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Current Phosphorus and Potassium Fertiliser Application Rates Do Not Limit Tuber Yield and Quality in Potato Production Systems in the Netherlands

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Abstract

Current ware potato yields 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 clay 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 clay 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, the K application led to a slight reduction in underwater weight on sandy soils in 2019 and a slight increase in the 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 the P and K application will decrease P and K use efficiency and hence is not recommended from an environmental and economic perspective.

Keywords Fertiliser · Nutrient management · Phosphorus · Potassium · Solanum tuberosum · Yield response

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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 the effects of pests and diseases. Actual ware potato yields in the Netherlands average 52 t ha^{-1}, which is estimated to be approximately 70% of their potential (Silva et al. 2017, 2020), and vary largely amongst farms and fields. Hence, there is still scope to increase potato yields; specifically in 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 et al. 2021). In an unpublished survey, some 69% of Dutch potato farmers indicated that with less strict phosphorus application legislation, they would be able to increase potato yields at their farms. Nutrient inputs in The Netherlands were increased after the Second World War until approximately the 1990s to stimulate crop productivity (Harms et al. 1987; van Dijk et al. 2016; FAOSTAT 2022). 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 obtained 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 potato crop's K uptake rates, leading to a negative K balance (Vos and Van Der Putten 2000). This hypothesis is not new as already in the 1980s, 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 clay soils in the Netherlands in polders that were created in the second half of the twentieth 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. Prummel 1969; Alblas 1984; Ehlert and Versluis 1990; Chapman et al. 1992; Maier et al. 1994; Mohr and Tomasiewicz 2011; Nyiraneza et al. 2017; Mokrani et al. 2018). These experiments were generally carried out on single or only a few experimental farms or fields, whilst 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 (Silva et al. 2017; Cassman and Grassini 2020). 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 amongst 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 Prummel 1969; Alblas 1984; Ehlert and Versluis 1990), mostly with the variety 'Bintje', whilst 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, whilst 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.

Materials and Methods

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. 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 clay soils where growers cultivated the variety 'Innovator'. These varieties were chosen as they are

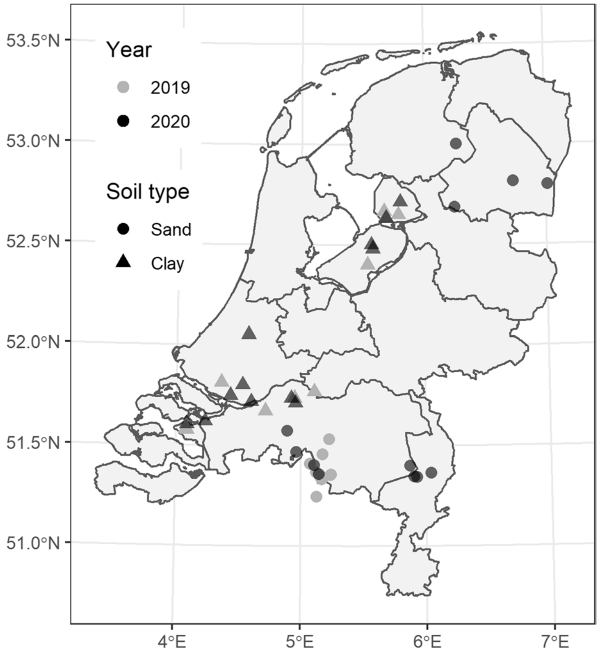

Fig. 1 Map of the Netherlands with locations of experimental sites

the most commonly cultivated cultivars on the respective soil types. In 2019, farmers were selected based on established contacts from earlier research and through contacts from the potato industry. In 2020, mostly the same farmers were selected as in 2019. In addition, participating farmers from 2019 proposed neighbouring farms to participate. From each farmer 1 to 3 fields cultivated with potatoes were selected for this study, representing a large range in soil conditions and nutrient management (Table 1).

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 to October 1), compared to 416 mm as the long-term average (Fig. 2A) (KNMI 2022a). The precipitation deficit averaged over all weather stations 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. 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.

Fields included in the study varied in soil conditions reflecting differences that are observed amongst farmers (Table 1). Soil organic matter (SOM) was, on average, 3.6% on clay 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 areas with naturally higher SOM were included in the study. Considering all

Table 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
Soil organic matter (%)	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 (mg kg^{-1})	Clay	151	32	88	185	97	49	12	170
	Sand	70	21	44	111	64	57	16	201
Plant available P (mg kg^{-1})	Clay	2.8	2.0	1.1	6.7	1.7	1.8	0.3	5.7
	Sand	4.7	4.4	1.1	15.2	5.8	4.8	0.6	15.2
Plant available K (mg kg^{-1})	Clay	132	62	66	268	102	54	55	196
	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

individual fields of both years, SOM ranged over 2 years from 2.3 to 5.9% on clay soils and from 2.0 to 9.5% on sandy soils. Soil pH was, on average, 7.5 on clay soils and 5.4 on sandy soils. Average plant available P was 2.2 mg P kg^{-1} on clay 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 clay soils than on sandy soils, with an

