Beaudoin, N., 2010. Effects of catch crops, no till and reduced nitrogen fertilization on nitrogen leaching and balance in three long-term experiments. Agric Ecosyst Environ 135, 268–278. https://doi.org/10.1016/j.agee.2009.10.005

Cooke, L.R., Schepers, H.T.A.M., Hermansen, A., Bain, R.A., Bradshaw, N.J., Ritchie, F., Shaw, D.S., Evenhuis, A., Kessel, G.J.T., Wander, J.G.N., Andersson, B., Hansen, J.G., Hannukkala, A., Nærstad, R., Nielsen, B.J., 2011. Epidemiology and Integrated Control of Potato Late Blight in Europe. Potato Res 54, 183–222. https://doi.org/10.1007/s11540-011-9187-0

Crosslin, J.M., Hamm, P.B., Hane, D.C., Jaeger, J., Brown, C.R., Shiel, P.J., Berger, P.H., Thornton, R.E., 2006. The occurrence of PVYO, PVYN, and PVYN:O strains of Potato virus Y in certified potato seed lot trials in Washington and Oregon. Plant Dis 90, 1102–1105. https://doi.org/10.1094/PD-90-1102

Dadrasi, A., Torabi, B., Rahimi, A., Soltani, A., Zeinali, E., 2022. Modeling Potential production and yield gap of potato using modelling and GIS approaches. Ecol Modell 471. https://doi.org/10.1016/j.ecolmodel.2022.110050

De Jong, F.M.W., De Snoo, G.R., 2002. A comparison of the environmental impact of pesticide use in integrated and conventional potato cultivation in The Netherlands. Ecosystems and Environment 91, 5–13. https://doi.org/https://doi.org/10.1016/S0167-8809(01)00262-6

de Vries, W., Schulte-Uebbing, L., Kros, H., Voogd, J.C., Louwagie, G., 2021. Spatially explicit boundaries for agricultural nitrogen inputs in the European Union to meet air and water quality targets. Science of the Total Environment 786. https://doi.org/10.1016/j.scitotenv.2021.147283

de Wit, A., Boogaard, H., Fumagalli, D., Janssen, S., Knapen, R., van Kraalingen, D., Supit, I., van der Wijngaart, R., van Diepen, K., 2019. 25 years of the WOFOST cropping systems model. Agric Syst 168, 154–167. https://doi.org/10.1016/j.agsy.2018.06.018

de Wit, A.J.W., Boogaard, H.L., Supit, I., van den Berg, M., 2020. System description of the WOFOST 7.2, cropping systems model. Wageningen Environmental Research.

Debrah, S., Hall, H.H., 1989. Data Aggregation and Farm Risk Analysis. Agric Syst 31, 239–245. https://doi.org/https://doi.org/10.1016/0308-521X(89)90023-1

Deguchi, T., Iwama, K., Haverkort, A.J., 2016. Actual and Potential Yield Levels of Potato in Different Production Systems of Japan. Potato Res 59, 207–225. https://doi.org/10.1007/s11540-016-9322-z

Deike, S., Pallutt, B., Melander, B., Strassemeyer, J., Christen, O., 2008. Long-term productivity and environmental effects of arable farming as affected by crop rotation, soil tillage intensity and strategy of pesticide use: A case-study of two long-term field experiments in Germany and Denmark. European Journal of Agronomy 29, 191–199. https://doi.org/10.1016/j.eja.2008.06.001

Dekker, P., Postma, R., 2008. Verhoging efficiëntie fosfaatbemesting. Praktijkonderzoek Plant & Omgeving, Business Unit Akkerbouw, Groene Ruimte en Vollegrondsgroenten.

Devaux, A., Goffart, J.P., Kromann, P., Andrade-Piedra, J., Polar, V., Hareau, G., 2021. The Potato of the Future: Opportunities and Challenges in Sustainable Agri-food Systems. Potato Res 64, 681–720. https://doi.org/10.1007/s11540-021-09501-4

Diogo, V., Reidsma, P., Schaap, B., Andree, B.P.J., Koomen, E., 2017. Assessing local and regional economic impacts of climatic extremes and feasibility of adaptation measures in Dutch arable farming systems. Agric Syst 157, 216–229. https://doi.org/10.1016/j.agsy.2017.06.013

Ditzler, L., Rossing, W.A.H., Schulte, R.P.O., Hageman, J., van Apeldoorn, D.F., 2023. Prospects for increasing the resolution of crop diversity for agroecosystem service delivery in a Dutch arable system. Agric Ecosyst Environ 351. https://doi.org/10.1016/j.agee.2023.108472

Dobermann, A., Bruulsema, T., Cakmak, I., Gerard, B., Majumdar, K., McLaughlin, M., Reidsma, P., Vanlauwe, B., Wollenberg, L., Zhang, F., Zhang, X., 2022. Responsible plant nutrition: A new paradigm to support food system transformation. Glob Food Sec 33, 100636. https://doi.org/10.1016/j.gfs.2022.100636

EC, 1991. Council Directive of 12 December 1991 Concerning the protection of waters against pollution caused by nitrates from agricultural sources (91/676/EEC), Official Journal. Brussels.

Edrris, M.K., Al-Gaadi, K.A., Hassaballa, A.A., Tola, E.K., 2020. The response of potato crop to the spatiotemporal variability of soil compaction under centre pivot irrigation system. Soil Use Manag 36, 212–222. https://doi.org/10.1111/sum.12553

Ehlert, P.A.J., Versluis, H.P., 1990. Toetsing van het kaliumbemestingsadvies op overgangsgronden= Testing of the potassiumfertilizing advice for transitional soils, in: Jaarboek 1987-1992: Verslagen van in 1987-1992 Afgesloten Onderzoekprojecten Op Regionale Onderzoek Centra En Het PAGV. Proefstation voor de Akkerbouw en de Groenteteelt in de Vollegrond, pp. 248–258.

English, B.C., Roberts, R.K., Mahajanashetti, S.B., 1999. Spatial Break-Even Variability for Variable Rate Technology Adoption, in: Proceedings of the Fourth International Conference on Precision Agriculture. Wiley Online Library, pp. 1633–1642. https://doi.org/https://doi.org/10.2134/1999.precisionagproc4.c68b

Espe, M.B., Cassman, K.G., Yang, H., Guilpart, N., Grassini, P., Van Wart, J., Anders, M., Beighley, D., Harrell, D., Linscombe, S., McKenzie, K., Mutters, R., Wilson, L.T., Linquist, B.A., 2016. Yield gap analysis of US rice production systems shows opportunities for improvement. Field Crops Res 196, 276–283. https://doi.org/10.1016/j.fcr.2016.07.011

EUNEP, 2015. Nitrogen Use Efficiency (NUE) an indicator for the utilization of nitrogen in food systems. Wageningen University, Alterra, Wageningen, Netherlands.

European Commission, 2020. Farm to Fork Strategy.

FAOSTAT, 2022. FAOSTAT [WWW Document]. URL faostat.fao.org (accessed 8.23.22).

Feddes, R.A., 1982. Simulation of field water use and crop yield, in: Simulation of Plant Growth and Crop Production. Pudoc, pp. 194–209.

Fixen, P.E., 2020. A brief account of the genesis of 4R nutrient stewardship. Agron J 112, 4511–4518. https://doi.org/10.1002/agj2.20315

Fraval, S., Hammond, J., Wichern, J., Oosting, S.J., De Boer, I.J.M., Teufel, N., Lannerstad, M., Waha, K., Pagella, T., Rosenstock, T.S., Giller, K.E., Herrero, M., Harris, D., Van Wijk, M.T., 2019. Making the most of imperfect data: A critical evaluation of standard information collected in farm household surveys. Exp Agric 55, 230–250. https://doi.org/10.1017/S0014479718000388

Getnet, M., Van Ittersum, M., Hengsdijk, H., Descheemaeker, K., 2016. Yield gaps and resource use across farming zones in the central rift valley of Ethiopia. Exp Agric 52, 493–517. https://doi.org/10.1017/S0014479715000216

Gil, J.D.B., Reidsma, P., Giller, K., Todman, L., Whitmore, A., van Ittersum, M., 2019. Sustainable development goal 2: Improved targets and indicators for agriculture and food security. Ambio 48, 685–698. https://doi.org/10.1007/s13280-018-1101-4

Gobbett, D.L., Hochman, Z., Horan, H., Navarro Garcia, J., Grassini, P., Cassman, K.G., 2017. Yield gap analysis of rainfed wheat demonstrates local to global relevance. Journal of Agricultural Science 155, 282–299. https://doi.org/10.1017/S0021859616000381

Gobin, A., 2012. Impact of heat and drought stress on arable crop production in Belgium. Natural Hazards and Earth System Science 12, 1911–1922. https://doi.org/10.5194/nhess-12-1911-2012

Gobin, A., Van de Vyver, H., 2021. Spatio-temporal variability of dry and wet spells and their influence on crop yields. Agric For Meteorol 308–309. https://doi.org/10.1016/j.agrformet.2021.108565

Goffart, J.P., Haverkort, A., Storey, M., Haase, N., Martin, M., Lebrun, P., Ryckmans, D., Florins, D., Demeulemeester, K., 2022. Potato Production in Northwestern Europe (Germany, France, the Netherlands, United Kingdom, Belgium): Characteristics, Issues, Challenges and Opportunities. Potato Res 65, 503–547. https://doi.org/10.1007/s11540-021-09535-8

Górski, T., Górska, K., 2003. The effects of scale on crop yield variability. Agric Syst 78, 425–434. https://doi.org/10.1016/S0308-521X(03)00036-2

Goulding, K.W.T., Poulton, P.R., Webster, C.P., Howe, M.T., 2000. Nitrate leaching from the broadbalk wheat experiment, Rothamsted, UK, as influenced by fertilizer and manure inputs and the weather. Soil Use Manag 16, 244–250. https://doi.org/10.1111/j.1475-2743.2000.tb00203.x

Grados, D., García, S., Schrevens, E., 2020. Assessing the potato yield gap in the Peruvian Central Andes. Agric Syst 181. https://doi.org/10.1016/j.agsy.2020.102817

Grassini, P., Eskridge, K.M., Cassman, K.G., 2013. Distinguishing between yield advances and yield plateaus in historical crop production trends. Nat Commun 4. https://doi.org/10.1038/ncomms3918

Grassini, P., Thorburn, J., Burr, C., Cassman, K.G., 2011. High-yield irrigated maize in the Western U.S. Corn Belt: I. On-farm yield, yield potential, and impact of agronomic practices. Field Crops Res 120, 142–150. https://doi.org/10.1016/j.fcr.2010.09.012

Grassini, P., van Bussel, L.G.J., Van Wart, J., Wolf, J., Claessens, L., Yang, H., Boogaard, H., de Groot, H., van Ittersum, M.K., Cassman, K.G., 2015. How good is good enough? Data requirements for reliable crop yield simulations and yield-gap analysis. Field Crops Res 177, 49–63. https://doi.org/10.1016/j.fcr.2015.03.004

Hack-ten Broeke, M.J.D., Mulder, H.M., Bartholomeus, R.P., van Dam, J.C., Holshof, G., Hoving, I.E., Walvoort, D.J.J., Heinen, M., Kroes, J.G., van Bakel, P.J.T., Supit, I., de Wit, A.J.W., Ruijtenberg, R., 2019. Quantitative land evaluation implemented in Dutch water management. Geoderma 338, 536–545. https://doi.org/10.1016/j.geoderma.2018.11.002

Hanse, B., Schneider, J.H.M., Termorshuizen, A.J., Varrelmann, M., 2011. Pests and diseases contribute to sugar beet yield difference between top and averagely managed farms. Crop Protection 30, 671–678. https://doi.org/10.1016/j.cropro.2011.02.018

Haverkort, A.J., Boonekamp, P.M., Hutten, R., Jacobsen, E., Lotz, L.A.P., Kessel, G.J.T., Visser, R.G.F., Van Der Vossen, E.A.G., 2008. Societal costs of late blight in potato and prospects of durable resistance through cisgenic modification. Potato Res 51, 47–57. https://doi.org/10.1007/s11540-008-9089-y

Haverkort, A.J., Linnemann, A.R., Struik, P.C., Wiskerke, J.S.C., 2023. On Processing Potato 2. Survey of Products, Processes and Operations in Manufacturing. Potato Res 66, 339–383. https://doi.org/10.1007/s11540-022-09563-y

Haverkort, A.J., Struik, P.C., Visser, R.G.F., Jacobsen, E., 2009. Applied biotechnology to combat late blight in potato caused by phytophthora infestans. Potato Res 52, 249–264. https://doi.org/10.1007/s11540-009-9136-3

Haverkort, A.J., Van De Waart, M., Bodlaender, K.B.A., 1990. Effect of pre-planting temperature and light treatments of seed tubers on potato yield and tuber size distribution. Potato Res 33, 77–88. https://doi.org/https://doi.org/10.1007/BF02358132

Heinen, M., Mulder, H.M., Bakker, G., Wösten, J.H.M., Brouwer, F., Teuling, K., Walvoort, D.J.J., 2022. The Dutch soil physical units map: BOFEK. Geoderma 427. https://doi.org/10.1016/j.geoderma.2022.116123

Hijbeek, R., ten Berge, H.F.M., Whitmore, A.P., Barkusky, D., Schröder, J.J., van Ittersum, M.K., 2018. Nitrogen fertiliser replacement values for organic amendments appear to increase with N application rates. Nutr Cycl Agroecosyst 110, 105–115. https://doi.org/10.1007/s10705-017-9875-5

Hochman, Z., Gobbett, D., Horan, H., Navarro Garcia, J., 2016. Data rich yield gap analysis of wheat in Australia. Field Crops Res 197, 97–106. https://doi.org/10.1016/j.fcr.2016.08.017

Hoekstra, O., 1989. Results of twenty-four years of crop rotation research at 'De Schreef' experimental site, in: Effects of Crop Rotation on Potato Production in the Temperate Zones: Proceedings of the International Conference on Effects of Crop Rotation on Potato Production in the Temperate Zones, Held August 14–19, 1988, Wageningen, The Netherlands. Springer, pp. 37–44.

Hoogsteen, M.J.J., Lantinga, E.A., Bakker, E.J., Groot, J.C.J., Tittonell, P.A., 2015. Estimating soil organic carbon through loss on ignition: Effects of ignition conditions and structural water loss. Eur J Soil Sci 66, 320–328. https://doi.org/10.1111/ejss.12224

Houba, V.J.G., Temminghoff, E.J.M., Gaikhorst, G.A., Van Vark, W., 2000. Soil analysis procedures using 0.01 M calcium chloride as extraction reagent. Commun Soil Sci Plant Anal 31, 1299–1396. https://doi.org/https://doi.org/10.1080/00103620009370514

Huntenburg, K., Dodd, I.C., Stalham, M., 2021. Agronomic and physiological responses of potato subjected to soil compaction and/or drying. Annals of Applied Biology 178, 328–340. https://doi.org/10.1111/aab.12675

Janssen, B.H., 2017. Crop yields and NPK use efficiency of a long-term experiment on a former sea bottom in the Netherlands. Wageningen University, Plant Production Systems. https://doi.org/https://doi.org/10.18174/409554

Jernigan, A.B., Wickings, K., Mohler, C.L., Caldwell, B.A., Pelzer, C.J., Wayman, S., Ryan, M.R., 2020. Legacy effects of contrasting organic grain cropping systems on soil health indicators, soil invertebrates, weeds, and crop yield. Agric Syst 177, 102719. https://doi.org/10.1016/j.agsy.2019.102719

Johansen, T.J., Møllerhagen, P., Haugland, E., 2008. Yield potential of seed potatoes grown at different latitudes in Norway. Acta Agric Scand B Soil Plant Sci 58, 132–138. https://doi.org/10.1080/09064710701412635

Johansen, T.J., Thomsen, M.G., Løes, A.K., Riley, H., 2015. Root development in potato and carrot crops – influences of soil compaction. Acta Agric Scand B Soil Plant Sci 65, 182–192. https://doi.org/10.1080/09064710.2014.977942

Johnson, P.A., Seeney, F., Williams, D., 1996. The effect of physiological age and planting date on the response of potatoes to applied nitrogen and on levels of residual nitrogen post-harvest. Potato Res 39, 561–569. https://doi.org/https://doi.org/10.1007/BF02358475

Jovović, Z., Broćić, Z., Velimirović, A., Dolijanović, Ž., Komnenić, A., 2021. The influence of flooding on the main parameters of potato productivity, in: VIII South-Eastern Europe Symposium on Vegetables and Potatoes 1320. pp. 133–138.

Juventia, S.D., Selin Norén, I.L.M., van Apeldoorn, D.F., Ditzler, L., Rossing, W.A.H., 2022. Spatio-temporal design of strip cropping systems. Agric Syst 201. https://doi.org/10.1016/j.agsy.2022.103455

Keijbets, M.J.H., 2008. Potato processing for the consumer: Developments and future challenges. Potato Res 51, 271–281. https://doi.org/10.1007/s11540-008-9104-3

Kempenaar, C., Oosterhuis, H.S., Van der Lans, A.M., Van der Schans, D.A., Stilma, E.S.C., Hendriks-Goossens, V.J.C., Verwijs, B.R., Van Wijk, C.A.P., Van de Zande, J.C., 2010. Ontwikkeling van het prototype van SensiSpray in de gewassen aardappel en tulp. Plant Research International.

Kessel, G.J.T., Mullins, E., Evenhuis, A., Stellingwerf, J., Cortes, V.O., Phelan, S., van den Bosch, T., Förch, M.G., Goedhart, P., van der Voet, H., Lotz, L.A.P., 2018. Development and validation of IPM strategies for the cultivation of cisgenically modified late blight resistant potato. European Journal of Agronomy 96, 146–155. https://doi.org/10.1016/j.eja.2018.01.012

Kheir, A.M.S., Hoogenboom, G., Ammar, K.A., Ahmed, M., Feike, T., Elnashar, A., Liu, B., Ding, Z., Asseng, S., 2022. Minimizing trade-offs between wheat yield and resource-use efficiency in the Nile Delta – A multi-model analysis. Field Crops Res 287. https://doi.org/10.1016/j.fcr.2022.108638

Kingwell, R., 2011. Managing complexity in modern farming. Australian Journal of Agricultural and Resource Economics 55, 12–34. https://doi.org/10.1111/j.1467-8489.2010.00528.x

Knibbe, M.T., 2007. De hoofdelijke beschikbaarheid van voedsel en de levensstandaard in Nederland, 1807-1913. TSEG-The Low Countries Journal of Social and Economic History 4, 71–107.

KNMI, 2023. Time series: monthly precipitation deficit [WWW Document]. URL https://climexp.knmi.nl/getindices.cgi?WMO=KNMIData/nt_nl&STATION=precipitationdeficit&TYPE=i&id=someone@somewhere&NPERYEAR=366 (accessed 9.9.23).

KNMI, 2022a. Dagwaarnemingen [WWW Document]. URL https://daggegevens.knmi.nl/klimatologie/daggegevens (accessed 6.17.22).

KNMI, 2022b. Historisch verloop neerslagtekort [WWW Document]. URL https://www.knmi.nl/nederland-nu/klimatologie/geografische-overzichten/historisch-neerslagtekort (accessed 8.24.22).

Koch, M., Naumann, M., Thiel, H., Gransee, A., Pawelzik, E., 2020. The Importance of Nutrient Management for Potato Production Part II: Plant Nutrition and Tuber Quality. Potato Res 63, 121–137. https://doi.org/10.1007/s11540-019-09430-3

Koenker, R., Portnoy, S., Ng, P.T., Zeileis, A., Grosjean, P., Ripley, B.D., 2018. Package 'quantreg.' Reference manual available at R-CRAN: https://cran. rproject. org/web/packages/quantreg/quantreg. pdf.

Krijthe, N.K., 1958. Changes in the germinating power of seed potatoes. Eur. Potato J 1, 69–72.

Kroes, J.G., Van Dam, J.C., Bartholomeus, R.P., Groenendijk, P., Heinen, M., Hendriks, R.F.A., Mulder, H.M., Supit, I., Van Walsum, P.E. V, 2017. SWAP version 4. Wageningen Environmental Research. https://doi.org/https://doi.org/10.18174/416321

Kuznetsova, A., Brockhoff, P.B., Christensen, R.H.B., 2015. Package 'lmertest.' R package version 2, 734.

Kwambai, T.K., Struik, P.C., Griffin, D., Stack, L., Rono, S., Nyongesa, M., Brophy, C., Gorman, M., 2022. Understanding Potato Production Practices in North-Western Kenya through Surveys: an Important Key to Improving Production. Potato Res. https://doi.org/10.1007/s11540-022-09599-0

Li, X., Storkey, J., Mead, A., Shield, I., Clark, I., Ostler, R., Roberts, B., Dobermann, A., 2023. A new Rothamsted long-term field experiment for the twenty-first century: principles and practice. Agron Sustain Dev 43. https://doi.org/10.1007/s13593-023-00914-8

Liu, C., Rubæk, G.H., Liu, F., Andersen, M.N., 2015. Effect of partial root zone drying and deficit irrigation on nitrogen and phosphorus uptake in potato. Agric Water Manag 159, 66–76. https://doi.org/10.1016/j.agwat.2015.05.021

LNV, 2021. 7e Nederlandse actieprogramma betreffende de Nitraatrichlijn (2022 - 2025).

Lobell, D.B., Ortiz-Monasterio, J.I., Falcon, W.P., 2007. Yield uncertainty at the field scale evaluated with multi-year satellite data. Agric Syst 92, 76–90. https://doi.org/10.1016/j.agsy.2006.02.010

Lobell, D.B., Ortiz-Monasterio, J.I., Lee, A.S., 2010. Satellite evidence for yield growth opportunities in Northwest India. Field Crops Res 118, 13–20. https://doi.org/10.1016/j.fcr.2010.03.013

López-Porrero, E.J., 2016. Explaining yield gaps of cereals in temperate regions using an expert-based survey (Internship report). Wageningen Univeristy, Wageningen.

Ludwig, J.W., 1972. Bepaling van het droge-stofgehalte van aardappelen via onderwaterweging. IBVL, Publicatie 247, IBVL, Wageningen, 12 pp.

Łukowiak, R., Grzebisz, W., Sassenrath, G.F., 2016. New insights into phosphorus management in agriculture - A crop rotation approach. Science of the Total Environment 542, 1062–1077. https://doi.org/10.1016/j.scitotenv.2015.09.009

Mackerron, D.K.L., Marshall, B., Jefferies, R.A., 1988. The distributions of tuber sizes in droughted and irrigated crops of potato. II. Relation between size and weight of tubers and the variability of tuber-size distributions. Potato Res 31, 279–288. https://doi.org/https://doi.org/10.1007/BF02365536

Maestrini, B., Basso, B., 2018. Drivers of within-field spatial and temporal variability of crop yield across the US Midwest. Sci Rep 8. https://doi.org/10.1038/s41598-018-32779-3

Maier, N.A., Dahlenburg, A.P., Williams, C., 1994. Effects of Nitrogen, Phosphorus, and Potassium on Yield, Specific Gravity, Crisp Colour, and Tuber Chemical Composition of Potato (Solanum Tuberosum La) cv. Kennebec. Aust J Exp Agric 34, 813–824. https://doi.org/10.1071/EA9940813

Mburu, H., Cortada, L., Haukeland, S., Ronno, W., Nyongesa, M., Kinyua, Z., Bargul, J.L., Coyne, D., 2020. Potato Cyst Nematodes: A New Threat to Potato Production in East Africa. Front Plant Sci 11. https://doi.org/10.3389/fpls.2020.00670

Meyer-Aurich, A., Karatay, Y.N., 2019. Effects of uncertainty and farmers' risk aversion on optimal N fertilizer supply in wheat production in Germany. Agric Syst 173, 130–139. https://doi.org/10.1016/j.agsy.2019.02.010

Mohr, R.M., Tomasiewicz, D.J., 2011. Effect of phosphorus fertilizer rate on irrigated russet Burbank potato. Commun Soil Sci Plant Anal 42, 2284–2298. https://doi.org/10.1080/00103624.2011.602457

Mokrani, K., Hamdi, K., Tarchoun, N., 2018. Communications in Soil Science and Plant Analysis Potato (Solanum Tuberosum L .) Response to Nitrogen , Phosphorus and Potassium Fertilization Rates Potato (Solanum Tuberosum L .) Response to Nitrogen , Phosphorus. Commun Soil Sci Plant Anal 49, 1314–1330. https://doi.org/10.1080/00103624.2018.1457159

Motyka-Pomagruk, A., Zoledowska, S., Sledz, W., Lojkowska, E., 2021. The occurrence of bacteria from different species of Pectobacteriaceae on seed potato plantations in Poland. Eur J Plant Pathol 159, 309–325. https://doi.org/10.1007/s10658-020-02163-x

Mourtzinis, S., Rattalino Edreira, J.I., Grassini, P., Roth, A.C., Casteel, S.N., Ciampitti, I.A., Kandel, H.J., Kyveryga, P.M., Licht, M.A., Lindsey, L.E., Mueller, D.S., Nafziger, E.D., Naeve, S.L., Stanley, J., Staton, M.J., Conley, S.P., 2018. Sifting and winnowing: Analysis of farmer field data for soybean in the US North-Central region. Field Crops Res 221, 130–141. https://doi.org/10.1016/j.fcr.2018.02.024

Mulders, P.J.A.M., 2023. Data Science on Farm Level: Explaining and Predicting Variability in Potato Yield. Eindhoven University of Technology, Eindhoven.

