Field Crops Research 341 (2026) 110396

Contents lists available at ScienceDirect

Field Crops Research

journal homepage: www.elsevier.com/locate/fcr

Management options to reduce nitrogen surplus in potato production in the Netherlands; a modelling approach

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ARTICLE INFO

Keywords:
Nitrogen surplus
Fertilization
WOFOST
Crop model
Crop growth model
Nitrogen use efficiency
Potato

ABSTRACT

Context and Objective: Nitrogen (N) overapplication leads to N surpluses and possible environmental problems. Overuse may particularly apply to cash crops which receive relatively high amounts of inputs, such as potato. To predict the effects of N fertilization regimes on crop production and to optimize N management, crop growth models can be used. In this study, we calibrated and evaluated the crop growth model WOFOST for potato and explored various management options to reduce N surpluses without yield loss.
Methods: WOFOST was calibrated and evaluated on an experimental potato data set conducted over two growing seasons, at two locations, using five cultivars and under a combination of two irrigation regimes and three N fertilization regimes. The calibrated model was then evaluated on data from 94 farmers' fields throughout the Netherlands. Next, three different management options to reduce N surplus were investigated: 1) close the efficiency yield gap, 2) reduce the N input without yield loss or soil mining, and 3) target 90 % of the water-limited yield without soil mining.
Results and conclusions: WOFOST reproduced dry matter production and partitioning, and tuber N amounts from the experiments well. Also, WOFOST simulations matched the tuber dry matter production of farmers' fields adequately throughout the season. Baseline N surpluses estimates were on average 2.6 times larger than the proposed maximum threshold values. All management options reduced the median N surplus to values slightly above or below these thresholds. However, both soil mining and N surplus above recommended threshold values still occurred in management option 1. In the other two options, it was possible on almost all fields with a clay soil to reach N surpluses below the recommended threshold values. The N surplus was slightly above the threshold value on sandy soils.
Significance: Our work on the calibration and evaluation of WOFOST for potato under N-limited growth conditions allows using this model to assess N fertilization regimes and their effects on yield and the environment in potato production. We subsequently did such an analysis on data from Dutch farmers' fields with potato. Only closing the efficiency yield gap was insufficient to prevent both soil mining and N surpluses above threshold values for more than half of the fields. However, it was possible to adjust the N input levels to either maintain current yields or obtain 90 % of the water-limited yields without soil mining on clay soils. Although adopting these management options also substantially reduced the N surplus for potato grown on sandy soils, the N surplus was still slightly above the recommended threshold value.

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https://doi.org/10.1016/j.fcr.2026.110396
Received 24 September 2025; Received in revised form 30 January 2026; Accepted 4 February 2026
Available online 13 February 2026

1. Introduction

Nitrogen (N) is an important nutrient for crop production. In the Netherlands, the costs of N application are low compared to potential revenue loss if N is deficient (Neeteson, 1990; Ravensbergen, 2024; Van Ittersum et al., 2025). To reduce risk of yield loss due to N deficiencies, farmers sometimes apply more N than is required (Sheriff, 2005; Silva et al., 2021; Van Oort et al., 2024; Yadav et al., 1997). However, over-applied N that is not taken up by the crop can be lost to the environment which can have various negative environmental consequences (Van Grinsven et al., 2019). These consequences consist of a reduction of plant biodiversity, eutrophication of surface waters due to N runoff, ground water pollution, contribution to global warming due to N_2O emission, and local air pollution (De Vries et al., 2003).

One indicator for overapplication is N surplus which is defined as the difference between the total amount of applied N ("N input") and the amount of N in the harvestable product ("N output"). The European Union Nitrogen Expert Panel (EUNEP) suggested 80 kg N ha^{-1} as a threshold for N surplus (EU Nitrogen Experts Panel, 2015). Ros et al. (2023) specified this threshold further for the Dutch conditions. They showed that N surplus should not exceed 50 kg N ha^{-1} on sandy soils and 125 kg N ha^{-1} on clay soils to prevent the nitrate concentration in the ground water to exceed 50 mg L^{-1}.