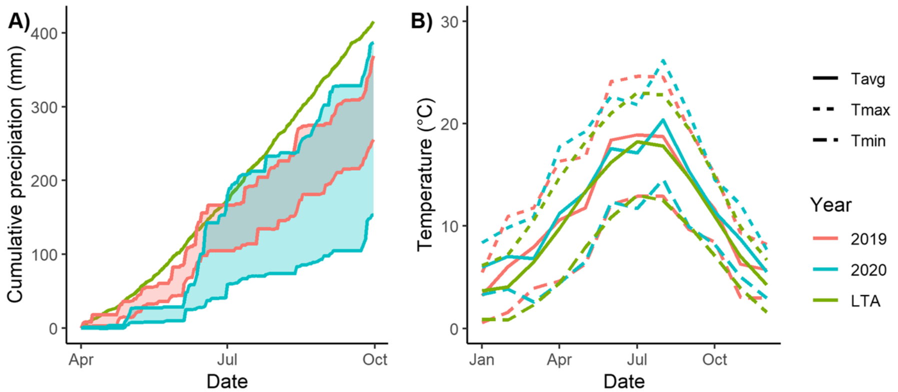

Fig. 2 Cumulative precipitation (in mm) (**A**) and average monthly mean, minimum and maximum temperature (in °C) (**B**) in the Netherlands. Plotted areas in figure A indicate regional variability in the respective years. LTA refers to the long-term average precipitation and temperatures over the past 30 years (Source: KNMI 2022a, b)

average available K of 117 mg K kg^{-1} on clay 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 amongst 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 1, see Appendix 1 Table 2 for detailed information per field). Details on the soil measurements can be found in the sub-section 'Data collection' and details on the nutrient application rates calculations can be found in the sub-section 'Data analysis'.

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 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 a 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 a broadcast application. In 2020, all 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 × 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 × 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 × 5 m. See Appendix 2 Fig. 8 for an example of the field layouts in 2019 and 2020.

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 until May 6. Irrigation was applied by most of the farmers and ranged, if applied, from 20 to 150 mm per growing season. Haulms were killed in most of the fields and haulm killing took place from August 30 until October 5. In the other fields, the crop senesced naturally or was harvested whilst 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 1 for detailed information on crop NPK-management, soil parameters, planting dates, and harvesting dates of each field.

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 °C for 3 h. 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, the final yield was measured from a 3-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.

Data Analysis

Measured yield data were used to calculate gross yield and marketable yield. Gross yield refers to the gross yield per ha of all harvested tubers after cleaning. Marketable yield was calculated as the yield per ha 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 to be 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 was 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 the average P and K tuber contents of the varieties 'Innovator' and 'Fontane' 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 an 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 a block was added to the statistical model as a 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. The 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.

Results

Yield Differences Between Treatments

The average gross yield of the control treatment was 65 t ha^{-1} in 2019 and 60 t ha^{-1} in 2020 for clay 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. 3). Furthermore, there were no significant differences in gross yield amongst 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 clay 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 to 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 3 Fig. 9).

Yield quality was affected by the treatments to a limited extent. Underwater 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 clay soils. The 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 clay soils (see figures in Appendix 3 Figs. 10, 11, 12, 13).

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). 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 response (Appendix 4 Figs. 14, 15, 16). Significant

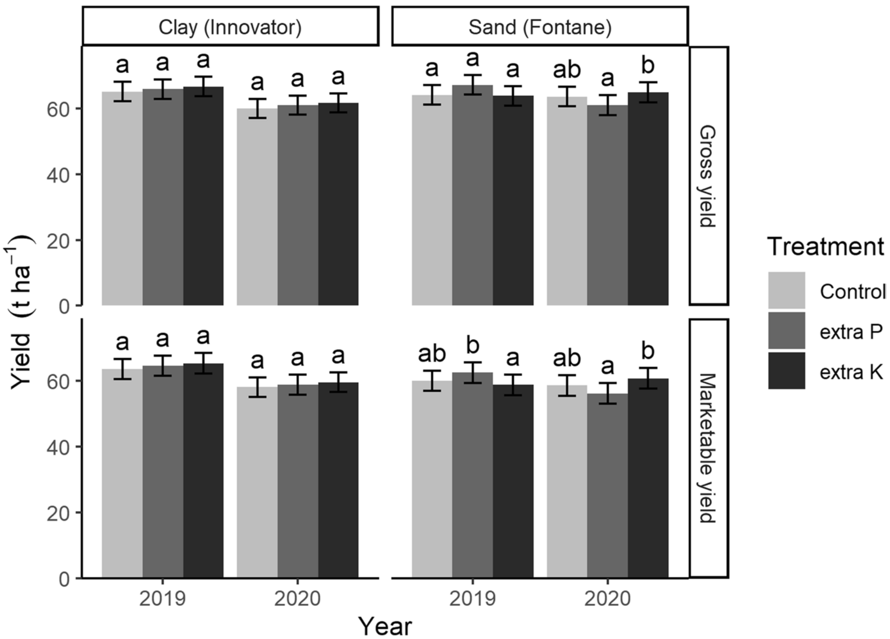

Fig. 3 Gross yield (top row) and marketable yield (bottom row) (in t ha^{-1}) of the different treatments for 2019 and 2020 for fields on sandy and clay soils. Significant differences between treatments within the year and soil type group are indicated by different letters