Mulders, P.J.A.M., van den Heuvel, E.R., van den Borne, J., van de Molengraft, R., Heemels, W.P.M.H. (Maurice), Reidsma, P., 2021. Data science at farm level: Explaining and predicting within-farm variability in potato growth and yield. European Journal of Agronomy 123. https://doi.org/10.1016/j.eja.2020.126220

Nawaz, M.F., Bourrié, G., Trolard, F., 2013. Soil compaction impact and modelling. A review. Agron Sustain Dev 33, 291–309. https://doi.org/10.1007/s13593-011-0071-8

Neeteson, J.J., 2000. Nitrogen and phosphorus management on Dutch dairy farms: Legislation and strategies employed to meet the regulations. Biol Fertil Soils 30, 566–572. https://doi.org/10.1007/s003740050037

Neeteson, J.J., 1990. Development of nitrogen fertilizer recommendations for arable crops in the Netherlands in relation to nitrate leaching. Fertilizer Research 26, 291–298. https://doi.org/https://doi.org/10.1007/BF01048767

Nepal, S., McIntosh, C.S., Thornton, M.K., Olsen, N., Nolte, P., Patterson, P.E., 2016. Manipulation of Physiological Seed Age of Russet Burbank and Ranger Russet Potatoes – Economic Evaluation. American Journal of Potato Research 93, 590–601. https://doi.org/10.1007/s12230-016-9539-z

NHI, 2023. Nederlands Hydrologisch Instrumentarium [WWW Document]. URL https://www.nhi.nu/ (accessed 3.21.23).

Novozamsky, I., Houba, V.J.G., Van Eck, R., Van Vark, W., 1983. A novel digestion technique for multi-element plant analysis. Commun Soil Sci Plant Anal 14, 239–248. https://doi.org/https://doi.org/10.1080/00103628309367359

Nyiraneza, J., Bizimungu, B., Messiga, A.J., Fuller, K.D., Fillmore, S.A.E., Jiang, Y., 2017. Potato yield and phosphorus use efficiency of two new potato cultivars in New Brunswick, Canada. Canadian Journal of Plant Science 97, 784–795. https://doi.org/10.1139/cjps-2016-0330

O'Brien, P.J., Allen, E.J., Bean, J.N., Griffith, R.L., Jones, S.A., Jones, J.L., 1983. Accumulated day-degrees as a measure of physiological age and the relationships with growth and yield in early potato varieties. J Agric Sci 101, 613–631. https://doi.org/10.1017/S002185960003865X

Oenema, O., 2004. Governmental policies and measures regulating nitrogen and phosphorus from animal manure in European agriculture. J Anim Sci 82 E-Suppl, 196–206. https://doi.org/10.2527/2004.8213_supplE196x

Oenema, O., Roest, C.W.J., 1998. Nitrogen and phosphorus losses from agriculture into surface waters; the effects of policies and measures in the Netherlands. Water Science and Technology 37, 19–30. https://doi.org/https://doi.org/10.1016/S0273-1223(98)00052-3

Oenema, O., Van Liere, L., Schoumans, O., 2005. Effects of lowering nitrogen and phosphorus surpluses in agriculture on the quality of groundwater and surface water in the Netherlands. J Hydrol (Amst) 304, 289–301. https://doi.org/10.1016/j.jhydrol.2004.07.044

Ozgen, S., Palta, J.P., 2005. Supplemental Calcium Application Influences Potato Tuber Number and Size. HORTSCIENCE 40. https://doi.org/https://doi.org/10.21273/HORTSCI.40.1.102

Panique, E., Kelling, K.A., Schulte, E.E., Hero, D.E., Stevenson, W.R., James, R. V, 1997. Potassium rate and source effects on potato yield, quality, and disease interaction. Am Potato J 74, 379–398.

Patrignani, A., Ochsner, T.E., 2015. Canopeo: A powerful new tool for measuring fractional green canopy cover. Agron J 107, 2312–2320. https://doi.org/https://doi.org/10.2134/agronj15.0150

Pretty, J., 2018. Intensification for redesigned and sustainable agricultural systems. Science (1979) 362. https://doi.org/10.1126/science.aav0294

Prikaziuk, E., Ntakos, G., ten Den, T., Reidsma, P., van der Wal, T., van der Tol, C., 2022. Using the SCOPE model for potato growth, productivity and yield monitoring under different levels of nitrogen fertilization. International Journal of Applied Earth Observation and Geoinformation 114. https://doi.org/10.1016/j.jag.2022.102997

Prummel, J., 1969. Fosfaatbemesting en bemestingstoestand van de grond en de invloed van groenbemesting op de beschikbaarheid van de fosfaat. Instituut voor Bodemvruchtbaarheid.

Qin, J., Bian, C., Duan, S., Wang, W., Li, G., Jin, L., 2022. Effects of different rotation cropping systems on potato yield, rhizosphere microbial community and soil biochemical properties. Front Plant Sci 13. https://doi.org/10.3389/fpls.2022.999730

Quemada, M., Lassaletta, L., Jensen, L.S., Godinot, O., Brentrup, F., Buckley, C., Foray, S., Hvid, S.K., Oenema, J., Richards, K.G., Oenema, O., 2020. Exploring nitrogen indicators of farm performance among farm types across several European case studies. Agric Syst 177. https://doi.org/10.1016/j.agsy.2019.102689

Rajsic, P., Weersink, A., 2008. Do farmers waste fertilizer? A comparison of ex post optimal nitrogen rates and ex ante recommendations by model, site and year. Agric Syst 97, 56–67. https://doi.org/10.1016/j.agsy.2007.12.001

Rattalino Edreira, J.I., Cassman, K.G., Hochman, Z., Van Ittersum, M.K., Van Bussel, L., Claessens, L., Grassini, P., 2018. Beyond the plot: Technology extrapolation domains for scaling out agronomic science. Environmental Research Letters 13. https://doi.org/10.1088/1748-9326/aac092

Rattalino Edreira, J.I., Mourtzinis, S., Conley, S.P., Roth, A.C., Ciampitti, I.A., Licht, M.A., Kandel, H., Kyveryga, P.M., Lindsey, L.E., Mueller, D.S., Naeve, S.L., Nafziger, E., Specht, J.E., Stanley, J., Staton, M.J., Grassini, P., 2017. Assessing causes of yield gaps in agricultural areas with diversity in climate and soils. Agric For Meteorol 247, 170–180. https://doi.org/10.1016/j.agrformet.2017.07.010

Ray, D.K., Gerber, J.S., Macdonald, G.K., West, P.C., 2015. Climate variation explains a third of global crop yield variability. Nat Commun 6. https://doi.org/10.1038/ncomms6989

Reidsma, P., Bakker, M.M., Kanellopoulos, A., Alam, S.J., Paas, W., Kros, J., de Vries, W., 2015. Sustainable agricultural development in a rural area in the Netherlands? Assessing impacts of climate and socio-economic change at farm and landscape level. Agric Syst 141, 160–173. https://doi.org/10.1016/j.agsy.2015.10.009

Reus, J.A.W.A., Leendertse, P.C., 2000. The environmental yardstick for pesticides: a practical indicator used in the Netherlands. Crop Protection 19, 637–641. https://doi.org/https://doi.org/10.1016/S0261-2194(00)00084-3

Rong, L. bing, Gong, K. yuan, Duan, F. ying, Li, S. kun, Zhao, M., He, J., Zhou, W. bin, Yu, Q., 2021. Yield gap and resource utilization efficiency of three major food crops in the world – A review. J Integr Agric 20, 349–362. https://doi.org/10.1016/S2095-3119(20)63555-9

Ros, G.H., de Vries, W., Jongeneel, R., van Ittersum, M., 2023. Gebieds-en bedrijfsgerichte handelingsperspectieven voor een duurzame landbouw in Nederland. Wageningen University & Research.

Rosen, C.J., Bierman, P.M., 2008. Potato yield and tuber set as affected by phosphorus fertilization. American Journal of Potato Research 85, 110–120. https://doi.org/10.1007/s12230-008-9001-y

Royal Eijkelkamp, 2022. Penetrologger handleiding.

Rui, Y., Sanford, G.R., Hedtcke, J.L., Ruark, M.D., 2020. Legacy effects of liquid dairy manure in grain production systems. Agric Syst 181. https://doi.org/10.1016/j.agsy.2020.102825

RVO, 2023a. Tabel 11 Normen en mestcodes aanvoer en afvoer (dierlijke) mest [WWW Document]. URL https://www.rvo.nl/sites/default/files/2021/06/Tabel-11-Normen-en-mestcodes-aanvoer-afvoer-dierlijke-mest-2019-2021.pdf (accessed 7.25.23).

RVO, 2023b. Fosfaatdifferentiatie [WWW Document]. URL https://www.rvo.nl/onderwerpen/mest/gebruiken-en-uitrijden/fosfaat-landbouwgrond/differentiatie (accessed 10.27.23).

RVO, 2018. Tabel 3 Werkingscoëfficient [WWW Document]. URL https://www.rvo.nl/sites/default/files/2019/01/Tabel-3-Werkingscoefficient-2019-2021.pdf (accessed 3.23.23).

Rykaczewska, K., 2010. The Effect of High Temperature during Storage on the Vigour of Potato Mother Tubers. Potato Res 53, 325–329. https://doi.org/10.1007/s11540-010-9175-9

Sattari, S.Z., Bouwman, A.F., Giller, K.E., Ittersum, M.K. Van, 2012. Residual soil phosphorus as the missing piece in the global phosphorus crisis puzzle. Proceedings of the National Academy of Sciences 109. https://doi.org/10.1073/pnas.1113675109

Schaap, B.F., Blom-Zandstra, M., Hermans, C.M.L., Meerburg, B.G., Verhagen, J., 2011. Impact changes of climatic extremes on arable farming in the north of the Netherlands. Reg Environ Change 11, 731–741. https://doi.org/10.1007/s10113-011-0205-1

Schaap, B.F., Reidsma, P., Verhagen, J., Wolf, J., van Ittersum, M.K., 2013. Participatory design of farm level adaptation to climate risks in an arable region in The Netherlands. European Journal of Agronomy 48, 30–42. https://doi.org/10.1016/j.eja.2013.02.004

Schepers, H.T.A.M., Kessel, G.J.T., Lucca, F., Förch, M.G., van den Bosch, G.B.M., Topper, C.G., Evenhuis, A., 2018. Reduced efficacy of fluazinam against Phytophthora infestans in the Netherlands. Eur J Plant Pathol 151, 947–960. https://doi.org/10.1007/s10658-018-1430-y

Schipper, P.N.M., Vissers, M.J.M., van der Linden, A.M.A., 2008. Pesticides in groundwater and drinking water wells: Overview of the situation in the Netherlands. Water Science and Technology 57, 1277–1286. https://doi.org/10.2166/wst.2008.255

Scholte, K.I., Jacob, J.J., 1990. Effect of crop rotation , cultivar and nematicide on growth and yield of potato (Solanum tuberosum L .) in short rotations on a marine clay soil. Potato Res 33, 191–200. https://doi.org/https://doi.org/10.1007/BF02358446

Schröder, J., 2005. Revisiting the agronomic benefits of manure: A correct assessment and exploitation of its fertilizer value spares the environment, in: Bioresource Technology. pp. 253–261. https://doi.org/10.1016/j.biortech.2004.05.015

Schröder, J.J., Smit, A.L., Cordell, D., Rosemarin, A., 2011. Improved phosphorus use efficiency in agriculture: A key requirement for its sustainable use. Chemosphere 84, 822–831. https://doi.org/10.1016/j.chemosphere.2011.01.065

Silva, J.V., Heerwaarden, J. van, Reidsma, P., Laborte, A.G., Tesfaye, K., Ittersum, M.K. van, 2023. Big data, small explanatory and predictive power: Lessons from random forest modeling of on-farm yield variability and implications for data-driven agronomy. Field Crops Res 302, 109063. https://doi.org/10.1016/j.fcr.2023.109063

Silva, J.V., Reidsma, P., van Ittersum, M.K., 2017. Yield gaps in Dutch arable farming systems: Analysis at crop and crop rotation level. Agric Syst 158, 78–92. https://doi.org/10.1016/j.agsy.2017.06.005

Silva, J.V., Tenreiro, T.R., Spätjens, L., Anten, N.P.R., van Ittersum, M.K., Reidsma, P., 2020. Can big data explain yield variability and water productivity in intensive cropping systems? Field Crops Res 255, 107828. https://doi.org/10.1016/j.fcr.2020.107828

Silva, J.V., van Ittersum, M.K., ten Berge, H.F.M., Spätjens, L., Tenreiro, T.R., Anten, N.P.R., Reidsma, P., 2021. Agronomic analysis of nitrogen performance indicators in intensive arable cropping systems: An appraisal of big data from commercial farms. Field Crops Res 269. https://doi.org/10.1016/j.fcr.2021.108176

Sinton, S.M., Falloon, R.E., Jamieson, P.D., Meenken, E.D., Shah, F.A., Brown, H.E., Dellow, S.J., Michel, A.J., Fletcher, J.D., 2022. Yield Depression in New Zealand Potato Crops Associated with Soil Compaction and Soil-Borne Diseases. American Journal of Potato Research 99, 160–173. https://doi.org/10.1007/s12230-022-09864-5

Small, I.M., Joseph, L., Fry, W.E., 2015. Evaluation of the BlightPro decision support system for management of potato late blight using computer simulation and field validation. Phytopathology 105, 1545–1554. https://doi.org/10.1094/PHYTO-05-15-0117-R

Spiertz, J.H.J., 2010. Nitrogen, sustainable agriculture and food security. A review. Agron Sustain Dev 30, 43–55. https://doi.org/10.1051/agro:2008064

Stalham, M.A., Allen, E.J., Rosenfeld, A.B., Herry, F.X., 2007. Effects of soil compaction in potato (Solanum tuberosum) crops. Journal of Agricultural Science 145, 295–312. https://doi.org/10.1017/S0021859607006867

Stark, J.C., Love, S.L., King, B.A., Marshall, J.M., Bohl, W.H., Salaiz, T., 2013. Potato Cultivar Response to Seasonal Drought Patterns. American Journal of Potato Research 90, 207–216. https://doi.org/10.1007/s12230-012-9285-9

Steén, I., 1997. A European fertilizer industry view on phosphorus retention and loss from agricultural soils. pp. 311–328.

Steinke, J., van Etten, J., Zelan, P.M., 2017. The accuracy of farmer-generated data in an agricultural citizen science methodology. Agron Sustain Dev 37. https://doi.org/10.1007/s13593-017-0441-y

Steyn, J.M., Franke, A.C., van der Waals, J.E., Haverkort, A.J., 2016. Resource use efficiencies as indicators of ecological sustainability in potato production: A South African case study. Field Crops Res 199, 136–149. https://doi.org/10.1016/j.fcr.2016.09.020

Struik, P.C., 2007. The canon of potato science: 40. Physiological age of seed tubers. Potato Res 50, 375–377. https://doi.org/10.1007/s11540-008-9069-2

Struik, P.C., Van Der Putten, P.E.L., Caldiz, D.O., Scholte, K., 2006. Response of stored potato seed tubers from contrasting cultivars to accumulated day-degrees. Crop Sci 46, 1156–1168. https://doi.org/10.2135/cropsci2005.08-0267

Struik, P.C., Wiersema, S.G., 1999. Seed potato technology. Wageningen Academic Publishers.

Susnoschi, M., 1981. Seed potato quality as influenced by high temperatures during the growth period. 1. Effect of storage temperature on sprout growth. Potato Res 24, 371–379. https://doi.org/https://doi.org/10.1007/BF02357319

Taylor, J.A., Chen, H., Smallwood, M., Marshall, B., 2018. Investigations into the opportunity for spatial management of the quality and quantity of production in UK potato systems. Field Crops Res 229, 95–102. https://doi.org/10.1016/j.fcr.2018.10.002

ten Berge, H.F.M., Hijbeek, R., van Loon, M.P., Rurinda, J., Tesfaye, K., Zingore, S., Craufurd, P., van Heerwaarden, J., Brentrup, F., Schröder, J.J., Boogaard, H.L., de Groot, H.L.E., van Ittersum, M.K., 2019. Maize crop nutrient input requirements for food security in sub-Saharan Africa. Glob Food Sec 23, 9–21. https://doi.org/10.1016/j.gfs.2019.02.001

ten Den, T., van de Wiel, I., de Wit, A., van Evert, F.K., van Ittersum, M.K., Reidsma, P., 2022. Modelling potential potato yields: Accounting for experimental differences in modern cultivars. European Journal of Agronomy 137. https://doi.org/10.1016/j.eja.2022.126510

Tittonell, P., Vanlauwe, B., Corbeels, M., Giller, K.E., 2008. Yield gaps, nutrient use efficiencies and response to fertilisers by maize across heterogeneous smallholder farms of western Kenya. Plant Soil 313, 19–37. https://doi.org/10.1007/s11104-008-9676-3

UN, 2022. World Population Prospects: The 2022 Revision, [WWW Document]. URL https://population.un.org/wpp/ (accessed 11.10.23).

Vakis, N.J., 1986. Influence of physiological ageing and earliness of seed potatoes on yield. Potato Res 29, 417–425. https://doi.org/https://doi.org/10.1007/BF02359973

van Bussel, L.G.J., Grassini, P., Van Wart, J., Wolf, J., Claessens, L., Yang, H., Boogaard, H., de Groot, H., Saito, K., Cassman, K.G., van Ittersum, M.K., 2015. From field to atlas: Upscaling of location-specific yield gap estimates. Field Crops Res 177, 98–108. https://doi.org/10.1016/j.fcr.2015.03.005

van de Steeg, J.A., van Diepen, C.A., 1997. Bepaling van de landbouwkundige potentie van gebieden in Nederland aan de hand van bodem, grondwater en klimaat; Strategische Expertise Ontwikkeling Plattelandsvernieuwing en Scenariomethodiek (SEOPS). DLO-Staring Centrum.

van den Akker, J.J.H., Hoogland, T., 2011. Comparison of risk assessment methods to determine the subsoil compaction risk of agricultural soils in The Netherlands. Soil Tillage Res 114, 146–154. https://doi.org/10.1016/j.still.2011.04.002

van den Hurk, B., Siegmund, P., Klein Tank, A., Attema, J., Bakker, A., Beersma, J., Bessembinder, J., Boers, R., Brandsma, T., Van Den Brink, H., Drijfhout, S., Eskes, H., Haarsma, R., Hazeleger, W., Jilderda, R., Katsman, C., Lenderink, G., Loriaux, J., Van Meijgaard, E., Van Noije, T., Van

Oldenborgh, J., Selten, F., Siebesma, P., Sterl, A., 2014. KNMI'14: Climate Change scenarios for the 21st Century-A Netherlands perspective.

van der Voort, M.P.J., 2022. KWIN-AGV 2022: Kwantitatieve Informatie Akkerbouw en Vollegrondsgroenteteelt.

van der Voort, M.P.J., 2019. Elektrisch beregenen. https://doi.org/10.18174/508399

van der Zaag, D.E., van Loon, C.D., 1987. Effect of physiological age on growth vigour of seed potatoes of two cultivars. 5. Review of literature and integration of some experimental results. Potato Res 30, 451–472. https://doi.org/https://doi.org/10.1007/BF02361922

van Dijk, K.C., Lesschen, J.P., Oenema, O., 2016. Phosphorus flows and balances of the European Union Member States. Science of the Total Environment 542, 1078–1093. https://doi.org/10.1016/j.scitotenv.2015.08.048

van Dijk, M., Morley, T., van Loon, M., Reidsma, P., Tesfaye, K., van Ittersum, M.K., 2020. Reducing the maize yield gap in Ethiopia: Decomposition and policy simulation. Agric Syst 183. https://doi.org/10.1016/j.agsy.2020.102828

van Evert, F.K., Booij, R., Jukema, J.N., ten Berge, H.F.M., Uenk, D., Meurs, E.J.J.B., van Geel, W.C.A., Wijnholds, K.H., Slabbekoorn, J.J.H., 2012a. Using crop reflectance to determine sidedress N rate in potato saves N and maintains yield. European Journal of Agronomy 43, 58–67. https://doi.org/10.1016/j.eja.2012.05.005

van Evert, F.K., van der Voet, P., van Valkengoed, E., Kooistra, L., Kempenaar, C., 2012b. Satellite-based herbicide rate recommendation for potato haulm killing. European Journal of Agronomy 43, 49–57. https://doi.org/10.1016/j.eja.2012.05.004

van Geel, W., Rietra, R., Verstegen, H., Duan, K., Groenendijk, P., Verhoeven, J., 2023. Effect N-vanggewassen na aardappel op zandgrond op de nitraatuitspoeling : Verslag van driejarig veldonderzoek op zuidelijk zandgrond te Vredepeel. https://doi.org/10.18174/631358

van Grinsven, H.J.M., van Eerdt, M.M., Westhoek, H., Kruitwagen, S., 2019. Benchmarking Eco-Efficiency and Footprints of Dutch Agriculture in European Context and Implications for Policies for Climate and Environment. Front Sustain Food Syst 3. https://doi.org/10.3389/fsufs.2019.00013

van Ittersum, M.K., 1992a. Relation between growth conditions and dormancy of seed potatoes. 1. Effects of nitrogen. Potato Res 35, 355–364. https://doi.org/https://doi.org/10.1007/BF02357592

van Ittersum, M.K., 1992b. Dormancy and growth vigour of seed potatoes (PhD Thesis). Wageningen University, Wageningen.

van Ittersum, M.K., Cassman, K.G., Grassini, P., Wolf, J., Tittonell, P., Hochman, Z., 2013. Yield gap analysis with local to global relevance-A review. Field Crops Res 143, 4–17. https://doi.org/10.1016/j.fcr.2012.09.009

van Ittersum, M.K., Leffelaar, P.A., van Keulen, H., Kropff, M.J., Bastiaans, L., Goudriaan, J., 2003. On approaches and applications of the Wageningen crop models. European Journal of Agronomy 18, 201–234. https://doi.org/https://doi.org/10.1016/S1161-0301(02)00106-5 van Ittersum, M.K., Rabbinge, R., 1997. Concepts in production ecology for analysis and quantification of agricultural input-output combinations. Field Crops Res 52, 197–208. https://doi.org/https://doi.org/10.1016/S0378-4290(97)00037-3

Van Loon, C.D., 1987. Effect of physiological age on growth vigour of seed potatoes of two cultivars. 4. Influence of storage period and storage temperature on growth and yield in the field. Potato Res 30, 441–450. https://doi.org/https://doi.org/10.1007/BF02361921

van Loon, C.D., Veerman, A., Bus, C.B., Zwanepol, S., 1993. Teelt van consumptie-aardappelen. PAGV.

van Loon, M.P., Adjei-Nsiah, S., Descheemaeker, K., Akotsen-Mensah, C., van Dijk, M., Morley, T., van Ittersum, M.K., Reidsma, P., 2019. Can yield variability be explained? Integrated assessment of maize yield gaps across smallholders in Ghana. Field Crops Res 236, 132–144. https://doi.org/10.1016/j.fcr.2019.03.022

van Noordwijk, M., Brussaard, L., 2014. Minimizing the ecological footprint of food: Closing yield and efficiency gaps simultaneously? Curr Opin Environ Sustain 8, 62–70. https://doi.org/10.1016/j.cosust.2014.08.008

van Oort, P.A.J., Timmermans, B.G.H., Meinke, H., Van Ittersum, M.K., 2012. Key weather extremes affecting potato production in The Netherlands. European Journal of Agronomy 37, 11–22. https://doi.org/10.1016/j.eja.2011.09.002

van Oort, P.A.J., Timmermans, B.G.H., Schils, R.L.M., van Eekeren, N., 2023. Recent weather extremes and their impact on crop yields of the Netherlands. European Journal of Agronomy 142. https://doi.org/10.1016/j.eja.2022.126662

van Rotterdam, D., 2021. Fosfaatvoorziening aardappel : Relatie tussen mestbeleid, fosfaattoestand van de bodem en voorziening van het gewas. Wageningen.

van Woerden, P., Cevaal, P.K., 1976. Het effect van beregening op enkele akkerbouwgewassen in de IJsselmeerpolders. Proefstation voor de Akkerbouw, Lelystad.

Vanongeval, F., Gobin, A., 2023. Adverse Weather Impacts on Winter Wheat, Maize and Potato Yield Gaps in northern Belgium. Agronomy 13. https://doi.org/10.3390/agronomy13041104

Vermeulen, G.D., Klooster, J.J., 1992. The potential of a low ground pressure traffic system to reduce soil compaction on a clayey loam soil. Soil Tillage Res 24, 337–358. https://doi.org/https://doi.org/10.1016/0167-1987(92)90118-U

Vonk, W.J., van Ittersum, M.K., Reidsma, P., Zavattaro, L., Bechini, L., Guzmán, G., Pronk, A., Spiegel, H., Steinmann, H.H., Ruysschaert, G., Hijbeek, R., 2020. European survey shows poor association between soil organic matter and crop yields. Nutr Cycl Agroecosyst 118, 325–334. https://doi.org/10.1007/s10705-020-10098-2

Vos, J., 1996. Input and offtake of nitrogen, phosphorus and potassium in cropping systems with potato as a main crop and sugar beet and spring wheat as subsidiary crops. European journal of agronomy 5, 105–114. https://doi.org/https://doi.org/10.1016/S1161-0301(96)02013-8

Vos, J., Van Der Putten, P.E.L., 2000. Nutrient cycling in a cropping system with potato, spring wheat, sugar beet, oats and nitrogen catch crops. II. Effect of catch crops on nitrate leaching in autumn and winter. Nutr Cycl Agroecosyst 70, 23–31. https://doi.org/10.1023/B:FRES.0000049358.24431.0d

Wagg, C., Hann, S., Kupriyanovich, Y., Li, S., 2021. Timing of short period water stress determines potato plant growth, yield and tuber quality. Agric Water Manag 247. https://doi.org/10.1016/j.agwat.2020.106731

Wang, N., Reidsma, P., Pronk, A.A., de Wit, A.J.W., van Ittersum, M.K., 2018. Can potato add to China's food self-sufficiency? The scope for increasing potato production in China. European Journal of Agronomy 101, 20–29. https://doi.org/10.1016/j.eja.2018.07.002

Wang, X., Duan, Y., Zhang, J., Ciampitti, I.A., Cui, J., Qiu, S., Xu, X., Zhao, S., He, P., 2022. Response of potato yield, soil chemical and microbial properties to different rotation sequences of green manure-potato cropping in North China. Soil Tillage Res 217. https://doi.org/10.1016/j.still.2021.105273

Waverijn, A., 2020. The effect of seed potato quality and management on the development of ware potato on a large-scale arable farm. (MSc thesis). Plant Production Systems Group, Wageningen University, Wageningen.

Whitehead, A.G., Webb, R.M., Beane, J., 1991. Effects of rotation length and oxamyl on potato yield and the potato cyst-nematode, Globodera rostochiensis, in a sandy loam soil. Annals of Applied Biology 118, 371–380. https://doi.org/10.1111/j.1744-7348.1991.tb05637.x

Wiersema, S.G., Booth, R.H., 1985. Influence of growing and storage conditions on the subsequent performance of seed potatoes under short-day conditions. Potato Res 28, 15–25. https://doi.org/https://doi.org/10.1007/BF02357566

Wiseman, L., Sanderson, J., Zhang, A., Jakku, E., 2019. Farmers and their data: An examination of farmers' reluctance to share their data through the lens of the laws impacting smart farming. NJAS - Wageningen Journal of Life Sciences 90–91. https://doi.org/10.1016/j.njas.2019.04.007

Wurr, D.C.E., 1979. The effect of variation in the storage temperature of seed potatoes on sprout growth and subsequent yield. J Agric Sci 93, 619–622. https://doi.org/doi:10.1017/S0021859600039022

Wustman, R., 2005. Qualitative analysis of starch potato production on farms in Northeast Netherlands. Potato Res 48, 117–129. https://doi.org/https://doi.org/10.1007/BF02742371

R

Appendices

A. **Supplementary to Chapter 2:** Yield variability across spatial scales in high input farming: Data and farmers' perceptions for potato crops in the Netherlands

B. **Supplementary to Chapter 3:** Field monitoring coupled with crop growth modelling allows for a detailed yield gap assessment at field level: a case study on ware potato production in the Netherlands

C. **Supplementary to Chapter 4:** Current phosphorus and potassium fertiliser application rates do not limit tuber yield and quality in potato production systems in the Netherlands

D. **Supplementary to Chapter 6:** Field monitoring shows scope for reducing environmental impact of ware potato cultivation in the Netherlands without compromising yield

Appendix A Chapter 2

A.1 Within-field yield variability for all studied years

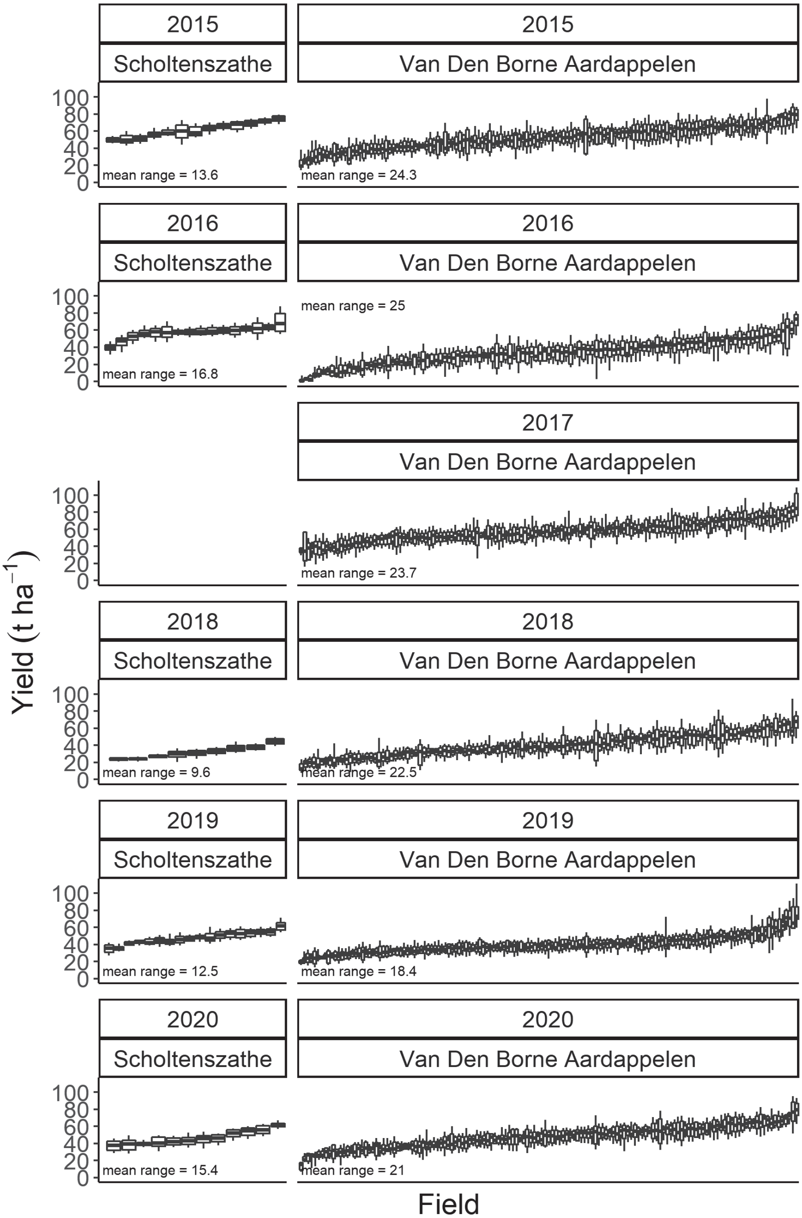


Figure A.1. Boxplots showing within-field yield variability (in t ha^{-1}) per field per year for the farms Scholtenszathe and Van Den Borne Aardappelen. Figure is based on the commercial farms dataset. Boxplot whiskers indicate lowest ten and highest 90% yield. The mean range depicted in each figure represents the average range of within-field yield variability per year (in t ha^{-1}).

A.2 Standard deviation across scales for a selected period and all years

Table A.2. Standard deviation (in t ha^{-1}) as indication for yield variability across scales calculated with mixed effects models for the period 2015 – 2020.

Data source	Province	Farm	Field	Within-field	year
CBS	1.6	-	-	-	3.8
Industry samples	2.0	-	-	-	4.7
FADN	3.5	6.1	-	-	3.5
Questionnaire	2.7	4.0	-	-	0.8
Farm 1	-	-	8.5	7.7	14.1
Farm 2	-	-	11.1	8.7	9.0

Table A.3. Standard deviation (in t ha^{-1}) as indication for yield variability across scales calculated with mixed effects models for all years that were available.

Data source	Province	Farm	Field	Within-field	year
CBS	2.6	-	-	-	3.0
Industry samples	1.9	-	-	-	4.3
FADN	4.2	7.1	-	-	3.2
Questionnaire	2.7	4.0	-	-	0.8
Farm 1	-	-	8.5	7.7	14.1
Farm 2	-	-	11.1	9.7	9.0

A.3 Variance explained by different scales for all years included in the analysis

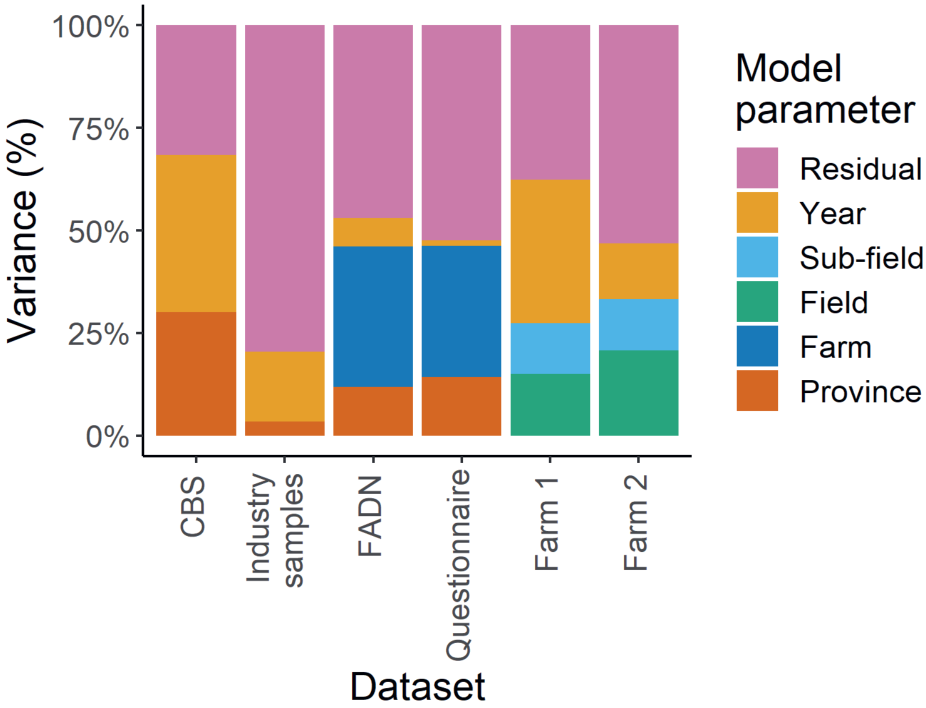


Figure A.4. Variance explained (in %) by the different model parameters for each dataset for all years that were available. Different colours indicate different sources of variance.

Appendix B Chapter 3

B.1 Complete overview of the methodology

Table B.1. Complete overview of measurements taken during the experiment, including measurements that were not used in the analysis.

Type of measurement	Method
Soil measurements	
Soil organic matter	SOM was measured using the loss on ignition method by placing the sample in a furnace at 550 ^{o}C for 3 hours. SOM was corrected for clay content using Hoogsteen et al. (2015), where clay content was provided from the farmer or taken from a soil map.
Soil pH	Soil pH was measured in water in a 1:2.5 soil:water ratio.
Total nitrogen and phosphorus	Total N and P were measured spectrophotometrically with a Skalar san++ system from a digestion with a mixture of H_2SO_4–Se and salicylic acid.
Available nitrogen, phosphorus, and potassium	Available N and P were measured spectrophotometrically with a Skalar san++ system from a 0.01 M $CaCl_2$ extraction (Houba et al., 2000). Available K was measured with a Varian AA240FS fast sequential atomic absorption spectrometer from the same extracts.
Soil penetration resistance	Soil penetration resistance was measured using a penetrologger (Royal Eijkelkamp, 2022) at the beginning of the growing season when it could be assumed that the soil moisture was at field capacity. The measurements were repeated on three locations per plot.
Potato cyst nematodes (2021 only)	Potato cyst nematode pressure was measured in each field in 2021 only. From exactly the same area as where the final harvest was measured, one square meter was intensively sampled for potato cyst nematodes at the beginning of the growing season. For each sample, the number of living eggs and larvae per gram dry soil was counted.
Soil profile	At the start of the growing season the soil profile was assessed visually till a depth of 60 cm to examine at which depth there were changes in soil layers or texture.
Crop measurements	
Soil cover	Soil cover was determined at each field visit with the Canopeo-app (Patrignani and Ochsner, 2015). Measurements were repeated four times per plot.

A

Crop health	Crop health was scored each visit using a scale from 1-5, where 5 was considered healthy and 1 was considered very diseased based on visual inspection.
Stem length	Stem length was measured each visit from the base till the youngest leave by stretching out the stem. Measurements were repeated four times per plot.
Number of leaf layers	Number of green fully emerged leave were counted at each visit. Measurements were repeated four times per plot.
Crop developmental stages	Crop developmental stages were recorded throughout the growing season. Emergence was assumed when 80% of the plants in the middle two ridges of a plot emerged. Tuber initiation was assumed when 3 out of 4 plants formed 3 or more tubers with a diameter of at least 1 cm. Flowering was assumed to take place when 50% of the plants were flowering. Senescence was assumed when less than 20% soil cover was remaining at the end of the growing season.
Emergence rate	Emergence rate was assessed before canopy closure by counting the number of emerged plants per plot.
Number of stems	The number of stems per plot were counted from a 3 m^2 area around canopy closure.
SPAD (2021 only)	SPAD was measured in 2021 at each visit using a SPAD-meter.
Aboveground biomass (2021 only)	In 2021, aboveground biomass was measured four times during the growing season for Innovator and five times during the growing season for Fontane. Haulms were collected from a 2 m^2 plot and measured for fresh weight in the field. A subsample was taken to measured dry matter concentration.
Yield measurements	
Gross yield	Gross yield was measured as the total harvested tuber biomass from a 2 m^2 area during the growing season and a 3 m^2 area at the final harvest.
Underwater weight / dry matter concentration	Dry matter concentration of the final yield was determined using underwater weight measurements in both years. In 2021, dry matter concentration was also measured after oven drying the tubers for 72 hours at 70 ^oC. In 2021, dry matter concentration was also measured for the intermediate harvests. This was done by oven drying tubers if the sample did not yet reach 6 kg and was done through underwater weight measurements once the composite soil sample reached 6 kg or more.
Tuber size distribution	The tuber size distribution was measured by measuring the tuber weight in the following size classes: 0-35mm; 35-40mm; 40-50mm; >50mm.

Number of tubers	Total number of tubers and number of tubers per size class were counted.
Tuber length	Tuber length was measured from 10 tubers in the size class >50 mm.
Percentage of green tubers	Weight percentage of green tubers were measured for the size class >40 mm.
Crop registration	
Irrigation	Information was collected on irrigation time and quantity
Fertilisation	Information was collected on the type, timing, and quantity of the applied fertilisers. We processed the information on applied fertilisers to calculate total applied nitrogen, phosphorus, and potassium. Total amounts were calculated as the sum of applied nutrients starting from the harvest of the previous crop till the end of the potato growing season. We calculated effective applied nitrogen in the same way, but used nitrogen fertiliser replacement values from the Dutch government to correct for the readily available nitrogen (RVO, 2018).
Pesticide application	Information was collected on the type, timing, and quantity of the applied crop protection products. We processed the information on crop protection products further to calculate the Environmental Impact Points of the product application, using the Environmental Yardstick tool (Reus and Leendertse, 2000). It is a tool that combines information on the applied quantity and harmfulness of the applied product to calculate the environmental pressure of the applied crop protection products.
Crop management dates	Farmers provided information on planting, haulm killing and harvesting dates.
Crop rotation	Farmers provided information on the crop rotation and in which year potatoes were cultivated previously.
Seed quality and planting characteristics	Farmers shared information on the seed tuber size, planting distance and planting depth. Also, information was shared on the quality class of the planting material.

B.2 Overview of important crop development and management dates

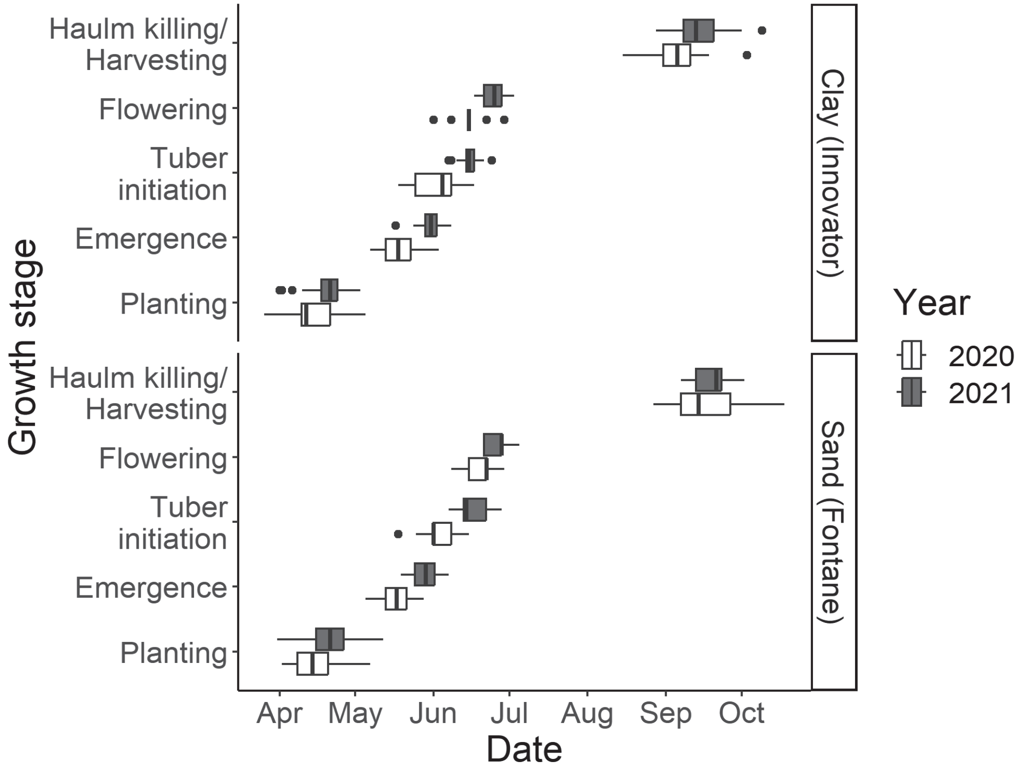


Figure B.1. Planting, emergence, tuber initiation, flowering, and haulm killing/harvesting date of the sampled fields. Different greyscales indicate different years.

B.3 Detailed results on the yield gap analysis

Comparing the 12 highest yielding fields (Ya_{FM}) with the 12 lowest yielding fields showed that for only two other variables there were significant differences between the two groups (Table B.2). Significantly more active ingredients were sprayed in high yielding fields with Innovator than in low yielding fields. Furthermore, the emergence rate in high yielding fields with Fontane was significantly higher than in low yielding fields.

Table B.2. Significant T-test or Mann-Whitney U test results of comparing the 12 highest with the 12 lowest yielding fields of 2020 and 2021 (yield in t fresh matter per ha^{-1}).

Soil type (variety)	Variable	p-value	Significance	Mean		Standard deviation	
				High yield	Low yield	High yield	Low yield
Clay (Innovator)	Active ingredients (kg ha^{-1})	0.045	*	11.6	8.8	3.8	2.2
Sand (Fontane)	Emergence rate (%)	0.007	**	97.6	93.4	2.9	8.1

*** p < 0.05 ** p < 0.01 *** p < 0.001**

Comparing the 12 fields with the largest (Yw_{irr} – Ya) yield gap with the 12 fields with the smallest (Yw_{irr} – Ya) yield gap revealed more significant differences between the two groups (Table B.3). For Innovator, the (Yw_{irr} – Ya) yield gap was smaller in fields with water stress, indicated by higher values of drought stress, oxygen stress and total water stress variables. This implies that in fields where water stress was large, nutrient availability or pests and diseases did not seem to limit or reduce yields. However, with decreasing water stress more of the actual yield gap could be explained by nutrient limitation or pest and diseases, suggesting farmers have difficulties to achieve the potential yield, even when water stress is not limiting yields. Furthermore, it was found that the Innovator yield gap was smaller in the group with higher scores for crop health. Finally, plant available P was larger in fields with a large yield gap than fields with a small yield gap, which is counterintuitive if P is limiting yield.

A

For Fontane, the (Yw_{irr} – Ya) yield gap was smaller in fields with larger drought stress. As for Innovator, this implies that nutrients or pests and diseases seemed to limit or reduce yield little when there was large water stress. However, as drought stress reduced, more of the (Yw_{irr} – Ya) yield gap could be explained by nutrient limitation or reducing factors. Furthermore, it was found that P and K application rates were significantly higher for the fields with a large yield gap. This would be somewhat understandable if soil fertility in these fields was lower. However, no difference in soil fertility was found between the two groups. Hence, a larger yield gap with larger nutrient application rates contradicts to what may be expected if nutrients are limiting.

Later in this appendix, a comparison of all variables is provided. It also provides the test results for Ya_{DM} and the (Yp_{fs} – Ya) yield gap. Group comparisons were also done for both years individually. These results provided similar insights in the potato yield gap and are therefore not shown.

Table B.3. Significant t-test or Mann-Whitney U test results for comparing the 12 fields with the highest yield gap (Yw_{irr} - Ya) and 12 fields with lowest yield gap of 2020 and 2021 (yield gap in dry matter). Tact refers to the actual transpiration during the growing season (in mm), total water stress refers to the sum of oxygen and drought stress (in mm).