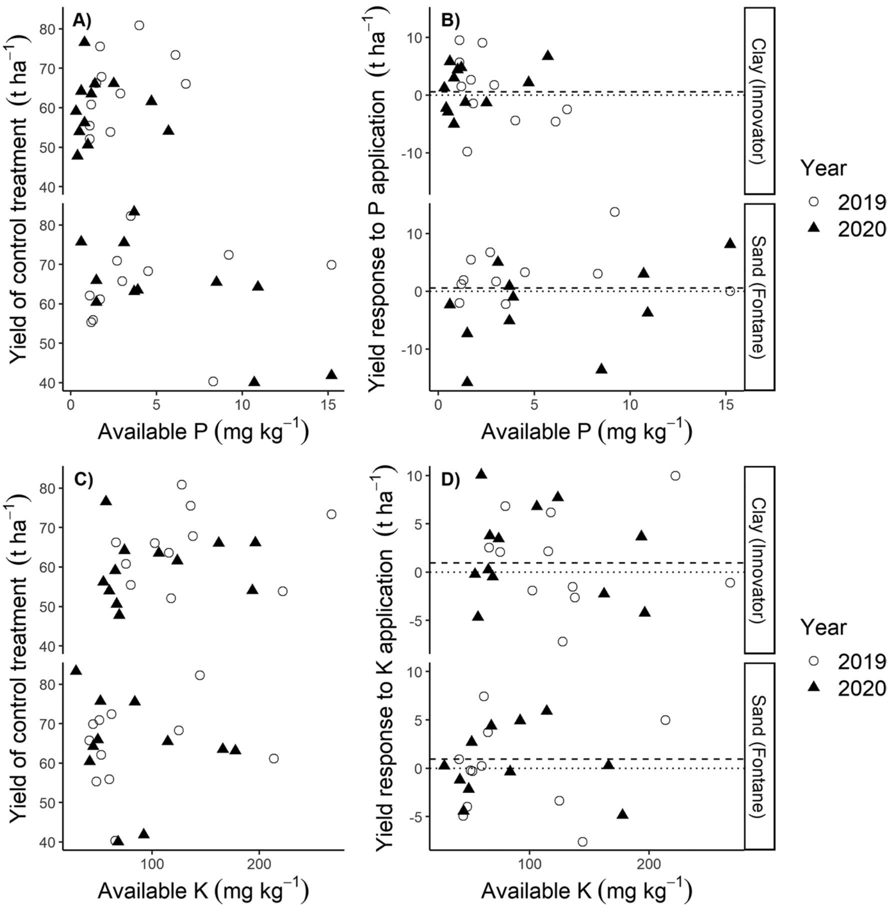

Fig. 4 Gross yield of the control treatment (in t ha^{-1}) (**A**, **C**), yield response to P application (in t ha^{-1}) (**B**), and yield response to K application (in t ha^{-1}) (**D**) against available P (in mg kg^{-1}) (**A**, **B**) or available K (**C**, **D**) separated for soil type and the 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

relationships between tuber quality parameters and soil parameters were neither observed (results not shown).

Yield and Yield Response in Relation to Fertiliser Application

No relationship was observed between the yield of the control treatment and farmer-applied P (control) on both soil types (Fig. 5A). Also, no relationship was observed between yield response from the P treatment and farmer-applied P (Fig. 5B). Similarly, on clay soils (cv. Innovator), no relationship was found between the yield of the control treatment or yield response from the K treatment and farmer-applied K (Fig. 5C and D). On sandy soils (cv. Fontane), no relationship was found between the yield of the control treatment and total K