Soil type (variety)	Variable	p-value	Signifi-cance	Mean		Standard deviation	
				Large gap	Small gap	Large gap	Small gap
Clay (Innovator)	Plant available P (mg kg-1)	0.033	*	2.7	1.2	2.0	0.7
Clay (Innovator)	Tact (mm)	0.001	***	219	153	36	28
Clay (Innovator)	Drought stress (mm)	0.010	**	2.1	7.7	2.7	7.6
Clay (Innovator)	Oxygen stress (mm)	0.000	***	11.7	38.9	8.7	8.8
Clay (Innovator)	Total water stress (mm)	0.000	***	13.8	46.7	9.6	13.5
Clay (Innovator)	Crop health score (-)	0.037	*	4.7	4.9	0.2	0.2
Sand (Fontane)	P applied (kg ha-1)	0.001	**	51	22	28	6
Sand (Fontane)	K applied (kg ha-1)	0.028	*	314	248	98	46
Sand (Fontane)	Drought stress (mm)	0.001	**	3.2	36.5	5.3	28.2
Sand (Fontane)	Total water stress (mm)	0.000	***	3.8	37.2	5.5	27.7

*** $p < 0.05$ ** $p < 0.01$ *** $p < 0.001$**

For Innovator, linear model results showed a significant effect of year and total active ingredients on Ya_{FM} (Table B.4). Plant available N, total N, pH, and crop health score appeared in one of the top-ranking models. However, their parameters were not significant in the final linear model, that was composed of the variables that appeared in one of the top-ranking models. Planting date, total water stress and environmental impact points had a significant negative effect on the (Yw_{irr} – Ya) yield gap for Innovator. For Fontane, increasing total water stress and total P application significantly reduced Ya_{FM} and increasing K application significantly increased Ya_{FM}. The (Yw_{irr} – Ya) yield gap was negatively related to harvesting date and emergence rate and positively related to season length, total P applied and pH.

Linear model results for the whole dataset showed similar relationships. Different was that the crop health score was negatively correlated to the (Yw_{irr} – Ya) yield gap, indicating that a healthier crop resulted in a lower yield gap. In addition, the model result showed that later planting increased actual yield or reduced the yield gap. This contradicts to earlier findings that earlier planting leads to a higher potential yield. Hence, it shows that although earlier planting increases potential yield, actual yield is not always higher for earlier planting date. All models were able to predict yield quite accurately with R^2 ranging from 0.40 to 0.65. In Appendix B.3.1, it is shown that the linear regression results were similar for Ya_{DM} and the (Yp_{fs} – Ya) yield gap.

Plotting Ya_{DM} or the (Yw_{irr} – Ya) yield gap against factors that explained Ya_{DM} or (Yw_{irr} – Ya) yield gap variability in earlier presented statistical analyses (Tables B.2, B.3 and B.4), showed often poor relationships between the parameters (Fig. B.2). Ya_{DM} or the (Yw_{irr} – Ya) yield gap were not directly correlated to planting date, harvesting date, growing season length, total P or K applied, plant available P, and pH (Fig. B.2A – C, E – H and J). We found a significant negative relationship between Ya_{DM} and total water stress (due to oxygen and/or drought stress) for the 90th percentile (Fig. B.2D). Excluding the deviating observation from Innovator in 2020 (top right, Fig. B.2D) improved the fit of the correlation (the outlier is field 46, see Fig. 3.5). This regression line indicates that yield was reduced by 1 t DM ha^{-1} for every 20 mm water stress. Emergence rate did not show a clear relationship with the (Yw_{irr} – Ya) yield gap, but it was observed that the yield gap was 3 t ha^{-1} or more for the fields with an emergence rate lower than 90%. Significant correlations were found between Ya_{DM} for Innovator and active ingredients or environmental impact points. However, the adjusted R^2 for both relationships were only 0.12 and 0.01 respectively, and thus explained little of the observed variation.

Table B.4. Linear regression model results. Ya_{FM} or the (Yw_{irr} – Ya) yield gap were used as dependent variables. Total water stress refers to the sum of oxygen and drought stress (in mm). doy indicates the day of the year. Results for Ya_{DM} and the (Yp_{fs} – Ya) yield gap can be found in Appendix B.3.1.

	Clay (Innovator)		Sand (Fontane)		All fields	
	Ya_{FM}	Yw_{irr}-Ya	Ya_{FM}	Yw_{irr}-Ya	Ya_{FM}	Yw_{irr}-Ya
Intercept	57.3	17.4***	68.3***	5.3	40.6	32.1***
Year 2021	-9.9***	0.2	-6.8	0.8	-11.7***	-
Innovator					5.3	1.7*
Planting date (doy)	-	-0.101***	-	-	0.209*	-0.102***
Harvesting date (doy)	-	-	-	-0.078*	-	-
Season length (number of days)	-	-	-	0.116***	-	-
Total water stress (mm)	-	-0.126***	-0.252**	-0.461	-	-0.0416***
Drought stress (mm)	-	-	-	0.429	-0.250***	-
Oxygen stress (mm)	-	-	2.201	-	-	-0.104***
Total N applied (kg ha^{-1})	-	-	-	-	-0.007	-
Effective N applied (kg ha^{-1})	-	-	-	-	-	-
Total P applied (kg ha^{-1})	-	-	-0.271**	0.046**	-	-
Total K applied (kg ha^{-1})	-	-	0.047**	-	0.0119	-
Plant available N (mg kg^{-1})	0.021	-	-	-	-	-
Plant available P (mg kg^{-1})	-	-	-	-	-	-

Plant available K (mg kg^{-1})	-	-	-	-	-	-
Total N in soil (g kg^{-1})	-	-0.409	-	-	-	-
Total P in soil (g kg^{-1})	0.062	-	-	-	-	-
pH (-)	-6.176	-	-	1.610**	-7.9**	-
Soil organic matter (%)	-	-	-	-	-0.828	-
Emergence rate (-)	-	-	-	-0.107*	-0.397*	-0.109*
Crop health (score)	8.738	-	-	-	3.884	-1.592^{+}
Total active ingredients (kg ha^{-1})	0.769*	-	-	-	-	-
Total environmental impact points (EIP ha^{-1})	-	-0.00075*	-	-	-0.00097	-
R^2-adjusted	0.39	0.65	0.40	0.53	0.41	0.56

$^{+}$ $p < 0.1$ * $p < 0.05$ ** $p < 0.01$ *** $p < 0.001$

A

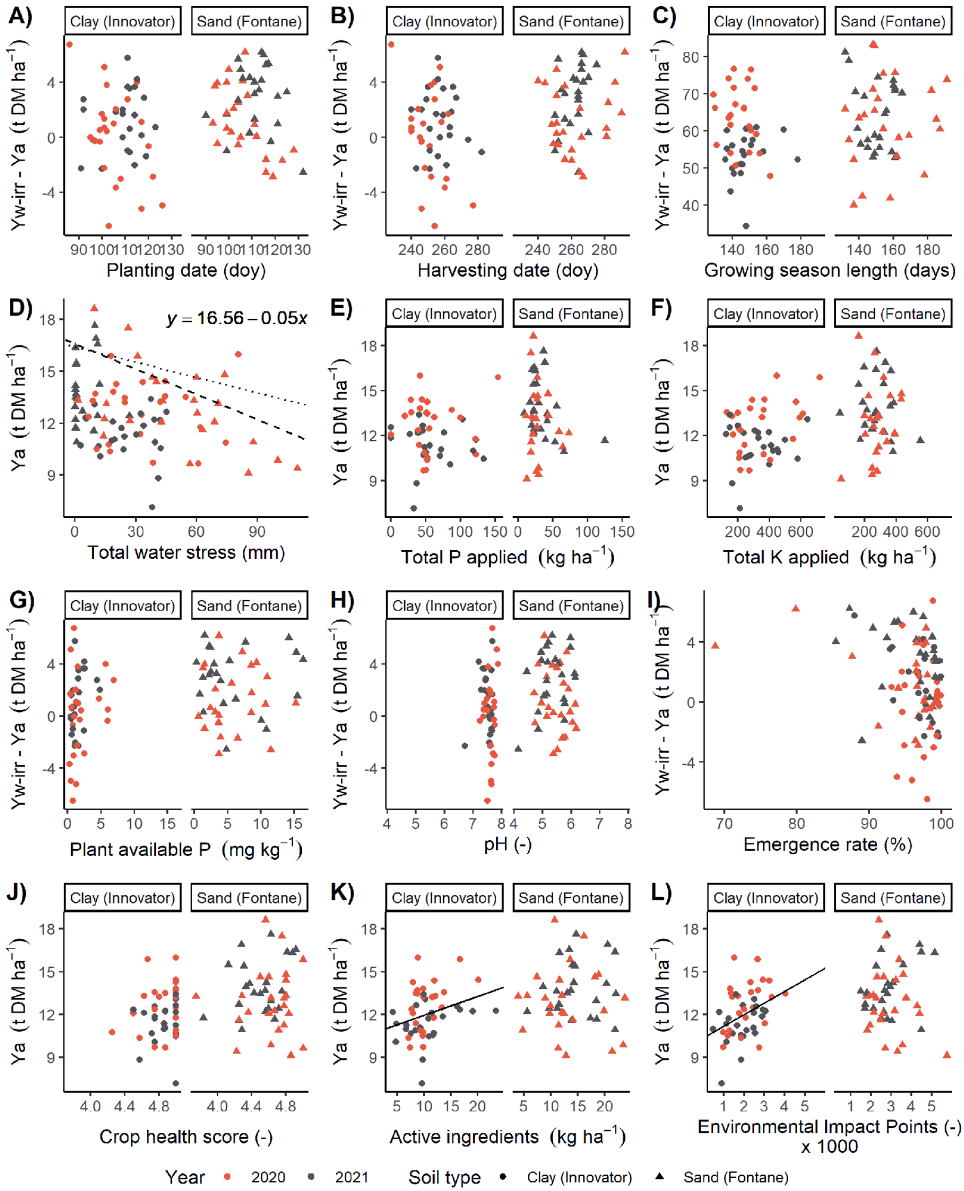


Figure B.2. (Yw_{irr} – Ya) yield gap (in t DM ha^{-1}) (A, B, C, G, H, I) or yield (in t DM ha^{-1}) (D, E, F, J, K, L) against planting date (in day of the year) (A), harvesting date (in day of the year) (B), length of the growing season (number of days) (C), total water stress due to drought and oxygen stress (in mm) (D), total P applied (in kg ha^{-1}) (E), total K applied (in kg ha^{-1}) (F), plant available P (in mg kg^{-1}) (G), pH (-) (H), emergence rate (%) (I), crop health score (-) (J), active ingredients (in kg ha^{-1}) (K) or environmental impact points (-) (L). The dashed line in panel D indicates a significant quantile regression line for the 90th percentile excluding the outlier from clayey soils on the top right. The dotted line in panel D indicates a significant quantile regression line for the 90th percentile including all data points. The solid line in panel K and L indicates a significant linear regression. doy indicates the julian day of the year.

B.3.1 Extra tables to Appendix B.3

This section shows t-test or Mann Whitney U test results of all comparisons between 12 highest and lowest yields or 12 largest or smallest yield gaps for both 2020 and 2021. Comparative analyses between groups were also done for each year individually. These results provided similar insights and are therefore not shown.

Table B.5. All t-test or Mann-Whitney U test results of comparison of 12 highest and 12 lowest yielding fields of 2020 and 2021 (yield in dry matter). Tact refers to the actual transpiration (in mm), Eact refers to the actual evaporation (in mm), total water stress refers to the sum of oxygen and drought stress (in mm).

Soil type	Variable	p-value	Significance	Mean		Standard deviation	
				large gap	small gap	large gap	small gap
Clay	Planting date	0.986	ns	106	106	7	10
Clay	Harvesting date	0.971	ns	251	253	12	11
Clay	Season length	0.563	ns	145	148	10	12
Clay	SOM	1.000	ns	4.1	3.8	1.6	0.8
Clay	pH	0.971	ns	7.6	7.6	0.1	0.2
Clay	Available N	0.971	ns	117	102	63	56
Clay	Available P	0.285	ns	1.8	1.9	1.5	2.2
Clay	Available K	0.843	ns	149	141	117	67
Clay	Total soil N	0.630	ns	1.9	1.7	0.7	0.4
Clay	Total soil P	0.971	ns	0.9	0.9	0.1	0.1
Clay	N applied	1.000	ns	438	414	185	120
Clay	Effective N applied	0.971	ns	345	338	86	67
Clay	P applied	0.194	ns	54	65	36	32
Clay	K applied	0.630	ns	358	302	195	117
Clay	Tact	0.971	ns	216	191	41	55
Clay	Eact	0.971	ns	197	192	26	23
Clay	Drought stress	0.713	ns	6.8	5.7	8.5	6.9
Clay	Oxygen stress	0.971	ns	26.3	20.7	16.3	13.3
Clay	Total water stress	0.971	ns	33.0	26.4	20.9	17.4
Clay	Number of stems	0.971	ns	13.0	15.2	2.9	3.9
Clay	Rooting depth	0.971	ns	47.7	50.3	19.0	18.7
Clay	Active ingredients	0.141	ns	11.5	9.2	3.7	2.1

A

Clay	Environmental impact points	0.463	ns	2317	1624	848	618
Clay	Crop health score	0.186	ns	4.9	4.8	0.1	0.2
Clay	Emergence rate	0.347	ns	97.5	96.8	2.4	3.1
Sand	Planting date	0.986	ns	107	107	12	9
Sand	Harvesting date	0.971	ns	265	261	12	14
Sand	Season length	0.971	ns	158	154	17	16
Sand	SOM	0.755	ns	4.5	4.7	1.5	2.4
Sand	pH	0.375	ns	5.1	5.5	0.4	0.4
Sand	Available N	0.644	ns	53	50	40	46
Sand	Available P	0.971	ns	6.2	7.0	4.9	4.8
Sand	Available K	0.590	ns	92	110	61	74
Sand	Total soil N	0.590	ns	1.6	1.4	0.6	0.5
Sand	Total soil P	0.971	ns	0.7	0.8	0.2	0.3
Sand	N applied	0.971	ns	307	324	44	85
Sand	Effective N applied	0.971	ns	236	243	29	54
Sand	P applied	0.402	ns	28	42	8	32
Sand	K applied	0.971	ns	287	297	84	125
Sand	Tact	0.971	ns	240	223	25	43
Sand	Eact	0.986	ns	156	156	17	14
Sand	Drought stress	0.163	ns	18.7	47.2	24.6	42.2
Sand	Oxygen stress	0.707	ns	0.7	0.4	1.2	0.5
Sand	Total water stress	0.143	ns	19.4	47.5	24.5	41.9
Sand	Number of stems	0.219	ns	14.7	13.3	3.4	4.4
Sand	Rooting depth	0.971	ns	31.3	32.0	7.1	4.5
Sand	Active ingredients	0.986	ns	14.8	15.0	4.1	5.6
Sand	Environmental impact points	0.971	ns	3319	3227	939	1146
Sand	Crop health score	0.971	ns	4.6	4.5	0.3	0.3
Sand	Emergence rate	0.006	**	97.7	93.4	2.9	8.3

*** p < 0.05 ** p < 0.01 *** p < 0.001**

Table B.6. All t-test or Mann-Whitney U test results of comparison of 12 highest and 12 lowest yielding fields of 2020 and 2021 (yield in fresh matter). Tact refers to the actual transpiration (in mm), Eact refers to the actual evaporation (in mm), total water stress refers to the sum of oxygen and drought stress (in mm).

Soil type	Variable	p-value	Significance	Mean		Standard deviation	
				Large gap	Small gap	Large gap	Small gap
Clay	Planting date	1.000	ns	106	106	8	10
Clay	Harvesting date	0.705	ns	248	253	7	11
Clay	Season length	0.583	ns	142	147	8	12
Clay	SOM	0.932	ns	4.2	3.8	1.6	0.8
Clay	pH	0.453	ns	7.6	7.6	0.2	0.2
Clay	Available N	0.705	ns	123	105	67	51
Clay	Available P	0.078	ns	2.2	1.5	1.9	1.8
Clay	Available K	0.932	ns	157	135	117	64
Clay	Total soil N	0.410	ns	2.0	1.7	0.7	0.4
Clay	Total soil P	0.860	ns	0.9	0.9	0.1	0.1
Clay	N applied	0.443	ns	453	406	178	118
Clay	Effective N applied	0.705	ns	353	328	83	61
Clay	P applied	0.977	ns	58	59	34	27
Clay	K applied	0.705	ns	379	323	180	121
Clay	Tact	0.333	ns	214	174	45	49
Clay	Eact	0.705	ns	204	191	23	19
Clay	Drought stress	0.551	ns	7.1	5.6	8.5	7.0
Clay	Oxygen stress	0.705	ns	28.3	23.8	15.5	12.6
Clay	Total water stress	0.705	ns	35.4	29.4	19.6	16.7
Clay	Number of stems	0.086	ns	11.8	15.8	2.1	3.6
Clay	Rooting depth	0.863	ns	47.9	50.0	19.1	20.1
Clay	Active ingredients	0.045	*	11.6	8.8	3.8	2.2
Clay	Environmental impact points	0.333	ns	2363	1759	844	575
Clay	Crop health score	0.302	ns	4.9	4.9	0.1	0.2
Clay	Emergence rate	0.590	ns	97.7	97.2	2.3	3.1
Sand	Planting date	0.942	ns	108	109	11	9
Sand	Harvesting date	0.954	ns	262	261	11	11

A

Sand	Season length	0.860	ns	154	152	15	12
Sand	SOM	0.799	ns	5	5	2	2
Sand	pH	0.333	ns	5.1	5.5	0.5	0.4
Sand	Available N	0.453	ns	52	45	40	45
Sand	Available P	0.705	ns	6.5	8.0	4.7	5.0
Sand	Available K	0.705	ns	96	128	58	66
Sand	Total soil N	0.590	ns	1.6	1.4	0.6	0.5
Sand	Total soil P	0.705	ns	0.7	0.8	0.2	0.3
Sand	N applied	0.860	ns	312	300	50	68
Sand	Effective N applied	0.705	ns	243	226	38	49
Sand	P applied	0.862	ns	26	30	6	16
Sand	K applied	0.860	ns	275	259	82	92
Sand	Tact	0.333	ns	245	218	28	39
Sand	Eact	0.860	ns	156	154	16	14
Sand	Drought stress	0.284	ns	18.9	45.1	19.1	43.3
Sand	Oxygen stress	0.112	ns	0.9	0.2	1.2	0.3
Sand	Total water stress	0.378	ns	19.7	45.3	19.1	43.2
Sand	Number of stems	0.630	ns	13.8	13.4	3.3	3.7
Sand	Rooting depth	0.705	ns	31.3	34.1	7.0	4.0
Sand	Active ingredients	0.860	ns	14.7	14.1	4.1	6.0
Sand	Environmental impact points	0.644	ns	3052	2968	772	1187
Sand	Crop health score	0.705	ns	4.6	4.5	0.3	0.3
Sand	Emergence rate	0.007	**	97.6	93.4	2.9	8.1

*** p < 0.05 ** p < 0.01 *** p < 0.001**

Table B.7. All t-test or Mann-Whitney U test results of comparison of 12 fields with the highest (Yp_{fs} - Ya) yield gap and 12 fields with the lowest (Yp_{fs} - Ya) yield gap of 2020 and 2021. Tact refers to the actual transpiration (in mm), Eact refers to the actual evaporation (in mm), total water stress refers to the sum of oxygen and drought stress (in mm).

Soil type	Variable	p-value	Significance	Mean		Standard deviation	
				Large gap	Small gap	Large gap	Small gap
Clay	Planting date	0.694	ns	104	107	10	8
Clay	Harvesting date	0.520	ns	253	248	12	7
Clay	Season length	0.022	*	150	141	11	7
Clay	SOM	0.932	ns	3.9	4.2	1.3	1.6
Clay	pH	0.787	ns	7.6	7.6	0.2	0.2
Clay	Available N	0.694	ns	97	116	58	66
Clay	Available P	0.078	ns	1.5	2.1	1.8	1.7
Clay	Available K	0.478	ns	124	167	62	120
Clay	Total soil N	0.590	ns	1.7	1.9	0.6	0.7
Clay	Total soil P	0.731	ns	0.9	0.9	0.1	0.2
Clay	N applied	0.443	ns	412	472	128	192
Clay	Effective N applied	0.694	ns	338	357	74	89
Clay	P applied	0.624	ns	63	59	32	38
Clay	K applied	0.291	ns	302	400	124	198
Clay	Tact	0.520	ns	187	214	52	44
Clay	Eact	0.694	ns	193	200	27	25
Clay	Drought stress	0.887	ns	7.8	6.5	10.8	8.7
Clay	Oxygen stress	0.789	ns	23.9	22.3	13.5	15.2
Clay	Total water stress	0.799	ns	31.7	28.9	21.5	20.6
Clay	Number of stems	0.694	ns	14	13	4	3
Clay	Rooting depth	0.694	ns	51	44	17	19
Clay	Active ingredients	0.315	ns	9.1	11.9	2.1	3.6
Clay	Environmental impact points	0.134	ns	1568	2481	686	752
Clay	Crop health score	0.303	ns	4.9	4.9	0.2	0.1
Clay	Emergence rate	0.671	ns	96.5	97.0	3.3	2.4
Sand	Planting date	0.520	ns	106	112	8	13
Sand	Harvesting date	0.385	ns	266	260	15	7

Sand	Season length	0.330	ns	160	148	16	12
Sand	SOM	0.977	ns	4.8	4.5	2.4	1.8
Sand	pH	0.520	ns	5.5	5.2	0.4	0.6
Sand	Available N	0.908	ns	57	51	47	40
Sand	Available P	0.773	ns	6.3	5.7	5.0	5.0
Sand	Available K	0.101	ns	126.0	84.6	68.2	58.4
Sand	Total soil N	0.694	ns	1.4	1.6	0.5	0.5
Sand	Total soil P	0.694	ns	0.7	0.8	0.3	0.2
Sand	N applied	0.315	ns	337	275	76	58
Sand	Effective N applied	0.520	ns	250	219	45	50
Sand	P applied	0.100	ns	42	24	31	7
Sand	K applied	0.694	ns	294	252	128	68
Sand	Tact	0.694	ns	229	238	41	26
Sand	Eact	0.198	ns	152	161	15	15
Sand	Drought stress	0.116	ns	45.6	15.3	40.7	14.9
Sand	Oxygen stress	0.728	ns	0.3	0.7	0.3	1.2
Sand	Total water stress	0.114	ns	46.0	16.0	40.5	14.9
Sand	Number of stems	0.694	ns	13	14	5	2
Sand	Rooting depth	0.694	ns	32	33	4	7
Sand	Active ingredients	0.694	ns	16.4	14.4	4.6	4.7
Sand	Environmental impact points	0.356	ns	3390	3100	998	1043
Sand	Crop health score	0.694	ns	4.5	4.6	0.3	0.3
Sand	Emergence rate	0.021	*	91.8	96.8	9.0	3.2

*** p < 0.05 ** p < 0.01 *** p < 0.001**

Table B.8. All t-test or Mann-Whitney U test results of comparison of 12 fields with the highest (Yp_{fs} - Ya) yield gap and 12 fields with the lowest (Yp_{fs} - Ya) yield gap of 2020 and 2021. Tact refers to the actual transpiration (in mm), Eact refers to the actual evaporation (in mm), total water stress refers to the sum of oxygen and drought stress (in mm).

Soil type	Variable	p-value	Significance	Mean		Standard deviation	
				Large gap	Small gap	Large gap	Small gap
Clay	Planting date	0.682	ns	107	110	10	10
Clay	Harvesting date	0.622	ns	254	258	10	12
Clay	Season length	0.807	ns	147	148	7	11
Clay	SOM	0.354	ns	3.6	4.1	0.8	0.7
Clay	pH	0.525	ns	7.5	7.6	0.2	0.3
Clay	Available N	0.787	ns	98	92	40	45
Clay	Available P	0.033	*	2.7	1.2	2.0	0.7
Clay	Available K	0.068	ns	180	111	88	43
Clay	Total soil N	0.233	ns	1.5	1.8	0.4	0.3
Clay	Total soil P	0.506	ns	0.9	1.0	0.1	0.1
Clay	N applied	0.422	ns	419	368	89	83
Clay	Effective N applied	0.630	ns	346	324	80	54
Clay	P applied	0.065	ns	66	45	29	32
Clay	K applied	0.506	ns	328	277	89	130
Clay	Tact	0.001	***	219	153	36	28
Clay	Eact	0.233	ns	181	201	25	23
Clay	Drought stress	0.010	**	2.1	7.7	2.7	7.6
Clay	Oxygen stress	0.000	***	11.7	38.9	8.7	8.8
Clay	Total water stress	0.000	***	13.8	46.7	9.6	13.5
Clay	Number of stems	0.622	ns	14.6	13.6	3.3	2.8
Clay	Rooting depth	0.233	ns	44.2	57.5	18.0	13.9
Clay	Active ingredients	0.312	ns	10.4	11.7	5.1	4.6
Clay	Environmental impact points	0.590	ns	1754	2060	848	704
Clay	Crop health score	0.037	*	4.7	4.9	0.2	0.2
Clay	Emergence rate	0.378	ns	96.3	97.6	3.5	1.9
Sand	Planting date	0.506	ns	109	114	6	11

Sand	Harvesting date	0.622	ns	264	260	13	9
Sand	Season length	0.310	ns	155	146	12	12
Sand	SOM	0.291	ns	5.2	4.4	2.0	1.8
Sand	pH	0.916	ns	5.4	5.4	0.4	0.6
Sand	Available N	0.312	ns	50	75	33	58
Sand	Available P	0.603	ns	7.1	5.4	5.6	3.6
Sand	Available K	0.143	ns	146	103	51	68
Sand	Total soil N	0.797	ns	1.6	1.6	0.5	0.5
Sand	Total soil P	0.410	ns	0.9	0.7	0.4	0.1
Sand	N applied	0.079	ns	336	262	71	60
Sand	Effective N applied	0.268	ns	242	206	41	53
Sand	P applied	0.001	**	51	22	28	6
Sand	K applied	0.028	*	314	248	98	46
Sand	Tact	0.506	ns	250	236	29	31
Sand	Eact	0.787	ns	162	160	12	13
Sand	Drought stress	0.001	**	3.2	36.5	5.3	28.2
Sand	Oxygen stress	0.212	ns	0.6	0.7	0.5	1.2
Sand	Total water stress	0.000	***	3.8	37.2	5.5	27.7
Sand	Number of stems	0.433	ns	12.0	13.2	2.4	1.7
Sand	Rooting depth	0.544	ns	36.7	33.5	11.2	6.8
Sand	Active ingredients	0.682	ns	14.5	13.0	5.4	6.4
Sand	Environmental impact points	0.682	ns	2634	2840	788	925
Sand	Crop health score	0.193	ns	4.5	4.6	0.3	0.3
Sand	Emergence rate	0.060	ns	93.4	96.5	5.4	3.1

*** $p < 0.05$ ** $p < 0.01$ *** $p < 0.001$**

Table B.9. Linear model results. Ya_{DM} or the (Yp_{fs} – Ya) yield gap were used as dependent variables.

	Fontane		Innovator		All	
	Ya_{DM}	Yp_{fs}-Ya	Ya_{DM}	Yp_{fs}-Ya	Ya_{DM}	Yp_{fs}-Ya
Intercept	18.197**	-15.094	7.134	-3.264	16.709***	21.807***
Year 2021	-	-	-1.358**	-	-1.522***	1.331**
Innovator					1.496	1.398**
Planting date	-	-	-	-0.040	-	-0.066**
Harvesting date	-	-	0.0093	-	-	-
season length	-	0.069**	-	-	-	-
Total water stress (mm)	-0.033***	-0.574^{+}	-	-	-	-
Drought stress (mm)	-	0.608^{+}	-	-	-0.046***	0.044***
Oxygen stress (mm)	0.598^{+}	-	-	-	-	-
Total N applied (kg ha^{-1})	-	-	0.0032^{+}	-	-	-
Effective N applied (kg ha^{-1})	-	-	-	-	-	-
Total P applied (kg ha^{-1})	-0.054**	0.067	-	-	-	-
Total K applied (kg ha^{-1})	0.0056	-0.0065	-	-	-	-
Plant available N (mg kg^{-1})	-	-	-	-	-	-
Plant available P (mg kg^{-1})	-	-	-	-	-	-
Plant available K (mg kg^{-1})	-0.0020	-	-	-	-	-
Total N in soil (g kg^{-1})	-	-	1.012	-	-	-
Total P in soil (g kg^{-1})	-	-	-	-	-	-
pH (-)	-1.681***	1.416*	-	1.844	-1.704**	-

Soil organic matter (%)	-0.132		-0.344	-	-0.142	-
Emergence rate (-)	0.0063	-	-	-	0.083*	-0.230**
Crop health (score)	-	-	-	-	-	-
Total active ingredients sprayed (kg ha^{-1})	-	-	0.130*	-	-	-
Total environmental impact points (EIP ha^{-1})	-	-	-	-0.00094**	0.0035^{+}	-
R^2-adjusted	0.455	0.476	0.225	0.155	0.361	0.266

*** p < 0.05 ** p < 0.01 *** p < 0.001**

B.4 Overview of the yield reducing factors in each field.

This appendix provides pictures of and information on the identified reducing factors in the different fields. All pictures have been taken by Ravensbergen, A.P.P.

Field 11

An infection with *Pectobacterium* caused plants to die early which resulted in a lower plant density.

Field 15

No picture shown, as no clear problem was indicated.

Field 18

No picture taken showing an infection with *Pectobacterium* in this field. Symptoms are similar to field 27.

Field 27

An infection with *Pectobacterium* caused plants to die early which resulted in a lower plant density.

Field 28

No picture taken showing an infection with *Pectobacterium* in this field. Symptoms are similar to field 27.

Field 33

Relatively low emergence rate because of rotten seed tubers.

Field 37

It is assumed that potato cyst nematodes infected parts of the field led to stunted growth of the plants. On the picture it can be seen that in the front the canopy had not yet closed whereas a bit further away the canopy already closed.

Field 41

Irregular emergence because of planting cut seed tubers.

Field 44

Picture showing rust symptoms in the tubers, this is possibly caused by a calcium deficiency.

Field 62

Beginning of an early blight infection.

Field 64

Irregular crop stand because of planting cut seed tubers.

Field 113

Beginning of a light late blight infection.

A

Rotten ware tubers leading to a yield reduction.

Field 114

Lower emergence rate because of rotten seed tubers.

Field 212

Recently emerged stems are wilting.

Field 214

Recently emerged plants are starting to wilt.

Late blight infection.

Early senesced plants, mid-august.

Field 217

Canopy development in this field was excessively large. Hence, we hypothesise that the plants invested too much in canopy biomass, resulting in a relatively lower investment in tubers which resulted in relatively low yields. We measured a total stem length of 200 cm, whereas average stem length for this variety was 120 cm. It is unclear what caused the excessive growth of aboveground biomass.

There was a light late blight infection in this field. This picture shows the beginning of the infection.

A

Field 311

A disease affected sprouts. It is unclear which disease affected the sprouts.

Field 314

Lower emergence rate because of rotten seed tubers.

Field 317

This picture shows that the plants are slightly wilting. Possibly because of a heavy nematode infection. In this field, the average infection rate with potato cyst nematodes was 45 eggs or larvae per gram soil. The damage threshold is assumed to be at 2 eggs or larvae per g of soil at planting (Been and Schomaker, 2000). In another study this infection rate resulted in a 6 t ha^{-1} yield loss (Mburu et al., 2020).

Field 411

Early blight infection, mid-August.

Field 413

Lower emergence rate as a result of Fusarium rot.

Rotten seed tuber.

Field 415

It appeared that in this field there was a second flush of tuber initiation. Although it is unclear why it happened, it could have reduced overall yield development.

Early senesce of stems in this field around mid-august, which is expected to be related to an infection with *Colletotrichum coccodes (Black dot disease).*

A

Field 612

Missing plants as a result of a mal-functioning planting machine.

Appendix C Chapter 4

C.1 crop management information of each field

Table C.1. Overview of farmer applied total N, farmer applied effective N, farmer applied P, farmer applied K, SOM, pH, available P, available K and available N for each individual field.

ID	year	Farmer applied total N (kg ha^{-1})	Farmer applied effective N (kg ha^{-1})	Farmer applied P (kg ha^{-1})	Farmer applied K (kg ha^{-1})	SOM (%)	pH (-)	available P (mg kg^{-1})	available K (mg kg^{-1})	available N (mg kg^{-1})	Planting date	Haulm killing date
1	2019	275	232	51	308	2.0	5.2	15.2	44.6	49.0	29/04/2019	10/09/2019
2	2019	243	170	37	186	2.9	5.0	9.2	61.9	60.7	27/04/2019	10/09/2019
3	2019	379	329	79	309	2.3	5.4	8.3	65.2	111.2	20/04/2019	10/09/2019
4	2019	321	271	79	250	4.1	5.6	3.5	144.5	50.3	11/04/2019	23/09/2019
5	2019	292	224	22	246	4.3	4.7	4.5	124.8	43.7	10/04/2019	05/09/2019
6	2019	311	243	26	209	4.0	5.7	1.3	59.8	88.4	04/05/2019	13/09/2019
7	2019	356	289	26	259	2.5	5.4	3.0	41.1	71.8	12/04/2019	13/09/2019
8	2019	198	177	22	152	2.9	5.4	1.7	213.5	64.0	24/04/2019	01/09/2019
9	2019	277	230	23	217	4.1	5.3	1.2	47.9	82.5	25/04/2019	01/09/2019
10	2019	286	223	31	339	4.8	5.2	1.1	52.3	86.0	09/04/2019	14/09/2019
11	2019	286	223	31	248	4.3	5.3	2.7	50.6	60.5	26/04/2019	25/09/2019
12	2019	694	414	108	478	3.4	6.8	6.1	267.6	185.0	10/04/2019	29/08/2019
13	2019	303	236	51	292	2.8	7.2	2.9	115.7	132.4	09/04/2019	29/08/2019
14	2019	591	392	117	530	3.0	7.3	6.7	102.4	168.2	08/04/2019	29/08/2019
15	2019	567	350	87	664	5.8	7.6	1.5	66.1	115.4	25/04/2019	20/09/2019
16	2019	271	271	18	217	3.8	5.9	4.0	127.7	87.5	15/04/2019	18/09/2019
17	2019	341	186	92	404	3.3	7.4	1.8	137.9	149.6	16/04/2019	03/09/2019
18	2019	373	285	41	259	4.1	7.3	2.3	222.1	184.2	16/04/2019	03/09/2019

A

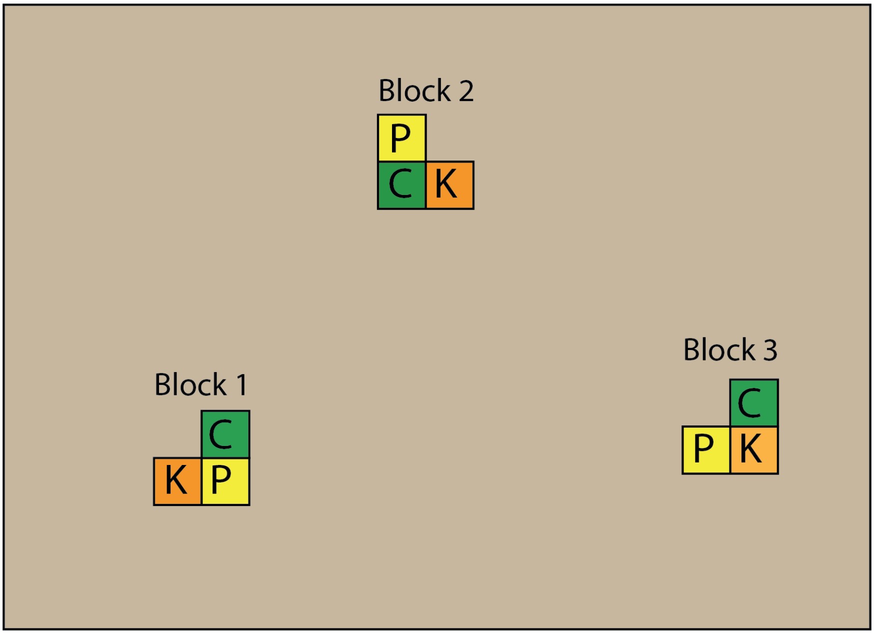
ID	year	Farmer applied total N ($kg\ ha^{-1}$)	Farmer applied effective N ($kg\ ha^{-1}$)	Farmer applied P ($kg\ ha^{-1}$)	Farmer applied K ($kg\ ha^{-1}$)	SOM (%)	pH (-)	available P ($mg\ kg^{-1}$)	available K ($mg\ kg^{-1}$)	available N ($mg\ kg^{-1}$)	Planting date	Haulm killing date
19	2019	351	286	39	287	2.3	7.5	1.2	75.5	132.7	18/04/2019	16/09/2019
20	2019	488	387	63	339	3.7	7.5	1.1	117.7	149.3	24/04/2019	01/09/2019
21	2019	404	297	39	396	3.6	7.4	1.7	135.9	181.3	22/04/2019	14/09/2019
22	2019	379	307	39	299	3.6	7.4	1.1	79.9	180.2	19/04/2019	23/09/2019
23	2020	395	322	27	431	3.5	6.0	3.1	83.7	23.8	10/04/2020	05/09/2019
24	2020	310	232	30	196	3.3	5.5	11.5	72.1	16.4	25/04/2020	13/09/2019
25	2020	337	288	18	261	3.1	5.4	3.7	28.7	73.6	28/04/2020	13/09/2019
26	2020	284	215	26	235	3.9	5.4	8.5	114.4	119.8	04/04/2020	01/09/2019
27	2020	225	177	20	286	3.9	6.2	1.5	49.1	43.4	05/07/2020	01/09/2019
28	2020	123	88	11	196	4.5	5.8	3.9	165.9	201.7	25/04/2020	14/09/2019
29	2020	218	201	13	49	3.0	6.1	10.7	68.1	17.0	20/04/2020	25/09/2019
30	2020	379	308	73	389	6.8	5.1	10.9	44.8	17.5	17/04/2020	29/08/2019
31	2020	303	204	29	246	9.5	5.0	15.2	92.2	16.4	02/04/2020	29/08/2019
32	2020	360	254	59	313	5.6	5.1	3.7	177.6	101.7	16/04/2020	29/08/2019
33	2020	325	225	28	318	7.5	5.2	0.6	51.6	43.4	14/04/2020	20/09/2019
34	2020	345	304	21	390	3.7	4.8	1.5	41.6	50.4	08/04/2020	18/09/2019
35	2020	489	387	122	365	3.7	7.9	5.7	193.6	102.1	24/04/2020	10/09/2020
36	2020	495	410	52	406	2.9	7.7	1.0	66.7	92.5	26/03/2020	15/08/2020
37	2020	397	307	41	448	5.9	7.5	0.8	56.8	137.4	12/04/2020	02/09/2020
38	2020	471	349	122	552	4.9	7.6	0.3	65.4	87.1	15/04/2020	10/09/2020

ID	year	Farmer applied total N (kg ha^{-1})	Farmer applied effective N (kg ha^{-1})	Farmer applied P (kg ha^{-1})	Farmer applied K (kg ha^{-1})	SOM (%)	pH (-)	available P (mg kg^{-1})	available K (mg kg^{-1})	available N (mg kg^{-1})	Planting date	Haulm killing date
39	2020	320	279	47	274	2.8	7.6	0.4	69.2	170.1	09/04/2020	18/09/2020
40	2020	479	317	52	614	2.8	7.7	0.6	74.1	130.50	10/04/2020	27/08/2020
41	2020	440	440	40	241	2.6	7.8	0.8	54.5	28.60	29/04/2020	07/09/2020
42	2020	605	395	100	593	2.7	7.5	4.7	123.5	161.30	10/04/2020	27/08/2020
43	2020	305	255	20	164	4.4	7.6	1.2	106.2	63.90	15/04/2020	31/08/2020
44	2020	467	414	52	208	2.9	7.8	0.5	59.8	12.40	10/04/2020	13/09/2020
45	2020	322	285	51	199	3.6	7.6	1.4	162.3	112.70	10/04/2020	04/09/2020
46	2020	348	294	55	207	4.4	7.7	2.5	196.3	69.60	01/05/2020	08/09/2020

A

C.2 Example of field layouts

Field layout 2019



Field layout 2020

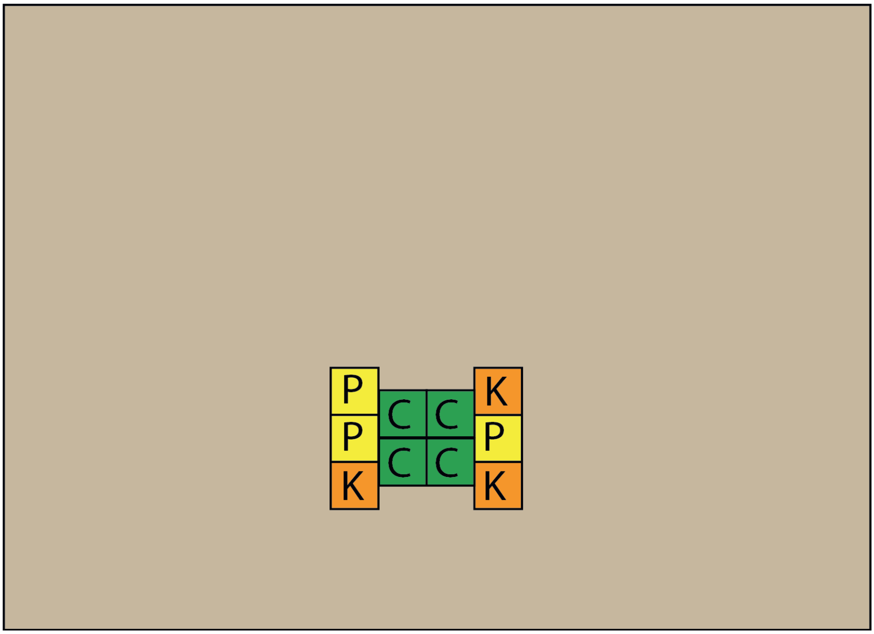


Figure C.1. Example of the experimental design in 2019 and 2020. In 2019 blocks were included in the experimental design. Figures are not at scale. Grey area represents the field. The green, yellow and orange boxes represent the C, P and K treatment plots, respectively.

C.3 Figures on yield and yield quality

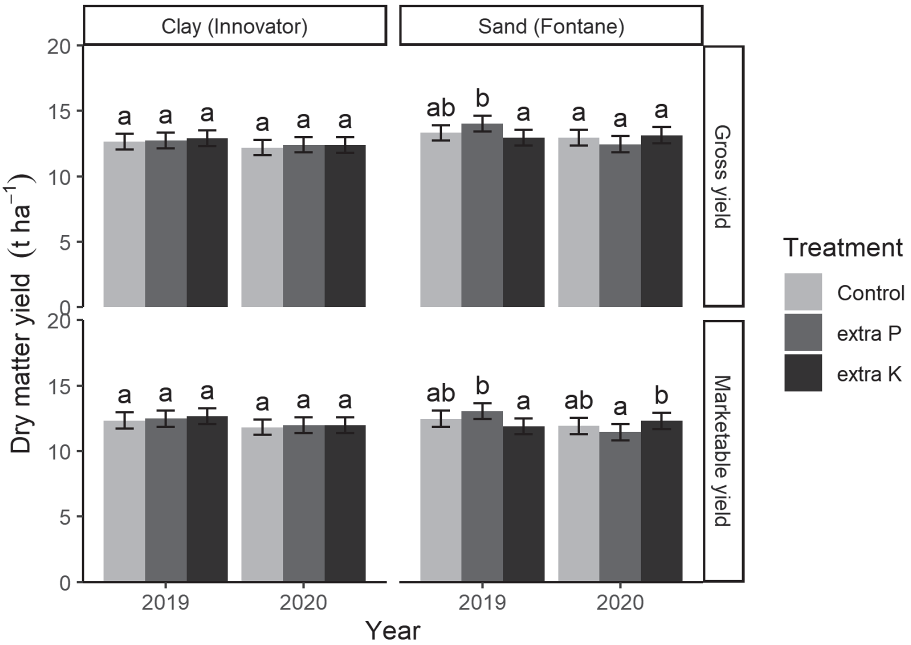


Figure C.2. Dry matter gross yield (top row) and dry matter marketable yield (bottom row) (in t ha^{-1}) of the different treatments for 2019 and 2020 for fields on sandy soils and fields on clayey soils. Significant differences between treatments within year and soil type group are indicated by different letters.

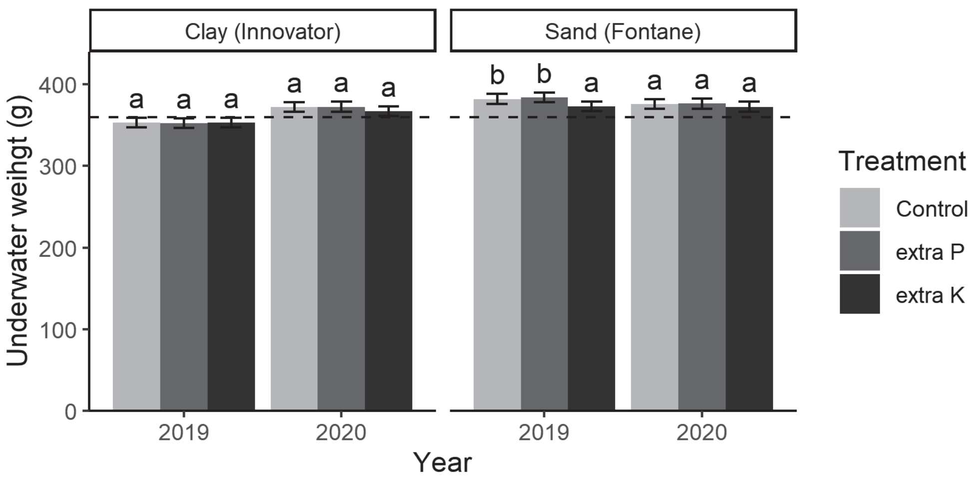


Figure C.3. Under water weight (in g) of the different treatments for 2019 and 2020 for fields on clay and sandy soils. Significant differences between treatments within year and soil type group are indicated by different letters.

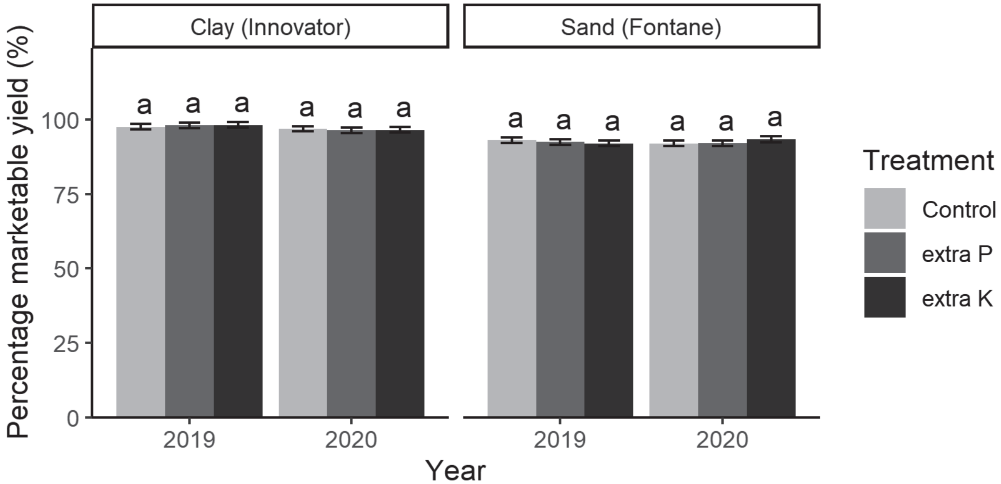


Figure C.4. Percentage marketable yield (in %) of the different treatments for 2019 and 2020 for fields on sandy soils and fields on clayey soils. Significant differences between treatments within year and soil type group are indicated by different letters.