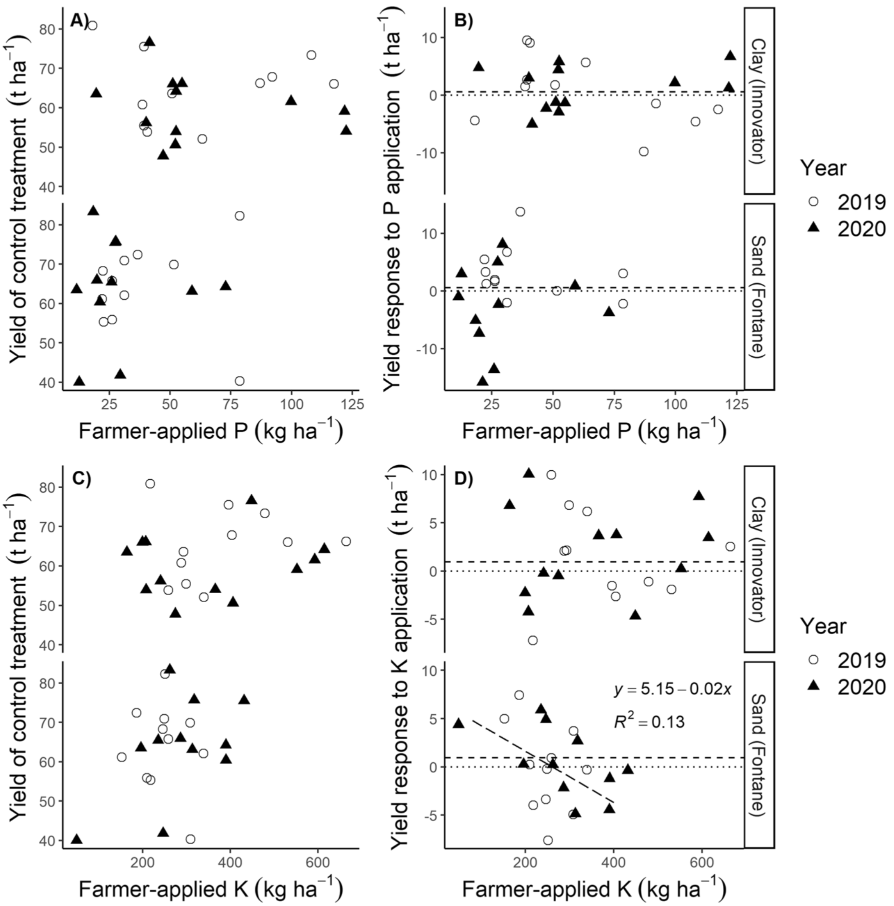

Fig. 5 Yield of the control treatment (in t ha^{-1}) (**A**, **C**), yield response to the P treatment (in t ha^{-1}) (**B**), and yield response to the K treatment (in t ha^{-1}) (**D**) against farmer-applied P (in kg ha^{-1}) (**A**, **B**) or farmer-applied K (in kg ha^{-1}) (**C**, **D**) separated 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

applied by the farmer (control) (Fig. 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. 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 levels of 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 5 Figs. 17 and 18 show the absence of relationships between yield or yield responses and farmer nitrogen application. Significant relationships between tuber quality and farmer-applied nutrients were not found (results not shown).

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

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 clay soils for both years (Fig. 6B). This means that at low yield levels of the control treatment, there was on average a positive yield response to K application. Such a negative correlation between yield response to extra K and yield of the control treatment was not observed on sandy soils (cv. Fontane) (Fig. 6B). Neither was such a correlation observed between yield response to extra P and yield of the control treatment on both soil types (Fig. 6A).

Phosphorus and Potassium Balance of the Control Treatments

The P balance (P input–P output, see "Materials and Methods" section) of the studied commercial potato fields showed that, on average, there was a positive balance of 39 kg P ha^{-1} in clay soils and 11 kg P ha^{-1} in sandy soils (Fig. 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 clay 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.

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

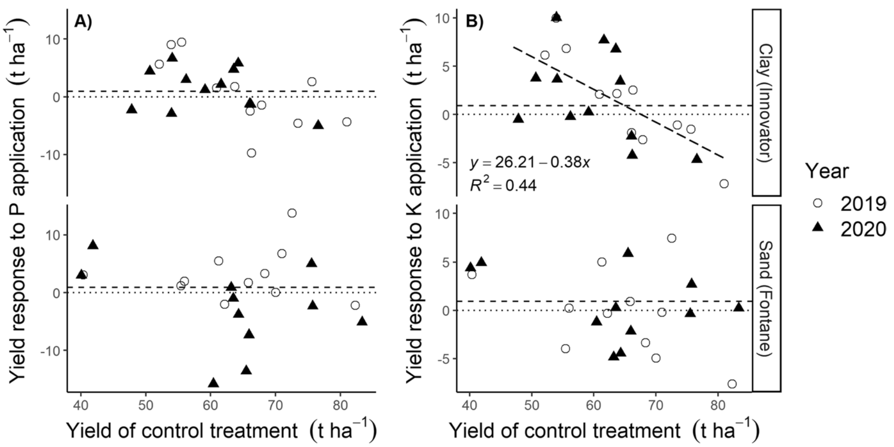

Fig. 6 Yield response to P application (in t ha^{-1}) (**A**) and yield response to K application (in t ha^{-1}) (**B**) against the yield of the control treatment (in t ha^{-1}) separated for soil type and the respective cultivar. The dotted horizontal line indicates no response of the crop to the P or K treatment. The dashed horizontal line indicates the average response to the P or K treatment

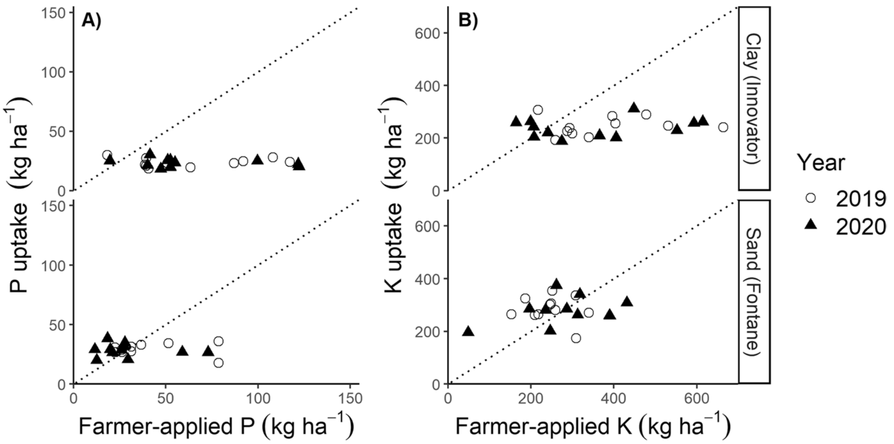

Fig. 7 P balance with P uptake (in kg ha^{-1}) against farmer-applied P (in kg ha^{-1}) (**A**) and K balance with K uptake (in kg ha^{-1}) against farmer-applied K (in kg ha^{-1}) (**B**) separated for soil type and the respective cultivars. The dotted line shows the 1:1 line representing a P or K balance of 0 kg ha^{-1}

increased P and K fertiliser application rates on potato yield compared to farmers' fertiliser application strategies (Fig. 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 the 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. 5D). On clay soils (cv. Innovator), increased K application rates led to slightly higher average potato yields at low yield levels of the control treatment (Fig. 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 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. 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 clay soils (balance: 125 kg ha^{-1}) and a small net K output on sandy soils (balance: – 17 kg K ha^{-1}) (Fig. 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. 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; Sattari et al. 2012; Łukowiak et al. 2016). Especially on clay 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 (Prummel 1969; Alblas 1984; Ehlert and Versluis 1990; Chapman et al. 1992; Panique et al. 1997) 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. 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. 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 amongst fields, but not necessarily why the yield gap is different amongst fields. Silva et al. (2017) suggested the 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 the lower utility of finite resources such 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 a maximum of 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.

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 clay 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 the 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.

Appendix 1

Crop Management Information of Each Field

Table 2 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
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

Table 2 (continued)

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
22	2019	379	307	39	299	3.6	7.4	1.1	79.9	180.2	19/04/2019	14/09/2019
23	2020	395	322	27	431	3.5	6.0	3.1	83.7	23.8	10/04/2020	11/09/2020
24	2020	310	232	30	196	3.3	5.5	11.5	72.1	16.4	25/04/2020	21/09/2020
25	2020	337	288	18	261	3.1	5.4	3.7	28.7	73.6	28/04/2020	23/09/2020
26	2020	284	215	26	235	3.9	5.4	8.5	114.4	119.8	04/04/2020	31/08/2020
27	2020	225	177	20	286	3.9	6.2	1.5	49.1	43.4	05/07/2020	16/09/2020
28	2020	123	88	11	196	4.5	5.8	3.9	165.9	201.7	25/04/2020	12/09/2020
29	2020	218	201	13	49	3.0	6.1	10.7	68.1	17.0	20/04/2020	04/09/2020
30	2020	379	308	73	389	6.8	5.1	10.9	44.8	17.5	17/04/2020	07/09/2020
31	2020	303	204	29	246	9.5	5.0	15.2	92.2	16.4	02/04/2020	07/09/2020
32	2020	360	254	59	313	5.6	5.1	3.7	177.6	101.7	16/04/2020	01/10/2020
33	2020	325	225	28	318	7.5	5.2	0.6	51.6	43.4	14/04/2020	22/09/2020
34	2020	345	304	21	390	3.7	4.8	1.5	41.6	50.4	08/04/2020	12/10/2020
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
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

Appendix 2

Example of Field Layouts

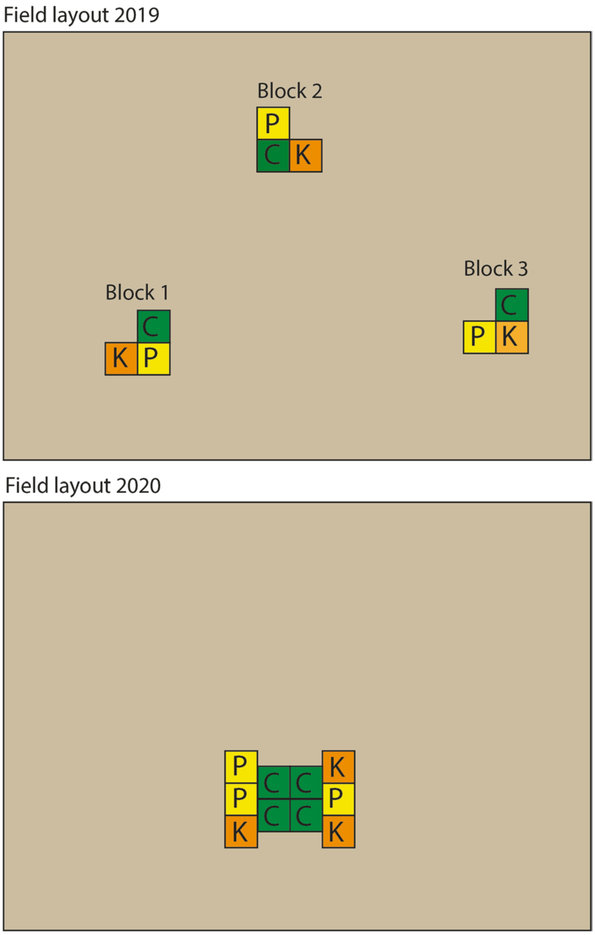

Fig. 8 Example of the experimental design in 2019 and 2020. In 2019 blocks were included in the experimental design. Figures are not at scale. Grey area represents the field. The green, yellow, and orange boxes represent the C, P, and K treatment plots, respectively