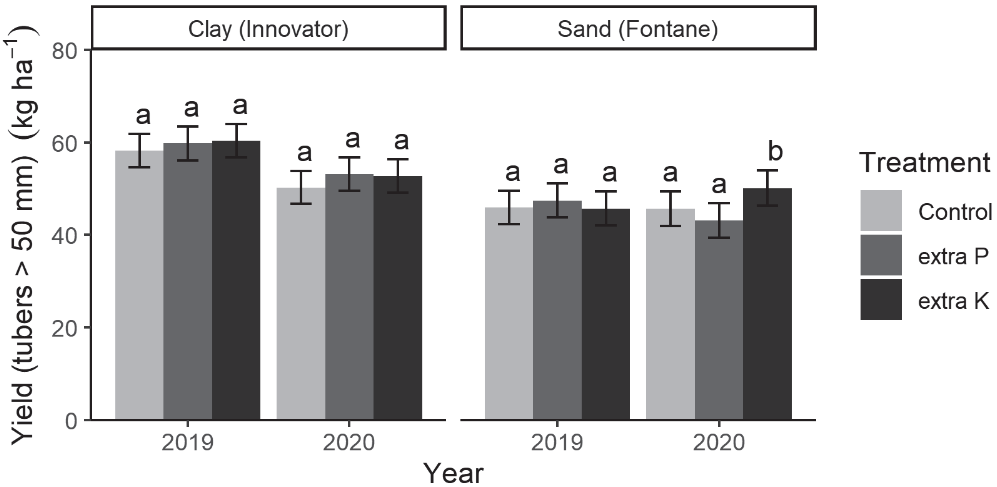


Figure C.5. Yield of tubers larger than 50 mm (in t ha^{-1}) of the different treatments for 2019 and 2020 for fields on sandy soils and fields on clayey soils. Significant differences between treatments within year and soil type group are indicated by different letters.

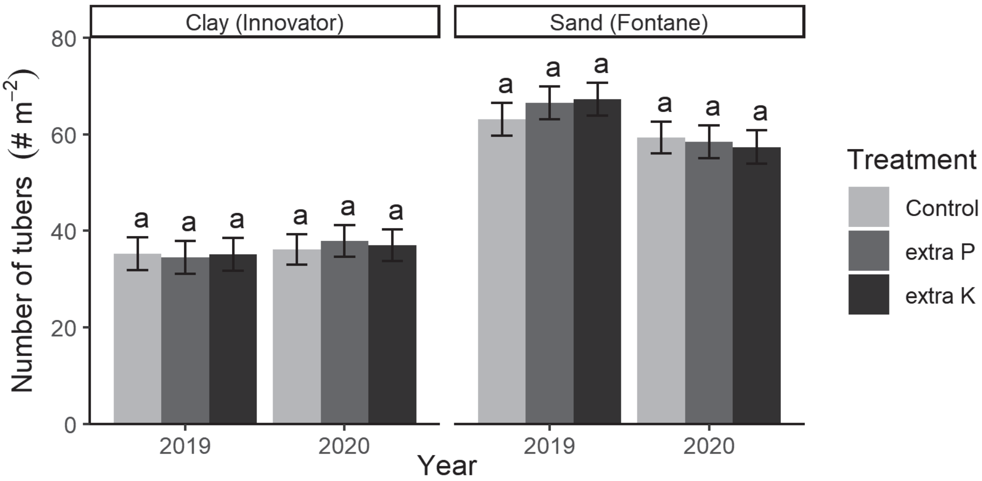


Figure C.6. Number of tubers (in number of tubers m^{-2}) of the different treatments for 2019 and 2020 for fields on sandy soils and fields on clayey soils. Significant differences between treatments within year and soil type group are indicated by different letters.

A

C.4 Figures on yield and yield response against soil parameters

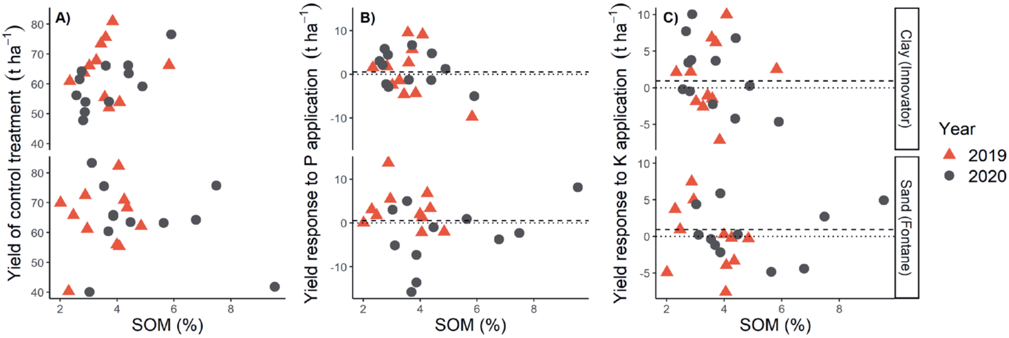


Figure C.7. Yield of the control treatment (in t ha^{-1}) (A), yield response to P application (in t ha^{-1}) (B) and yield response to K application (in t ha^{-1}) (C) against soil organic matter (in %). The dotted horizontal line (B, C) indicates no response of the crop to the P or K treatment. The dashed horizontal line (B, C) indicates the average response to the P or K treatment.

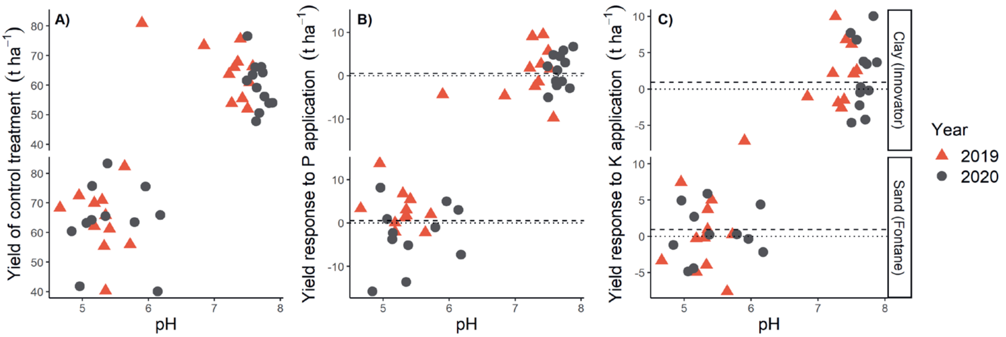


Figure C.8. Yield of the control treatment (in t ha^{-1}) (A), yield response to P application (in t ha^{-1}) (B) and yield response to K application (in t ha^{-1}) (C) against soil pH (-).The dotted horizontal line (B, C) indicates no response of the crop to the P or K treatment. The dashed horizontal line (B, C) indicates the average response to the P or K treatment.

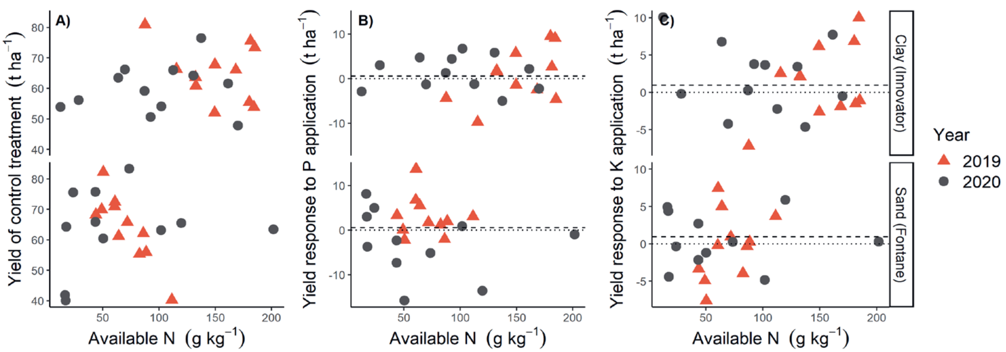


Figure C.9. Yield of the control treatment (in t ha^{-1}) (A), yield response to P application (in t ha^{-1}) (B) and yield response to K application (in t ha^{-1}) (C) against available N (in mg kg^{-1}). The dotted horizontal line (B, C) indicates no response of the crop to the P or K treatment. The dashed horizontal line (B, C) indicates the average response to the P or K treatment.

C.5 Figures on yield and yield response against fertiliser application

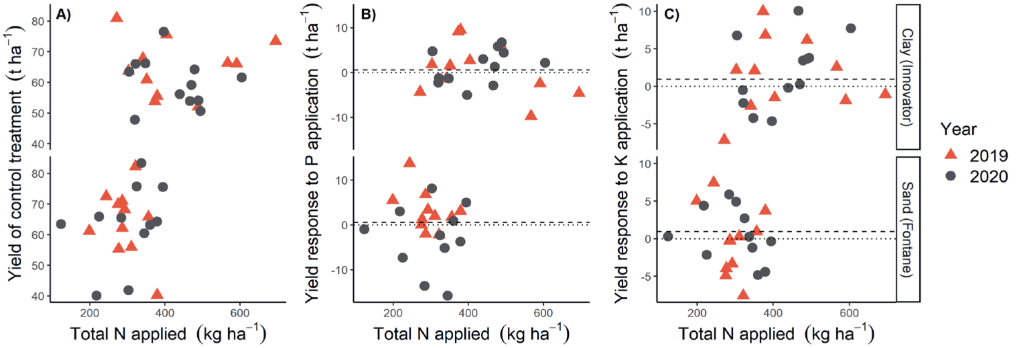


Figure C.10. Yield of the control treatment (in t ha^{-1}) (A), yield response to P application (in t ha^{-1}) (B) and yield response to K application (in t ha^{-1}) (C) against farmer applied total N (in kg ha^{-1}). The dotted horizontal line (B, C) indicates no response of the crop to the P or K treatment. The dashed horizontal line (B, C) indicates the average response to the P or K treatment.

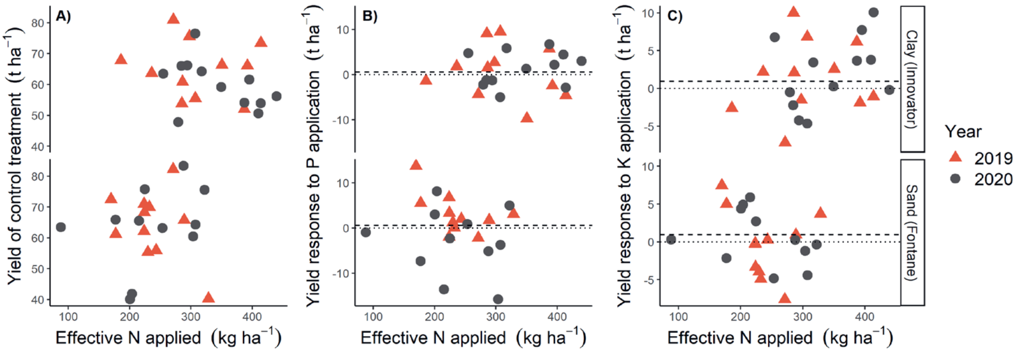


Figure C.11. Yield of the control treatment (in t ha^{-1}) (A), yield response to P application (in t ha^{-1}) (B) and yield response to K application (in t ha^{-1}) (C) against farmer applied effective N (in kg ha^{-1}). The dotted horizontal line (B, C) indicates no response of the crop to the P or K treatment. The dashed horizontal line (B, C) indicates the average response to the P or K treatment.

A

Appendix D Chapter 6

D.1 Overview of measurements taken during on-farm observations

This following explanatory variables were used in linear regression analysis:

1. Soil organic matter
2. Soil pH
3. Total N and P in the soil
4. Plant available N, P and K
5. Crop health score
6. Emergence rate
7. Fertilisation
8. Pesticide application
9. Crop management dates
10. Transpiration reduction due to drought and/or oxygen stress

See for a full overview of the methods Appendix B.1. In addition, crop growth modelling output was used (Table C.2).

Table C.2. Additional information to table B.1 which is particularly relevant for Chapter 6.

Crop growth model output	Method
Water-limited potential yield under rainfed and partially irrigated conditions	SWAP-WOFOST was run to simulate water-limited yield under rainfed and partially irrigated conditions (Kroes et al., 2017; ten Den et al., 2022). For sandy soils it was assumed that there was no interaction with the groundwater level, while for clayey soils there was an interaction with the groundwater level.
Transpiration reduction due to drought and/or oxygen stress	The output from the SWAP-WOFOST model simulations under partially irrigated conditions were used to assess transpiration reduction due to drought and/or oxygen stress. Drought stress was simulated using Feddes (1982) and oxygen stress using Bartholomeus et al. (2008).

D.2 Nutrient use

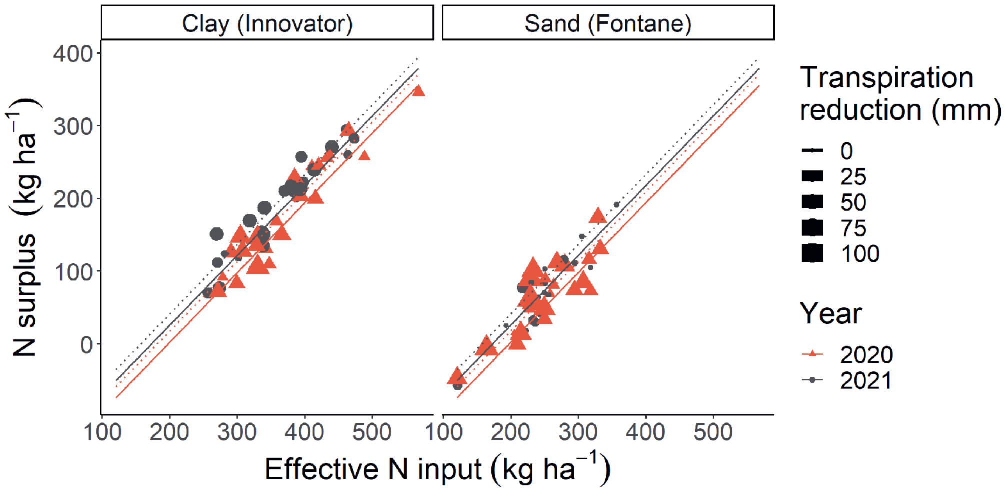


Figure D.1. N surplus (in kg ha^{-1}) against effective N input (in kg ha^{-1}) for two different years and soil types (and respective cultivars). The solid lines indicate the regression lines without any transpiration reduction due to drought and/or oxygen stress. The dotted lines indicate the regression lines with 100 mm transpiration reduction due to drought and/or oxygen stress. Different colours and symbols indicate different years.

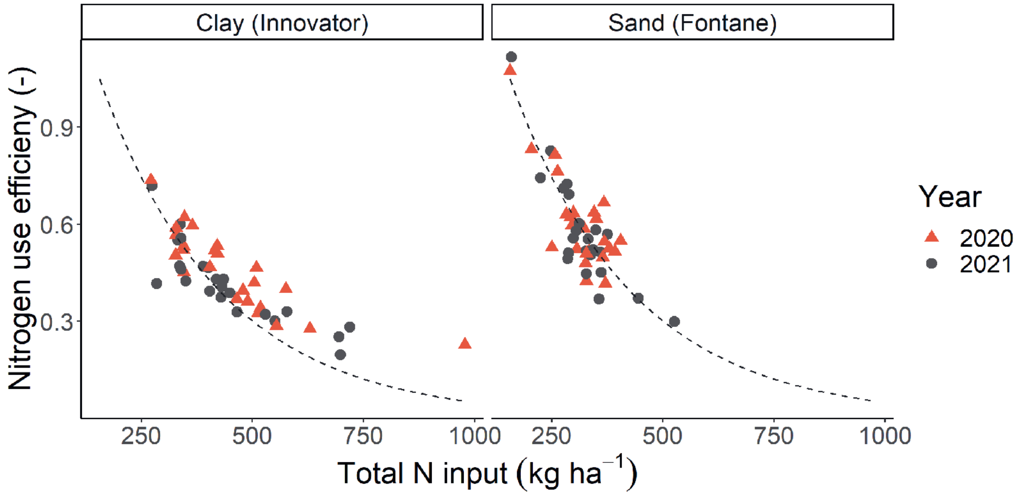


Figure D.2. N use efficiency (in kg N kg N^{-1}) against total N input (in kg ha^{-1}) for two different years and soil types (and respective cultivars). The dashed lines indicate the exponential regression lines. Different colours and symbols indicate different years.

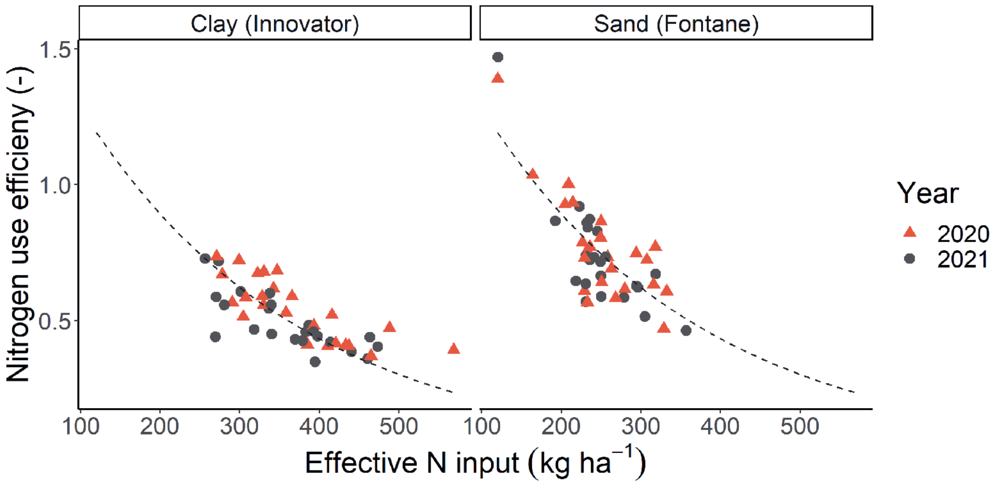


Figure D.3. N use efficiency (in kg N kg N^{-1}) against effective N input (in kg ha^{-1}) for two different years and soil types (and respective cultivars). The dashed lines indicate the exponential regression lines. Different colours and symbols indicate different years.

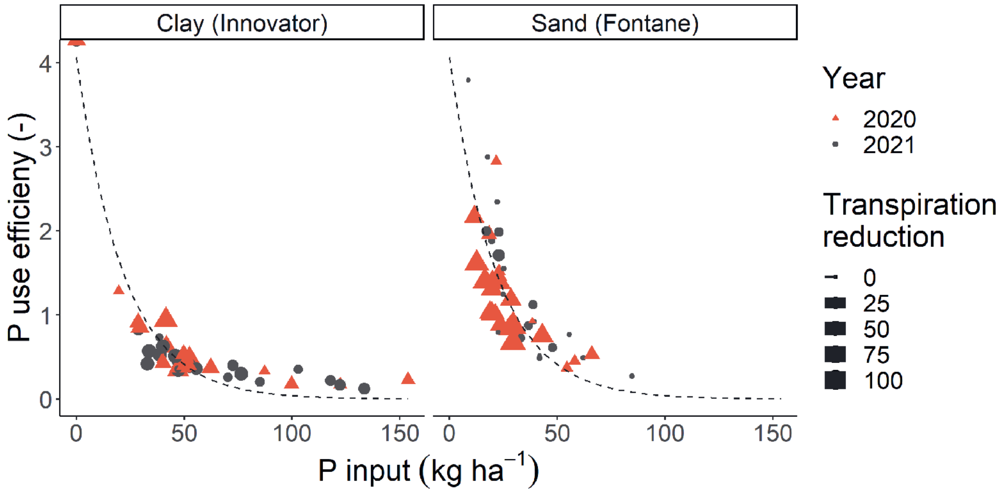


Figure D.4. P use efficiency (in kg P kg P^{-1}) against total P input (in kg ha^{-1}) for two different years and soil types (and respective cultivars). The dashed lines indicate the exponential regression lines. Different colours and symbols indicate different years. Different symbol sizes indicate differences in transpiration reduction due to drought and/or oxygen stress.

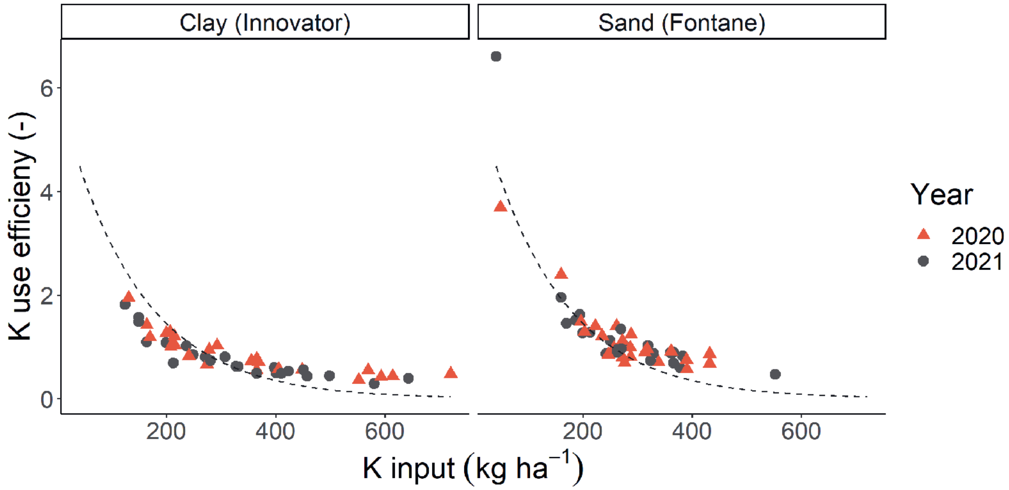


Figure D.5. K use efficiency (in kg K kg K^{-1}) against total K input (in kg ha^{-1}) for two different years and soil types (and respective cultivars). The dashed lines indicate the regression lines. Different colours and symbols indicate different years. Different symbol sizes indicate differences in transpiration reduction due to drought and/or oxygen stress.

A

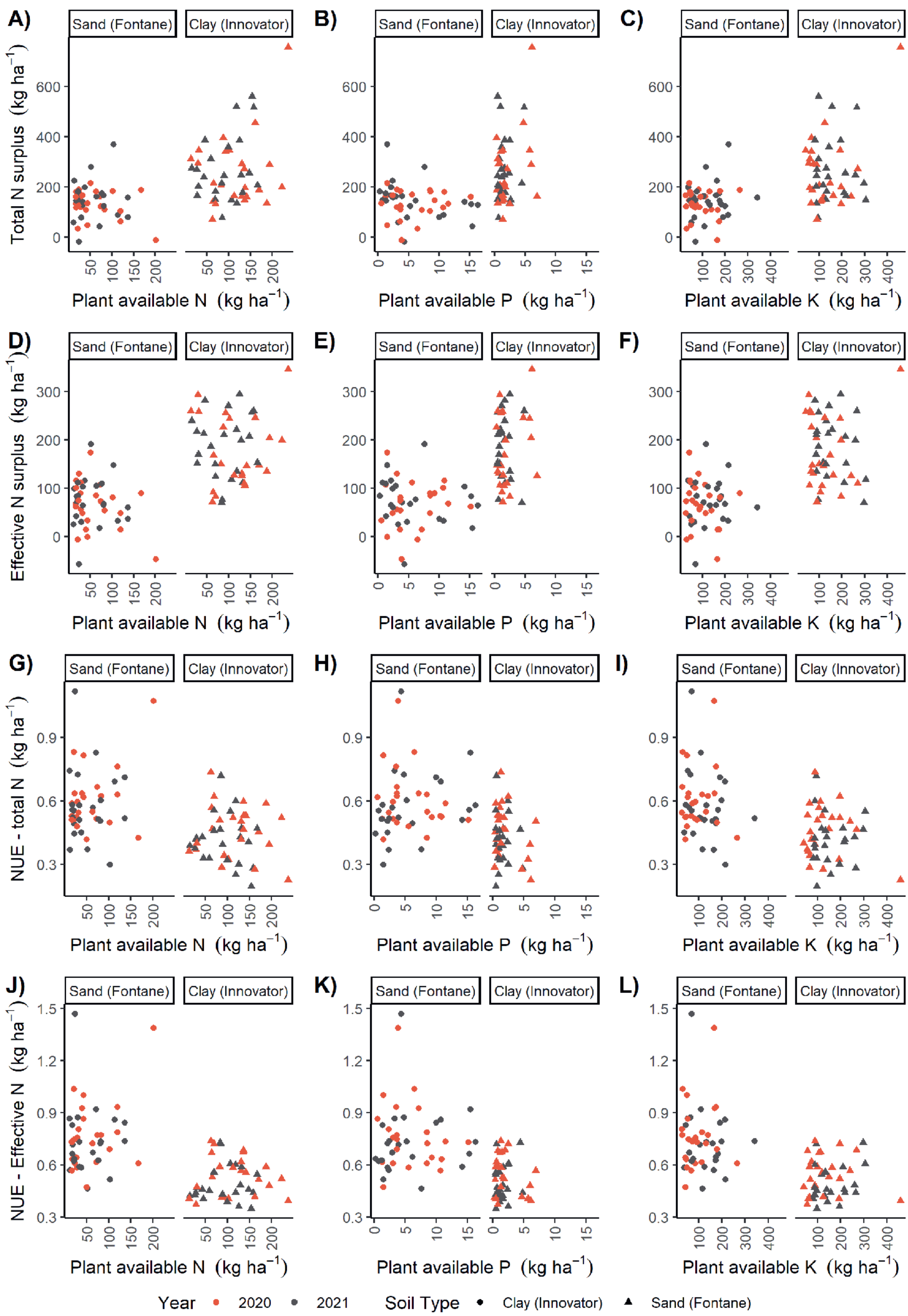


Figure D.6. Total N surplus (A, B, C), Effective N surplus (D, E, F), NUE (based on total N; G, H, I) or NUE (based on effective N; J, K, L) against plant available N (A, D, G, J), P (B, E, H, K) or K (C, F, I, L). Different colours indicate different years and different symbol shapes indicate different soil types (with respective varieties).