Appendix 3

Yield and Yield Quality

Gross Yield, Dry Weight

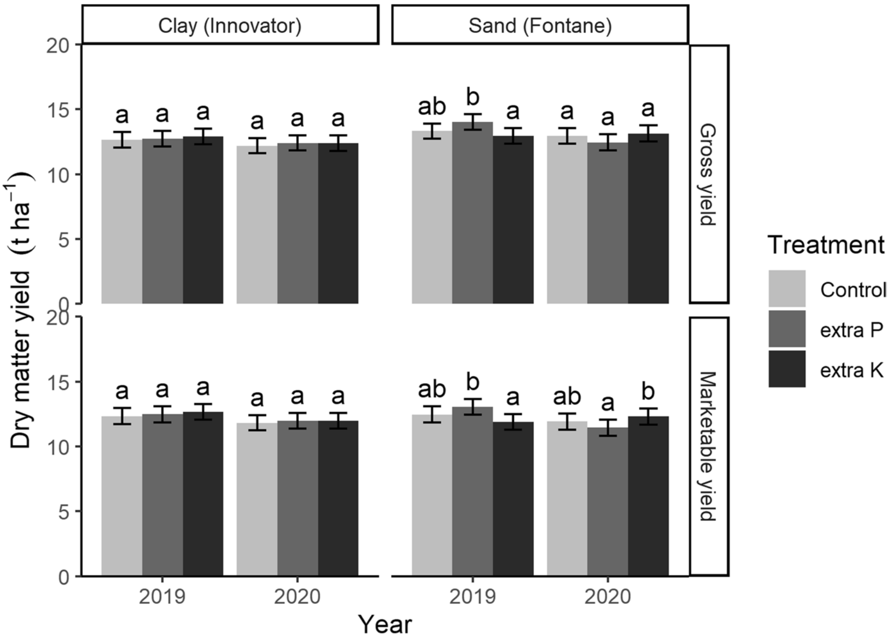

Fig. 9 Dry matter gross yield (top row) and dry matter marketable yield (bottom row) (in t ha^{-1}) of the different treatments for 2019 and 2020 for fields on sandy soils and fields on clay soils. Significant differences between treatments within the year and soil type group are indicated by different letters

Underwater Weight

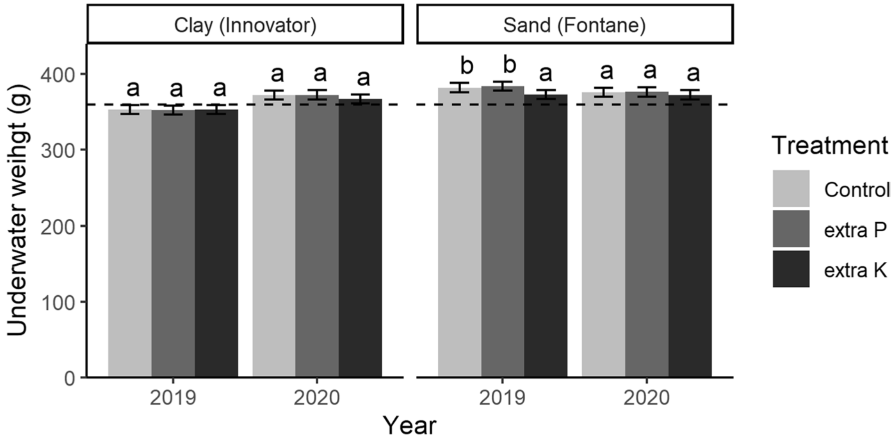

Fig. 10 Under water weight (in g) of the different treatments for 2019 and 2020 for fields on clay and sandy soils. Significant differences between treatments within the year and soil type group are indicated by different letters

Percentage Marketable Yield

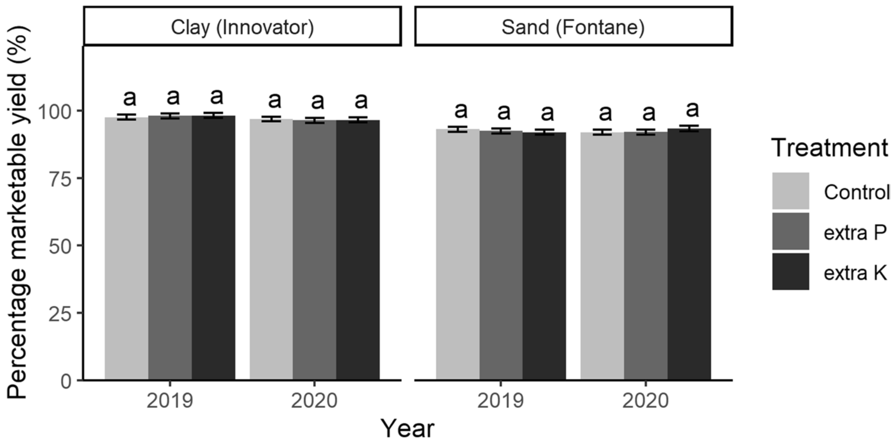

Fig. 11 Percentage marketable yield (in %) of the different treatments for 2019 and 2020 for fields on sandy soils and fields on clay soils. Significant differences between treatments within the year and soil type group are indicated by different letters

Yield of Tubers Larger than 50 mm

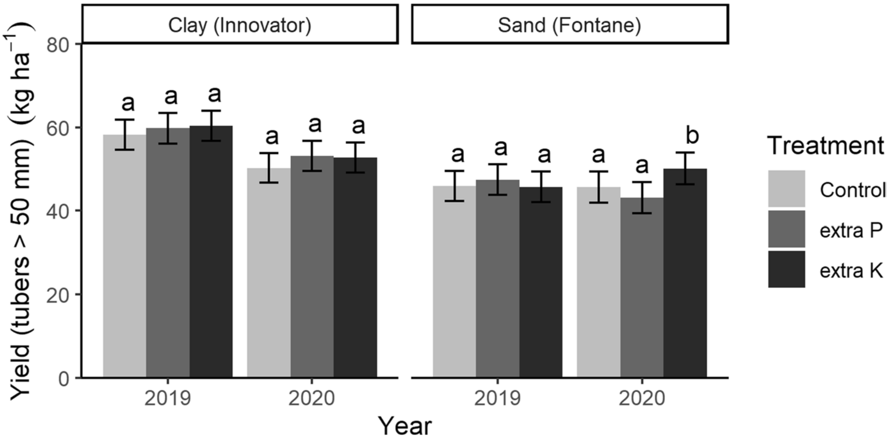

Fig. 12 Yield of tubers larger than 50 mm (in t ha^{-1}) of the different treatments for 2019 and 2020 for fields on sandy soils and fields on clay soils. Significant differences between treatments within the year and soil type group are indicated by different letters

Number of Tubers

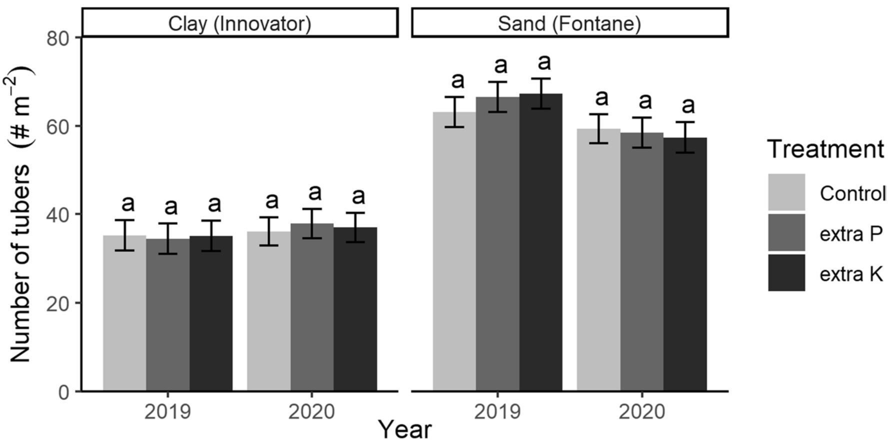

Fig. 13 Number of tubers (in the number of tubers m^{-2}) of the different treatments for 2019 and 2020 for fields on sandy soils and fields on clay soils. Significant differences between treatments within the year and soil type group are indicated by different letters

Appendix 4

Yield and Yield Response Against Soil Parameters

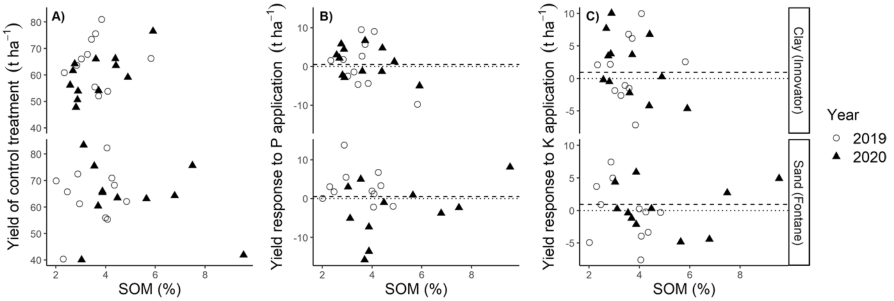

Fig. 14 Yield of the control treatment (in t ha^{-1}) (**A**), yield response to P application (in t ha^{-1}) (**B**), and yield response to K application (in t ha.$^{-1}$) (**C**) against soil organic matter (in %). The dotted horizontal line (**B**, **C**) indicates no response of the crop to the P or K treatment. The dashed horizontal line (**B**, **C**) indicates the average response to the P or K treatment