D.3 Pesticide use

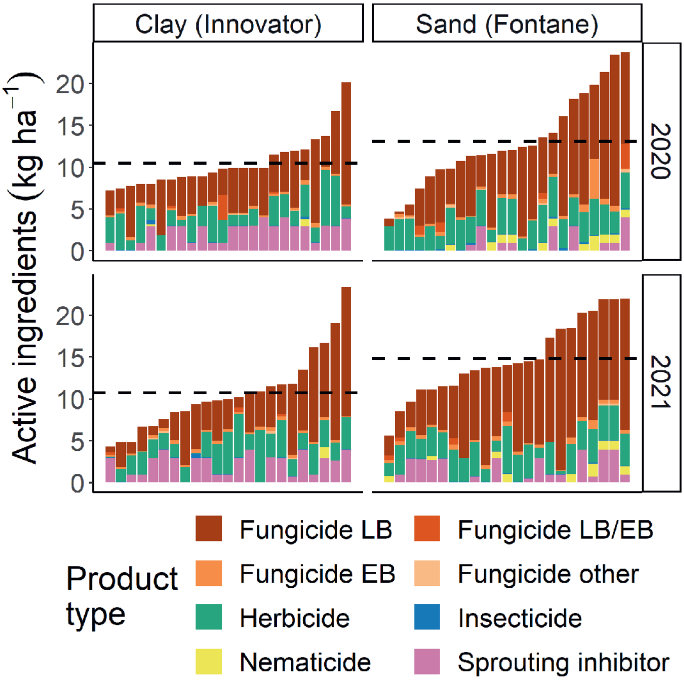


Figure D.7. Active ingredients (in kg ha^{-1}) from crop protection product application for two different years and soil types (and respective cultivars). Different colours indicate different product types. Different colours in panel B indicate how the environment is impacted. Fungicide LB and/or EB refer to fungicides that protect the crop against late and/or early blight. Fungicide other refers to fungicides that are used against other fungi. Horizontal dashed lines show average applied active ingredients.

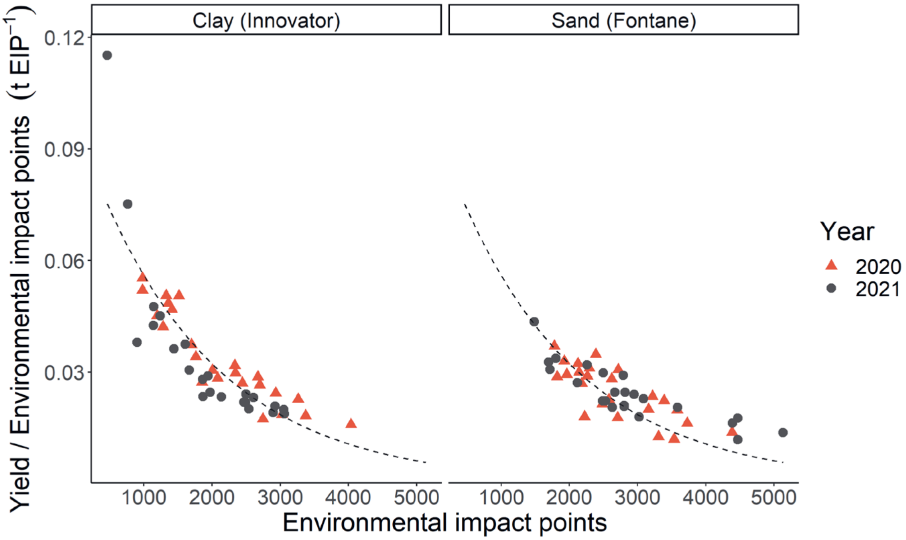


Figure D.7. Yield per EIP (in t EIP^{-1}) against total environmental impact points for two different years and soil types (and respective cultivars). The dashed lines indicate the exponential regression lines. Different colours and symbols indicate different years.

A


3640

Summary

In the Netherlands, the potato is a high value crop that serves as a cash crop for farmers and is economically important for the value chain. In addition, it plays an important role in the agricultural landscape as it is cultivated on 30% of the cropped land, by 50% of the farmers, and in all provinces of the Netherlands. Average ware potato yield is high, with a reported mean fresh matter yield around 52 t ha^{-1}. Despite its high mean productivity, large yield variability is observed among fields and farms. This implies that there is potential to increase production and hence farmers' revenues. Moreover, when relatively low yields come with similar input levels, resources are not well utilised leading to low resource use efficiency and larger emissions to the environment. This provides scope to reduce the environmental impact of ware potato production in the Netherlands.

Productivity of cropping systems can be quantified using yield gap analyses. In such analyses, actual farmers' yields are compared to a productivity benchmark, which can be defined based on the climatic conditions and adjusted considering limiting factors such as water availability. Previously, yield gap analyses have been done for ware potato in the Netherlands. These analyses provided useful information on the existing yield gap and yield gap explaining factors at higher aggregation levels, but were insufficient to understand yield gap variability and its causes across individual fields. To potentially increase production and farmers' revenues, and to reduce the environmental impact of ware potato production, there is a need to better understand variability among fields. It complements earlier studies by using frequent on-farm monitoring along with datasets at different levels, questionnaires and experiments to better understand variability among fields, and provide solutions towards more sustainable and resilient potato production.

This thesis aims to quantify and explain variability in yield, yield gaps, resource use efficiency and environmental impact of ware potato production at field level in the Netherlands. The results can be used to provide recommendations on how to increase yields, improve resource use efficiency and reduce the environmental impact of ware potato production. The research was approached in three steps: (1) to quantify spatio-temporal yield variability using existing data sources, (2) to identify different productivity levels and asses factors that explain yield (gap) variability through questionnaires, frequent on-farm monitoring and experiments and (3) to quantify and explain variability in resource use, use efficiency and environmental impact of ware potato production in the Netherlands using on-farm observations.

Chapter 2 starts with an assessment of spatio-temporal yield variability at four agronomically relevant scales (among provinces, farms and fields and within fields) using five datasets with data on potato yield across space and time. We found that spatial yield

variability was largest among fields, with a standard deviation of 8.5 – 11.1 t ha^{-1}, and within fields, with a standard deviation of 7.7 – 8.7 t ha^{-1}. Spatial yield variability was lower at higher aggregation levels, i.e., the standard deviation of among-farm yield variability was 4.0 – 6.1 t ha^{-1} and that of among-provinces 1.6 – 3.5 t ha^{-1}. Temporal yield variability explained 10 – 55% of the total observed variation in crop yield and its magnitude was equal or larger than the spatial yield variability for almost all datasets. We conclude that reducing spatial potato yield variability in the Netherlands can be achieved best at the field and within-field level, rather than at farm or regional level. In addition, reducing temporal variability is an important contributor to reducing overall yield variability.

In Chapter 2, we also explored farmers' perception on the yield gap and yield gap explaining factors. Farmers estimated the ware potato yield gap at 13 – 18 t ha^{-1}, corresponding to 20 – 24% of estimated yield potential, depending on the soil type and variety. Water deficit and water excess were considered the most important yield gap explaining biophysical factors. In addition, soil structure was an important biophysical factor on clayey soils and diseases on sandy soils. Irrigation and fertilisation were identified as the most important yield gap explaining management factors, whereas legislation and potato prices were identified as the key socio-economic factors influencing potato yields.

Yield gap variability and its causes were explored further in Chapter 3, where we found that frequent on-farm monitoring across 96 commercial fields combined with crop growth modelling was a powerful way to benchmark productivity and to evaluate the most important yield gap explaining factors at field level. The average yield gap ranged from 20 – 31% depending on the year and soil type. Among fields, the yield gap ranged from 0 – 51%. On clayey soils, the yield gap was mostly attributed to oxygen stress. On sandy soils, the yield gap was mostly attributed to drought stress in 2020, a relatively dry year, and by reducing factors (pests, diseases and poor agronomic practices) in 2021, an average year in terms of precipitation. It varied widely from field to field which reducing factor(s) affected crop yield. Lastly, we found that the potential yield was determined by radiation and that earlier planting and/or later harvesting could also increase yield.

The on-farm monitoring in Chapter 3 provided detailed insight in the yield gap and yield gap explaining factors. However, the collected data did not allow to study the effect of specific factors on potato yield that require testing under controlled conditions or that are not commonly reported by farmers. In Chapter 4, using on-farm experiments, we analysed for 46 farmers' fields on sandy and clayey soils whether increased phosphorus (P) and potassium (K) fertiliser application rates led to a higher yield. We found that, on average, increased P and K fertiliser application rates did not result in a significantly higher yield on both soil types and in two years (2019 and 2020). However, on sandy soils at relatively low farmer K application rates, our K application led to a small positive yield response up to 5 t ha^{-1}. On clayey soils, there was an average positive yield response to our K application at lower yield levels of the control. For P, we did not find any correlation between yield response to P application and the amount of P applied by farmers or any of the measured soil parameters. We conclude that, although in some fields there was a small positive yield effect of increased K application, increasing P and K application rates will not narrow the potato yield gap and improve potato yield quality in the Netherlands. Instead, in most fields increasing P and K application will decrease P and K use efficiency, and hence is not recommended from an environmental and economic perspective.

In Chapter 5, we tested through a two-year on-farm experiment on a large-scale potato farm, whether seed potatoes (cultivar Fontane) originating from different seed potato growers show variability in crop characteristics and yield. Furthermore, we evaluated if seed potato origin interacted with planting date and/or field type. Origin significantly affected the number of stems per plant and number of tubers per stem in both years. This resulted in a significant effect of origin on number of tubers per plant in the first year. In that year, the origin with the lowest number of tubers per plant also produced the highest yield of tubers larger than 50 mm. Despite these (small) effects of seed potato origin on crop characteristics, origin did not significantly affect gross and marketable yield. Moreover, there was no significant interaction between origin and planting date and/or field type. However, there was a significant main effect of field type and planting date on yield. Yield in the wet rainfed field was up to 17 t ha^{-1} higher than in the dry irrigated field and late planting resulted in a yield reduction of up to 10 t ha^{-1}. In conclusion, physiological aspects of seed potato origin for the cultivar Fontane were not important in explaining yield variability on this farm and likely also not on other farms in the Netherlands.

Throughout Chapter 2 – 5, it became apparent that ware potato productivity in the Netherlands is high but that the scope to increase yield in the Netherlands is limited because of a multitude of challenges farmers are facing and because crop management priorities are also given to other crops. In addition, we observed that high input rates were used to obtain high yields, but that variability in input rates were not correlated to variability in yield. In Chapter 6, we therefore evaluated whether there is scope to reduce input levels and environmental impact of ware potato production without compromising yield. We assessed variability in yield, use and use efficiency of nitrogen (N), phosphorus, potassium and crop protection products as well as water productivity using the same data as employed in Chapter 3. Average total N surplus was large, being 265 kg N ha^{-1} on clayey soils and 139 kg N ha^{-1} on sandy soils. Variability in N surplus among fields was also large; it varied among fields by a factor three. Phosphorus and K input exceeded P and K output on clayey soils by 33 and 105 kg ha^{-1}, respectively, while on sandy soils P and K balances were close to zero. Mean water productivity was 43 kg DM mm^{-1} ha^{-1} and ranged from 30 to 60 kg DM mm^{-1} ha^{-1} for both soil types. In terms of crop protection product use, lowest and highest use differed

by a factor four. Variability in environmental impact of the different indicators was mostly explained by variability in input use. Mean performance across indicators showed that it was possible to achieve relatively high yields with relatively low N surplus, high water productivity and low crop protection product use. Yet, in the best performing fields N surplus was still above the environmental threshold for nitrate concentration in the groundwater and crop protection product use would not meet the 50% reduction (as targeted in the Farm to Fork strategy) compared to the average pesticide use of all fields. Hence, this means that further reduction in input use will be needed to meet environmental targets for N surplus or crop protection product use reduction.

This thesis showed that a wide variety of yield gap influencing factors determine yield and therefore also affect resource use efficiency in potato cultivation. However, not all yield gap influencing factors could be taken into account. In Chapter 7, I identified that soil compaction, narrow rotations and flooding are also expected to influence yields. Overall, I conclude that yields could be increased for individual fields through improved irrigation on sandy soils, better drainage on clay soils, earlier planting and improved disease control. However, I identified that there are additional environmental and socio-economic constraints that play a role at farm level and that prevent farmers from obtaining higher yields. Therefore, there is limited scope to increase average actual ware potato yields in the Netherlands. Only in particular fields a yield gain could be achievable, which would then result in decreased yield variability.

Given the environmental challenges that the Netherlands is facing, there is a need to reduce environmental impact of ware potato production Netherlands. Simultaneously, there is a need to maintain minimum productivity levels. The observed variability among fields suggests that it is possible to obtain similar high yields while reducing the environmental impact of ware potato production. However, there will be a need to evaluate how far and under which conditions input reduction is possible without yield loss. In addition, it needs to be assessed how current ware potato production systems can be integrated with alternative cropping systems that can contribute to improved sustainability of ware potato production in the Netherlands.

Samenvatting

In Nederland is de aardappel voor boeren een hoog salderend rooivrucht en een belangrijk gewas voor de keten. Het gewas wordt geteeld op 30% van de akkerbouwgrond, door 50% van de akkerbouwers en in alle provincies in Nederland. Gemiddelde opbrengsten van consumptieaardappelen zijn hoog; rond de 52 ton versgewicht per ha. Ondanks de gemiddeld hoge opbrengsten per ha, wordt er een grote variatie in opbrengsten waargenomen tussen bedrijven en percelen van hetzelfde bedrijf. Dit suggereert dat productie en dus het rendement voor telers zou kunnen toenemen. Bovendien, wanneer relatief lage opbrengsten behaald worden met vergelijkbare inputs als bij hoge opbrengsten, worden deze inputs niet volledig benut. Dit leidt tot een lagere inputgebruiksefficiëntie en mogelijk grotere emissies naar de leefomgeving. Dit biedt mogelijkheden om de impact van consumptieaardappelproductie op de leefomgeving in Nederland te verlagen.

Productiviteit van akkerbouwsystemen kan gekwantificeerd worden door middel van een analyse van de opbrengstkloof (“yield gap”). In een dergelijke analyse worden daadwerkelijk behaalde opbrengsten van telers vergeleken met de potentiële opbrengst. Deze laatstgenoemde maatstaf wordt gedefinieerd op basis van weersomstandigheden en perfect management en kan aangepast worden door rekening te houden met beperkende factoren zoals waterbeschikbaarheid. In dit laatste geval is er sprake van de water-gelimiteerde potentiële opbrengst. In eerdere studies zijn er al opbrengstkloofanalyses gedaan voor consumptieaardappelproductie in Nederland. Deze analyses hebben tot waardevolle inzichten geleid met betrekking tot de bestaande opbrengstkloof en factoren die de opbrengstkloof bepalen op hogere schaalniveaus. Echter, deze analyses konden de variabiliteit in opbrengsten tussen percelen onvoldoende verklaren. Om opbrengsten en rendement te verhogen, en om de impact van aardappelproductie op de leefomgeving te verlagen, is het noodzakelijk om de variabiliteit tussen percelen beter te begrijpen.

Het doel van dit proefschrift is om voor de Nederlandse consumptieaardappelteelt de variabiliteit in opbrengsten, opbrengstkloven, inputgebruiksefficiëntie en impact van aardappelproductie op de leefomgeving te kwantificeren en verklaren. De resultaten kunnen gebruikt worden om aanbevelingen te doen over hoe opbrengsten en inputgebruiksefficiëntie verhoogd kunnen worden, en hoe de impact van consumptieaardappelteelt op de leefomgeving verlaagd kan worden. Dit onderzoek is in drie stappen verricht: (1) kwantificering van de ruimtelijke en temporele variatie in opbrengsten met gebruik van beschikbare databronnen, (2) bepaling van verschillende productiviteitsmaatstaven en beoordeling welke factoren variatie in opbrengsten en/of opbrengstkloven kunnen verklaren middels enquêtes en door observaties en experimenten op boerenbedrijven, en (3) kwantificering en verklaring van variabiliteit in inputgebruik,

gebruiksefficiëntie en impact op de leefomgeving van aardappelproductie in Nederland op basis van gedetailleerde metingen op boerenbedrijven.

Hoofdstuk 2 begint met een beoordeling van de ruimtelijke en temporele variatie in opbrengsten voor vier agronomisch relevante schaalniveaus (tussen provincies, bedrijven en percelen en binnen percelen) door gebruik te maken van vijf verschillende datasets met opbrengstdata in ruimte en tijd. De ruimtelijke variatie in versgewicht opbrengsten was het grootste tussen percelen, met een standaarddeviatie van 8.5 – 11.1 t ha^{-1}, en binnen percelen, met een standaarddeviatie van 7.7 – 8.7 t ha^{-1}. Ruimtelijke variatie in opbrengsten was lager op hogere schaalniveaus, namelijk, de standaarddeviatie van ruimtelijke variatie in verse opbrengst was 4.0 – 6.1 t ha^{-1} tussen bedrijven en 1.6 – 3.5 t ha^{-1} tussen provincies. Temporele variatie in opbrengsten verklaarde 10 – 55% van de totale waargenomen variatie in opbrengsten. De grootte van die variatie was gelijk of groter dan de ruimtelijke variatie in opbrengsten voor bijna alle datasets. We concluderen dat het verlagen van de ruimtelijke variatie in aardappelopbrengsten in Nederland het beste bereikt kan worden op perceelsniveau en binnen percelen, in plaats van op bedrijfs- of regionaal niveau. Daarnaast is het verlagen van de temporele variatie in opbrengsten een belangrijke factor in het verlagen van de algehele variatie in opbrengsten.

In Hoofdstuk 2 hebben we tevens onderzocht hoe groot telers de opbrengstkloof schatten en hoe de opbrengstkloof verklaard kan worden. Telers schatten de opbrengstkloof van consumptieaardappelen op 13 – 18 t ha^{-1}, wat overeenkomt met 20 – 24% van de geschatte opbrengstpotentie, afhankelijk van de grondsoort en het geteelde ras. Watertekort en -overschot werden gezien als de belangrijkste biofysische factoren die de opbrengstkloof kunnen verklaren. Daarnaast werd bodemstructuur gezien als een belangrijk biofysische factor op kleigrond en ziekten op zandgrond. Irrigatie en bemesting werden benoemd als de belangrijkste managementfactoren die de opbrengstkloof kunnen verklaren. Wetgeving en aardappelprijzen werden gezien als de belangrijkste sociaaleconomische factoren die aardappelopbrengsten beïnvloeden.

Variabiliteit in opbrengsten en de oorzaken ervan werden verder onderzocht in Hoofdstuk 3. In dit hoofdstuk vonden we dat het frequent monitoren van aardappelpercelen op 96 commerciële bedrijven gecombineerd met het gebruik van gewasgroeimodellen een geschikte manier was om productiviteit te beoordelen en te onderzoeken welke factoren de verschillen in opbrengstkloven op perceelsniveau verklaren. De gemiddelde opbrengstkloof varieerde van 20 – 31% afhankelijk van het jaar en grondsoort. Van perceel tot perceel varieerde de opbrengstkloof van 0 – 51%. Op kleigronden werd de opbrengstkloof voornamelijk toegeschreven aan zuurstofstress. Op zandgronden werd de opbrengstkloof voornamelijk verklaard door droogtestress in 2020, een relatief droog jaar, en door reducerende factoren (ziekten, plagen en suboptimale landbouwpraktijk) in 2021, een gemiddeld jaar wat betreft neerslag. Welke reducerende factoren de lagere opbrengsten verklaarden varieerde sterk van perceel tot perceel. Als laatste vonden we dat de potentiële opbrengst bepaald werd door straling en dat door eerder poten en/of later oogsten de opbrengstpotentie verhoogd kan worden.

De perceelsbezoeken in Hoofdstuk 3 gaven gedetailleerd inzicht in de opbrengstkloof en de verklarende factoren. Echter, de verzamelde data was niet toereikend om het effect van specifieke factoren op de opbrengst te onderzoeken. Het gaat hier om factoren die onder gecontroleerde omstandigheden getest moeten worden of die niet algemeen vastgelegd worden door telers. Door middel van experimenten op bedrijven hebben we in Hoofdstuk 4 voor 46 praktijkpercelen op zand- en kleigrond geanalyseerd of het verhogen van de fosfor (P) en kalium (K) gift tot hogere opbrengsten leidt. Gemiddeld genomen was dat niet het geval op beide grondsoorten en voor beide jaren (2019 en 2020). Echter, op zandgronden met een relatief lage praktijk K gift, leidde onze K gift tot een licht positieve opbrengstrespons tot 5 t ha^{-1}. Op kleigronden was er gemiddeld genomen een positieve respons van een verhoogde K gift met lagere opbrengsten in de controleplots. Voor P hebben we geen enkele correlatie gevonden tussen opbrengstrespons als gevolg van P bemesting en de P giften van telers of bodemvruchtbaarheid. Alhoewel er in sommige velden een licht positieve opbrengstrespons was als gevolg van de hogere K gift, concluderen we dat het verhogen van P en K giften niet zal leiden tot een vermindering van de opbrengstkloof of verbeteren van de opbrengstkwaliteit. In plaats daarvan zal het verhogen van de P en K gift in de meest percelen leiden tot een verlaging van de P en K gebruiksefficiëntie, en is daarom niet wenselijk vanuit een ecologisch en economisch perspectief.

In Hoofdstuk 5 hebben we middels een tweejarig experiment op een grootschalig aardappelbedrijf getest of pootgoed (van het ras Fontane) afkomstig van verschillende pootgoedtelers varieert in gewasgroei en opbrengst. Daarnaast hebben we geëvalueerd of er een interactie was tussen herkomst van het pootgoed, pootdatum en type perceel. Herkomst had een significant effect op het aantal stengels en het aantal knollen per stengel in beide jaren. Dit leidde tot een significant effect van herkomst op aantal knollen per plant in het eerste jaar. In dat jaar produceerde de herkomst met het laagste aantal knollen per plant ook de hoogste opbrengst van knollen groter dan 50 mm. Ondanks de (kleine) effecten van herkomst op gewasgroei had herkomst geen significant effect op bruto- en netto-opbrengst. Bovendien was er geen significante interactie tussen herkomst en pootdatum en/of type perceel. Echter, er was een significant effect van type perceel en pootdatum op de opbrengst. Opbrengst in het natte, niet-beregende perceel was tot 17 t ha^{-1} hoger dan in het droge, beregende perceel en laat poten resulteerde in een opbrengstreductie tot 10 t ha^{-1}. We concluderen dat fysiologische aspecten van herkomst van pootgoed voor het ras

Fontane niet belangrijk waren voor het verklaren van opbrengstverschillen op dit bedrijf en waarschijnlijk ook niet op andere bedrijven in Nederland.

In de Hoofdstukken 2 – 5 werd het duidelijk dat productiviteit van consumptieaardappelen in Nederland hoog is, maar dat de mogelijkheden om opbrengsten te verhogen in Nederland beperkt zijn door een grote verscheidenheid aan uitdagingen waar boeren tegenaan lopen en omdat er in het management ook deels prioriteit gegeven wordt aan andere gewassen op het bedrijf. Daarnaast hebben we gezien dat hoge giften van inputs werden gebruikt om hoge opbrengsten te behalen, maar dat de variabiliteit in de giften niet gecorreleerd was met de variabiliteit in opbrengsten. In Hoofdstuk 6 hebben we daarom geëvalueerd of het gebruik van inputs en de impact van aardappelproductie op de leefomgeving verlaagd kunnen worden zonder dat dit ten koste gaat van de opbrengst. We hebben variabiliteit in opbrengst, gebruik en gebruiksefficiëntie van stikstof (N), fosfor, kalium en gewasbeschermingsmiddelen en de waterproductiviteit beoordeeld aan de hand van de data uit Hoofdstuk 3. Het gemiddelde totale N overschot was hoog met een overschot van 265 kg N ha^{-1} op kleigronden en 139 kg N ha^{-1} op zandgronden. Het gemiddelde effectieve N overschot was 182 kg N ha^{-1} op kleigronden en 70 kg N ha^{-1} op zandgronden. Variabiliteit in N overschotten tussen percelen was ook groot; het varieerde van perceel tot perceel met een factor drie. Fosfor en K giften overschreden P en K afvoer op kleigronden met respectievelijk 33 en 105 kg ha^{-1}, terwijl op zangronden de P en K balansen rond de nul lagen. De gemiddelde waterproductiviteit was 43 kg droge stof mm^{-1} ha^{-1} en varieerde van 30 tot 60 kg droge stof mm^{-1} ha^{-1} voor beide grondsoorten. Gebruik van gewasbeschermingsmiddelen varieerde met een factor vier tussen het hoogste en laagste gebruik. Variabiliteit van impact op de leefomgeving werd voornamelijk verklaard door variabiliteit in gebruik van inputs. De gemiddelde prestatie over de verschillende indicatoren liet zien dat het mogelijk was om relatief hoge opbrengsten te behalen met een relatief laag N overschot, hoge waterproductiviteit en laag gebruik van gewasbeschermingsmiddelen. Echter, in de best presterende percelen was het N overschot nog steeds boven de omgevingsnorm voor nitraatconcentratie in het grondwater en de reductie in gebruik van gewasbeschermingsmiddelen zou niet de 50% halen (zoals beoogd in de van Boer-tot-Bord strategie van de EU) vergeleken met het gemiddelde gebruik in alle percelen. Dit betekent dus dat verdere reductie van gebruik van inputs nodig is om omgevingsdoelen voor N overschot en reductie van gewasbeschermingsmiddelengebruik te behalen.

Dit proefschrift heeft laten zien dat een grote verscheidenheid aan factoren opbrengstniveaus bepaalt en daarmee ook inputgebruiksefficiëntie in de aardappelteelt. Echter, niet alle bepalende factoren konden meegenomen worden in dit onderzoek; in Hoofdstuk 7 suggereer ik dat van bodemverdichting, nauwe rotaties en wateroverlast ook verwacht wordt dat deze opbrengsten beïnvloeden. Op basis van het onderzoek in dit proefschrift concludeer ik dat voor individuele percelen de opbrengsten verhoogd zouden kunnen worden door verbeterde irrigatie op zandgronden, betere drainage op kleigronden, vroeger planten en betere bescherming tegen ziekten en plagen. Echter, ik heb ook vastgesteld dat er additionele omgevings- en sociaaleconomische factoren zijn op bedrijfsniveau die telers beperken in het behalen van hogere opbrengsten. Om die reden lijken er beperkte mogelijkheden tot het verhogen van consumptieaardappelopbrengsten in Nederland. Echter, in specifieke percelen is een verhoging van de opbrengst mogelijk, welke dan zou leiden tot een verlaging van de opbrengstvariabiliteit.

Gezien de uitdagingen waar Nederland voor staat met betrekking tot de leefomgeving, is het noodzakelijk om de impact van de aardappelteelt in Nederland te verlagen. Tegelijkertijd zijn minimale opbrengstniveaus vereist voor voldoende voedselvoorziening en bedrijfsrendement. De waargenomen variabiliteit tussen percelen suggereert dat het mogelijk is om vergelijkbare opbrengsten te halen en tegelijkertijd de impact van de aardappelteelt op de leefomgeving drastisch te verminderen. Echter, het is noodzakelijk om te evalueren tot hoever en onder welke omstandigheden een reductie in het gebruik van inputs mogelijk is zonder opbrengstverlies. Daarnaast zal onderzocht moeten worden hoe het huidige systeem van consumptieaardappelproductie geïntegreerd kan worden met alternatieve gewasproductiesystemen die bijdragen aan een verhoogde duurzaamheid van de aardappelteelt in Nederland.

Acknowledgements

Dit proefschrift had niet op dezelfde manier tot stand kunnen komen zonder de onmisbare hulp van alle aardappeltelers die deelgenomen hebben aan dit onderzoek. Ontzettend bedankt voor jullie interesse en betrokkenheid! Niet één hoofdstuk in dit proefschrift had geschreven kunnen worden zonder jullie bijdrage. Gert-Jan Heidemans en Jacob van den Borne, ik wil jullie in het bijzonder bedanken voor jullie hulp. Ik heb veel van jullie geleerd over het telen van aardappels. Daarnaast is ook het beschikbaar stellen van jullie data en/of proefvelden van onschatbare waarde geweest voor dit proefschrift.

I would like to thank my (co-)promotors, Pytrik Reidsma, Martin van Ittersum and Corné Kempenaar, for their support. Pytrik, your positive attitude is admirable, despite setbacks in your personal health in the past few years. You have always been and still are on the lookout for valuable collaborations, trying to connect to the work of others. I admire how you evaluate findings in relation to the broader context in which we do our research. This has been very valuable to put a broader perspective to my research. I also really appreciated how you stayed involved, although you could not always be physically present. Martin, thank you for your genuine interest in me and my research. Your ever constructive feedback has been really valuable for improving the quality of this thesis. I am still amazed by the speed and detailedness of your reactions. Your calendar seems very full. Nevertheless, you always made time available to answer my questions. Corné, thank you for sharing your practical knowledge and network with me. Your connections have been very helpful to set up the field work at various farms. I have also appreciated how you always made sure that the research that we have been doing is also valuable to farmers. Thanks to all three of you for letting me set up my own research project. I am really grateful how you have always been supportive, but never directive. This really made me feel that I could take ownership of my own PhD project, which has been a valuable learning experience.

I would like to express my gratitude to the thesis committee, to prof. dr. ir. N.P.R. Anten, dr. J.P. Goffart, prof. dr. ir. L. Kooistra and prof. dr. ir. M.P.M. Meuwissen for offering their valuable time to critically evaluate my thesis.

There is an endless list of people who helped me in the field for one or more days. I would like to thank them all! Anna Gomes, Anne Waverijn, Arie W. Ravensbergen, Arjen van Putten, Arlind Stublla, Bas Wullems, Cameron Ludemann, Chris van Vilsteren, Chunmei Zou, David de Wit, Elodie Mansard, Eltjo Stobbelaar, Eva Thuijsman, Harmen den Braber, Heleen van Diggele, Hugo Bosland, Inge van de Wiel, Jelle Toebes, Jeroen Theelen, Jerom Frints, João Vasco Silva, Kas Blok, Katerina Mouka, Kyu Hee Do, Laura Stoll, Lisa Hoonhout, Lotte Woittiez, Majid Ali Magham, Mariska Tol, Marston Domingues Franceschini, Martin van Ittersum, Massimo Tolomio, Nicole Chudy, Nicole Ramsebner, Peter Seghers, Piet

Ravensbergen, Pytrik Reidsma, Qiuhong Huang, Renske Hijbeek, Roos van Dortmont, Sebastian Pinzon Gonzalez, Sofanne Ravensbergen, Tamara ten Den, Thomas Awio, Wytse Vonk, Yin-Jung Li (I hope I included everyone), thank you all so much for your effort, for the lively discussions on the road and for making the field work much more fun. Without your help this work would have been impossible.

There are others with whom I have collaborated, who I would like to thank as well. Chunmei, I really enjoyed working with you. We have had our challenges while setting up the seed potato origin experiment together, as we had different interests, backgrounds and approaches. We needed some discussion time to get to an agreement on the methodology. In addition, the experiment was for both of us an extra commitment on top of our already busy field work schedule. This made it sometimes hard to get everything organised. Despite the challenges, I really valued our collaboration. Apart from that, I also very much enjoyed our discussions about other things than potatoes. Puck, it has always been a pleasure to talk to you about our PhD trajectories. It was refreshing to see how you approached your research and how it is totally different from what I have been doing, while we worked on similar topics. Unfortunately the Covid-19 pandemic has limited our interactions. Nevertheless, I really appreciated them. João, thanks a lot for sharing your experience in doing research and knowledge on potato yield gaps in the Netherlands. Our discussions at the start of my PhD have really helped to shape my research. Your input has also been invaluable for Chapter 2 and I am glad you agreed to be a co-author of that chapter. Bernardo, every time I saw you scripting in R, I was amazed by the ease of your programming. Your skills have been very helpful in organising the, sometimes chaotic, data from farmers. Paul, your knowledge about the potato crop is endless. We have collaborated to a limited extent only, but it was still very useful to shape the content of Chapter 5. Furthermore, I would like to thank all partners from the HIP consortium, which co-funded this research, for the interactions during the discussions. Cees van den Hoek, Leo van Marion, Matthijs Meijer en Sjaak Aben, your help has been particularly valuable in discussing and interpreting the results, obtaining yield data at field scale, disseminating the questionnaire of Chapter 2, connecting with farmers who wanted to participate, and for analyses of tuber samples. Thank you for that. Lastly, I would like to thank Ruud van der Meer for his support in using the FADN data, employed in Chapter 2.

To all my colleagues of the PPS chair group I would like to express my sincere gratitude for being such nice colleagues. Since I came into the chair group as a master student I have always felt very welcome and enjoyed open discussions that are ever ongoing within the group. I am very happy that I can continue to work within such a nice group! I am not going to list everyone, so I cannot forget someone. Nevertheless, there are a few people I would like to address a few words to in particular. Renske, you were a great supervisor during my master thesis and internship. You were very open, asked a lot of interesting questions and

challenged me to further improve my work. Above all, it was a lot of fun working with you. I was more than glad that you were willing to co-supervise a master student with me and to contribute to the final chapter. I am sure that you played a great role in the fact that I continued at PPS with a PhD. Marloes, thank you too for being such a nice supervisor, although it was for a relatively short time. To the potato team, Inge, Massimo, Tamara, thank you enormously for your support and contribution. Our personalities are very diverse, but I think that made us a great team, where each one of us had her/his strengths. Bert, thank you for sharing your vast knowledge about agronomy, for your interest in potatoes and for organising great excursions, no matter the group size. Of course I would also like to express my gratitude to our secretariat. Linda, Karen, Irma, thank you for all the hard work and organising all sorts of things so smoothly. Thanks to all students who participated in the field work and contributed to the data analysis. David, your dedication was incredible. You happily woke up early each day to go to the field at 6 am. In the very hot week in August you even proposed to leave one hour earlier, so we could escape the worst heat of the day. It really showed your motivation. Also thanks a lot for the useful chats about the daily life as a farmer. This has helped me enormously to understand the context in which farmers operate. Nicole, Arlind, and Katerina, thank you as well for your dedication during the field work, for the diverse discussions we had on the road and of course for the harvesting competitions. A considerable part of my PhD trajectory I occupied a desk at Agrosystems Research. Thanks to all colleagues of that group for being such welcoming hosts. It was wonderful how I was part of the group, even though I was employed by another group.

Gelukkig is er meer in het leven dan een PhD. Wat is het fijn om familie te hebben waarop ik altijd terug kan vallen, om vrienden te hebben om lol mee te trappen en flauwe grappen mee te maken, en om muziek te mogen maken in verschillende orkesten en ensembles voor de nodige afleiding. Daarom wil ik iedereen bedanken die het leven erbuiten heel aangenaam gemaakt hebben. (Schoon)familie, vrienden, medemuzikanten, bedankt voor jullie steun en gezelligheid!

Lieve Sofanne, voordat ik aan het schrijven van dit dankwoord begon had ik het dankwoord uit jouw proefschrift nog eens nagelezen. Je haalde precies datgene aan wat ik ook wilde aanhalen, namelijk dat je in juli 2019 twee dagen mee ging aardappels rooien in Noord-Brabant in de brandende zon tijdens die hele hete week. Dat je er altijd voor me bent ongeacht de omstandigheden betekent veel voor me, bedankt daarvoor! Barzi, wat is het fijn om jou als zwager te hebben en te zien hoe je een goede partner voor mijn zus bent. Sofanne en Barzi, ik ben heel blij dat jullie mijn paranimfen willen zijn en dat we het promoverende leven van ons drieën nu ook met ons drieën (of eigenlijk met ons vieren) af kunnen sluiten!

Lieve pappa en mamma, zonder jullie had ik deze PhD nooit succesvol ten einde kunnen brengen. Jullie hebben mij een aantal hele belangrijke eigenschappen meegegeven: doorzettingsvermogen, in oplossingen denken, het avontuur aangaan, efficiënt werken wanneer nodig en vooral ook plezier hebben in wat je doet. Ik heb dit allemaal veelvuldig toe moeten passen tijdens mijn PhD. Tijdens de PhD waren jullie er altijd voor me, of het nu ging over de morele support of de fysieke support. Ik vond het super leuk dat jullie ook een aantal keer mee geweest zijn in het veld. Hopelijk is de spierpijn inmiddels over ;).

Lieve Lisa, je hebt heel wat moeten doorstaan met mij de afgelopen paar jaar. Je hebt getolereerd dat elke dag de wekker weer vroeg ging, dat het hele huis vol lag met aardappels, dat er zeven dagen per week aardappels op het menu stonden, dat er 10 cm aarde in de auto lag, dat ik in slaap viel tijdens het kijken van een film aan het einde van de week, dat ik weer weg moest naar het veld en nog veel meer. Ik zit natuurlijk te dollen! Een paar zinnen in het dankwoord zijn niet genoeg om uit te drukken hoe blij ik met jou ben. Je geeft me ontzettend veel liefde, bent er echt altijd voor me, hebt aandacht voor de medemens en zorgt ervoor dat ik af en toe ook wat rustiger aan doe. Ik heb er ontzettend veel zin in om binnenkort samen een nieuw avontuur aan te gaan!

About the author

Arie Pieter Paulus Ravensbergen was born on the 26th of August 1994 in Rijnsburg, the Netherlands. After graduating from the Adelbert College in Wassenaar, he obtained a BSc degree in International Land and Water Management at Wageningen University in 2015 (cum laude). He conducted an internship and bachelor thesis project at ECOSUR (El Colegio de La Frontera Sur), Campeche, Mexico. At Wageningen University he followed the minor Systems in Plant Production. During the bachelor, he was treasurer of the board and chair of the 'lustrum' committee of student orchestra De Ontzetting.

Out of a combined interest for sustainable land management and crop production, he continued with two masters. In 2019, he graduated from the masters International Land and Water Management with a specialisation in Sustainable Land Management and Plant Sciences with a specialisation in Natural Resource Management (cum laude). For the first master thesis, he did research on the effect of soil management practices on yield and soil properties in olive orchards in Enguera, Valencia, Spain in collaboration with Universitat de Valencia. For the second master thesis, he conducted a literature study on the synergies and trade-offs of integrating legumes in maize cropping systems in Kenya and Tanzania. For a Capita Selecta he went to Kenya to test a spectral device for non-destructive measurements of P concentration in maize leaves, in collaboration with IPNI (International Plant Nutrition Institute). He conducted an internship at CIMMYT, Nairobi office, where he calibrated the QUEFTS model for Nigeria using data characterised by imperfect management. During his master studies, he was also a general member of the education committee of the study International Land and Water Management and chair of the tour committee of student orchestra De Ontzetting, organizing a concert tour to Poland.

He started his PhD in January 2019 at the Plant Production Systems Group under supervision of prof. dr. ir. Martin van Ittersum, dr. Pytrik Reidsma and dr. Corné Kempenaar in the project Yield Gap Analysis for Sustainable Potato Production. In this project, he analysed variability in yield, resource use efficiency and environmental impact of ware potato production in the Netherlands, using existing datasets, questionnaires, on-farm observational studies and on-farm experiments. He is currently employed as a researcher in the Plant Production Systems Group (WUR) with a focus on sustainable crop cultivation within ecological boundaries in highly productive cropping systems. In addition, he is a board member of Harmonie Koningin Wilhelmina, Wamel.

List of publications

Peer reviewed scientific publications

Ravensbergen, A. P. P., van Ittersum, M.K., Hijbeek, R., Kempenaar, C., & Reidsma, P. Field monitoring shows scope for reducing environmental impact of ware potato cultivation in the Netherlands without compromising yield. To be submitted.

Ravensbergen, A. P. P., Zou, C., Struik, P.C., Reidsma, P., Kempenaar, C. & van Ittersum, M.K. Effects of planting date and field type on yield outweigh effect of seed potato origin. To be submitted.

Ravensbergen, A. P. P., van Ittersum, M. K., Kempenaar, C., Ramsebner, N., de Wit, D. & Reidsma, P. In press. Field monitoring coupled with crop growth modelling allows for a detailed yield gap assessment at field level: a case study on ware potato production in the Netherlands. *Field Crops Research.*

Ravensbergen, A. P. P., van Ittersum, M. K., Silva, J. V., Maestrini, B., Kempenaar, C., & Reidsma, P. (2023). Yield variability across spatial scales in high input farming: Data and farmers' perceptions for potato crops in the Netherlands. *European Journal of Agronomy*, *150*, 126925. https://doi.org/10.1016/j.eja.2023.126925

Ravensbergen, A. P. P., van Ittersum, M. K., Kempenaar, C., & Reidsma, P. (2023). Current Phosphorus and Potassium Fertiliser Application Rates Do Not Limit Tuber Yield and Quality in Potato Production Systems in the Netherlands. *Potato Research*, 1-26. https://doi.org/10.1007/s11540-022-09613-5

Ravensbergen, A. P. P., Chamberlin, J., Craufurd, P., Shehu, B. M., & Hijbeek, R. (2021). Adapting the QUEFTS model to predict attainable yields when training data are characterized by imperfect management. *Field Crops Research*, *266*, 108126. https://doi.org/10.1016/j.fcr.2021.108126

Conference Proceedings

Ravensbergen, A.P.P., Hijbeek, R., Mouka, K., Kempenaar, C., Reidsma, P. & van Ittersum, M.K., 2022. Dutch case study shows that large variability in farmers' input use and efficiency provides scope to maintain potato productivity levels while using less inputs, XVII Congress of the European Society for Agronomy (ESA 2022), August 29 – September 2 2022, Potsdam, Germany

Maestrini, B., Kallenberg, M., **Ravensbergen, A.P.P.**, van Bree, R., Athanasiadis, I. & van Evert, F.K., 2022. Integrating crop growth simulation models with a data driven approach, XVII Congress of the European Society for Agronomy (ESA 2022), August 29 – September 2 2022, Potsdam, Germany

Ravensbergen, A.P.P., Ramsebner, N., de Wit, D., Kempenaar C., Reidsma, P. & van Ittersum M.K., 2022. Can drought stress explain potato yield (gap) variability in the Netherlands? 11th World Potato Congress (WPC 2022), May 30 – June 2 2022, Dublin, Ireland

Ravensbergen, A.P.P., Hijbeek, R., Njoroge, S., Carstensen, A., ten Berge, H. F. M., & van Ittersum, M. K., 2019. Measuring P deficiency in maize leaves: comparing spectral and wet chemical measurements under tropical conditions. 16th International Symposium on Soil and Plant Analysis (ISSPA 2019), 17-20 June 2019, Wageningen, the Netherlands

PE&RC Training and Education Statement

With the training and education activities listed below the PhD candidate has complied with the requirements set by the C.T. de Wit Graduate School for Production Ecology and Resource Conservation (PE&RC) which comprises of a minimum total of 32 ECTS (= 22 weeks of activities)

Review/project proposal (6 ECTS)

- Understanding yield variation in potato cultivation to move towards more sustainable potato production

Post-graduate courses (7.3 ECTS)

- Design of experiments; PE&RC & WIAS (2019)
- Geostatistics; PE&RC & WIMEK (2019)
- Crop physiology and climate change; PE&RC (2022)
- Land dynamics in an era of change; PE&RC (2023)

Invited review of journal manuscripts (5 ECTS)

- Potato Research: yield gap analysis and prospect for increasing potato production in Iran (2019)
- Field Crops Research: assessing approaches for stratifying producer fields based on biophysical attributes for regional yield-gap analysis (2020)
- Agricultural Systems: coupling landscape-scale diagnostics surveys, on-farm experiments, and simulation to identify entry point for sustainably closing rice yield gaps in Nepal (2020)
- Scientific Reports: influence of organic manures, inorganic fertilisers and bio-fertilisers on yield and quality attributes of potato (*Solanum tuberosum L.*) (2021)
- Agronomy Journal: estimating nutrient uptake requirements for melon based on the QUEFTS model (2021)

Competence, skills and career-oriented activities (3.94)

- Supervising thesis students; ESC (2020)
- The choice: un-box your PhD process & take charge of your performance; WGS (2020)
- Scientific writing; In'to languages (2021)
- Communication with the media and the general public; WGS (2021)

Scientific integrity/ethics in science activities (0.3 ECTS)

- Ethics in plant and environmental sciences; WGS (2019)

PE&RC Annual meetings, seminars and PE&RC weekend/retreat (1.95 ECTS)

- PE&RC First year's weekend (2019)
- PE&RC Workshop carousel (2019)

- PE&RC Day; online (2020)
- PE&RC Last year's retreat (2022)

Discussion groups/local seminars or scientific meetings (5.2 ECTS)

- Intensification and diversification of smallholder oil palm systems (2019)
- Soil and plant interactions (2020/2021)
- Emissions & nutrient management (2022)
- Diversification and intensification of smallholder farming through grain legumes (2022)
- SIAS discussion group (2022/2023)

International symposia, workshops and conferences (6.2 ECTS)

- ISSPA; Wageningen (2019)
- WPC; Dublin (2022)
- ESA; Potsdam (2022)

Societally relevant exposure (0.3 ECTS)

- Nieuwe Oogst: onderzoeker vraagt telers naar opbrengstverschillen (2021)

Committee work (1 ECTS)

- Appointment advisory committee (2021)

Lecturing/supervision of practicals/tutorials (9 ECTS)

- QUALUS (2020-2022)

BSc/MSc thesis supervision (18 ECTS)

- Current status of commercialised microbial biopesticides for potato and RNAi for potato crop protection
- Evaluation of water use efficiency of ware potato commercial fields in South Africa
- The effect of seed potato quality and management on the development of ware potato on a large-scale arable farm
- Ware potato and water availability: a study on the effect of water availability on the variability in crop senescence, yield and yield quality
- Analysing the effect of P and K fertiliser application rates in commercial potato fields
- The sustainability of *Solanum tuberosum L.* (potato) production in the Netherlands
- Effect of drought and oxygen stress on the growth and yield of ware potato in the Netherlands
- Assessing the sustainability of fertiliser and pesticide use in ware potato fields in the Netherlands
- Analysing the effect of seed potato origin on crop performance in the Netherlands

The research described in this thesis is part of the project Potato Gap NL (project number 16891) of the research programme Holland Innovative Potato which was (partly) financially supported by the Dutch Research Council (NWO).

Financial support from Wageningen University for printing this thesis is gratefully acknowledged.

Cover design by Irene R. den Toom

Printed by ProefschriftMaken