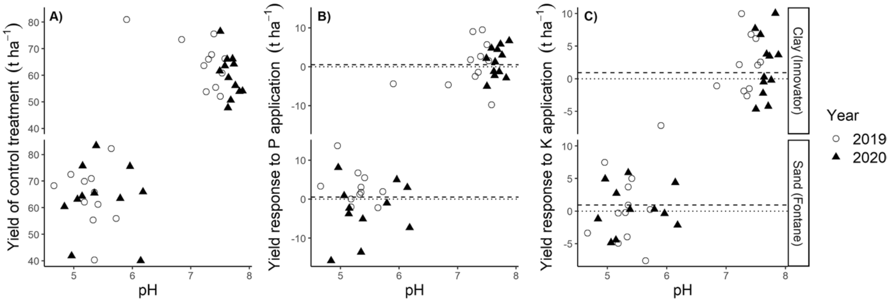

Fig. 15 Yield of the control treatment (in t ha^{-1}) (**A**), yield response to P application (in t ha^{-1}) (**B**) and yield response to K application (in t ha.$^{-1}$) (**C**) against soil pH (-). The dotted horizontal line (**B**, **C**) indicates no response of the crop to the P or K treatment. The dashed horizontal line (**B**, **C**) indicates the average response to the P or K treatment

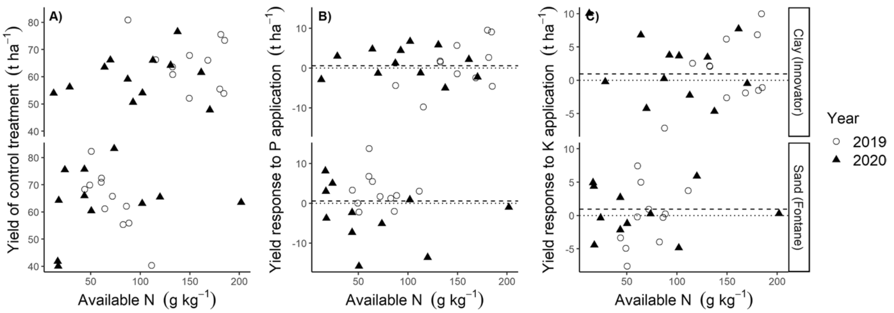

Fig. 16 Yield of the control treatment (in t ha^{-1}) (**A**), yield response to P application (in t ha^{-1}) (**B**) and yield response to K application (in t ha^{-1}) (**C**) against available N (in mg kg^{-1})**.** The dotted horizontal line (**B**, **C**) indicates no response of the crop to the P or K treatment. The dashed horizontal line (**B**, **C**) indicates the average response to the P or K treatment

Appendix 5

Yield and Yield Response Against Fertiliser Application

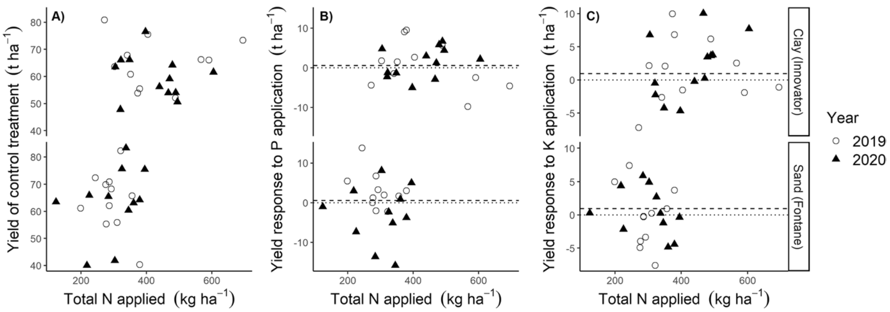

Fig. 17 Yield of the control treatment (in t ha^{-1}) (**A**), yield response to P application (in t ha^{-1}) (**B**) and yield response to K application (in t ha^{-1}) (**C**) against farmer-applied total N (in kg ha^{-1}). The dotted horizontal line (**B**, **C**) indicates no response of the crop to the P or K treatment. The dashed horizontal line (**B**, **C**) indicates the average response to the P or K treatment

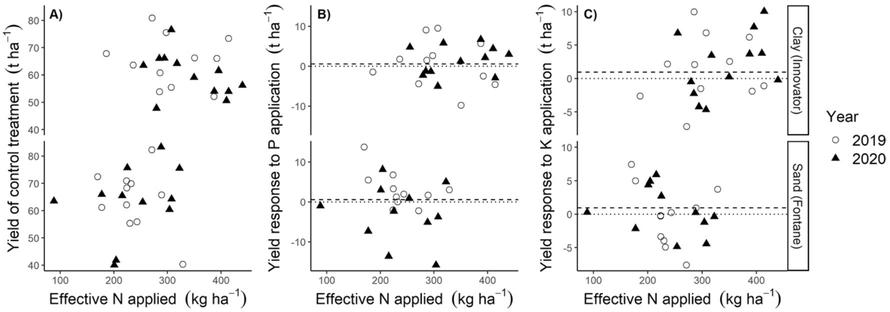

Fig. 18 Yield of the control treatment (in t ha^{-1}) (**A**), yield response to P application (in t ha^{-1}) (**B**), and yield response to K application (in t ha^{-1}) (**C**) against farmer-applied effective N (in kg ha^{-1}). The dotted horizontal line (**B**, **C**) indicates no response of the crop to the P or K treatment. The dashed horizontal line (**B**, **C**) indicates the average response to the P or K treatment

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Data Availability Data is available upon request.

Declarations

Competing Interests The authors declare no competing interests.

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