EUNEP also recommended that the N use efficiency (NUE), defined as the ratio of the N output to N input, should be at least 0.50 kg kg^{-1} to prevent inefficient use of N. EUNEP acknowledged that N under-application also has negative consequences in the form soil mining if done so for several years, and hence they recommend that the NUE should not exceed 0.90 kg kg^{1} (EU Nitrogen Experts Panel, 2015). The EUNEP recommendations have been used in various studies to explore options to reduce the N input at the regional level, while preventing soil mining (Berghuijs et al., 2024; Chukalla et al., 2020; De Vries et al., 2003, 2021; Silva et al., 2021)

Thus, the EUNEP framework can be used to assess if N management meets environmental thresholds, and whether the N use in a particular field in a particular year is inefficient (NUE < 0.5 kg kg^{-1}), or may lead to soil mining (NUE > 0.9 kg kg^{-1}). However, the framework does not assess whether a farmer would risk yield losses if a lower N input level had been used, because the framework does not calculate a yield response to the N input. It is challenging to obtain field specific yield response curves without conducting experiments in which a crop is grown under various fertilization regimes, because crop growth, N uptake and resulting N surpluses are the result of genotypic, environmental, and management factors and the interactions between them (Hatfield and Walthall, 2015). Crop growth models that simulate N-limited crop growth are capable of considering the effect of all these factors on crop growth simultaneously (Wallach et al., 2019; Boote et al., 1996). This makes them a useful tool to explore management strategies to reduce the N surplus without yield loss or soil mining (Berghuijs et al., 2024).

A commonly used crop growth model is WOFOST (Berghuijs et al., 2024; De Wit et al., 2019; Van Diepen et al., 1989). WOFOST has been calibrated for 23 different crop species for various pedoclimatic zones in Europe (Boons-Prins et al., 1993). It has been widely used in agricultural research to, for example, enable regional yield forecasting (De Wit et al., 2010), to assess the impact of climate change (Alimagham et al., 2024). WOFOST is a key component in the European MARS crop yield forecasting system to support decision making regarding agricultural markets throughout the EU (Van der Velde et al., 2019). In the Global Yield Gap Atlas (GYGA), it is used for many countries to analyse yield gaps revealing the untapped crop production potential on existing farmland (Van Ittersum et al., 2013). WOFOST is thus widely used in both research and policy making. Recently, WOFOST was extended with a soil N module and the possibility to simulate N-limited growth, which was tested for winter wheat grown under various N fertilization regimes in the Netherlands. These extensions were then used to explore the feasibility of the EUNEP criteria for winter wheat (Berghuijs et al., 2024) and subsequently used to optimize N fertilizer regimes for winter wheat in the Netherlands using reinforcement learning (Baja et al., 2025).

Besides wheat, potato is also a prominent crop as it was grown on 17.8 million ha globally in 2024. In the Netherlands, it was grown on 0.155 million ha in 2023 (FAO, 2024) which makes it the most commonly grown crop in the country besides grass. Given the importance of this crop in Dutch arable farming, finding management options to reduce the N surplus of this crop can substantially reduce overall N loss to the environment. Besides N, a second major yield limiting factor is water (Chukalla et al., 2020; Ravensbergen et al., 2024b). Water can limit potato growth through both drought stress or, in case of a surplus, oxygen stress (Bartholomeus et al., 2008; Feddes, 1982). It has been shown that the difference between the potential and water-limited yields of potato in the Netherlands can be as large as 7 Mg DM (dry matter) ha^{-1} (Ravensbergen et al., 2024b). These strong yield reductions due to drought and oxygen stress reduce the amount of N that potato needs to take up to obtain the N-limited yields. Closing these yield gaps by making irrigation regimes more effective will also increase the amount of N that potato needs to take up to obtain the maximum yield. The recent extensions of WOFOST enable the model to take these interactions between crop production, N uptake and water uptake into account.

If WOFOST, or any other crop growth model, would be used to explore options to reduce N surpluses in potato production, it is crucial that its capability of simulating N limited growth of potato is first thoroughly tested (Berghuijs et al., 2023; Silva and Giller, 2020). WOFOST has been shown to be able to simulate the growth of modern potato cultivars under potential (Ten Den et al., 2022b) and water-limited growth conditions (Ten Den et al., 2024a), but it has not been tested under N-limited growth conditions of potato. Therefore, the first aim of this this study was to test the capability of WOFOST to simulate N-limited growth of potatoes for various cultivars and N-fertilization regimes. The second aim was to design and apply a framework that uses WOFOST to explore management options to reduce the N surplus in potato cultivation in the Netherlands without yield loss or soil mining. This framework was then applied to explore management options to reduce N surplus under both water and non-water-limiting conditions.

2. Material and methods

2.1. Model overview

PCSE WOFOST 7.2 (De Wit et al., 2019) and its original parametrization (Boons-Prins et al., 1993) were used as a starting point for a recalibration of the model for modern Dutch cultivars (Ten Den et al., 2022a;Ten Den et al., 2024a). Until this version, the model was capable of simulating potential and water-limited crop production, but not N-limited crop production. In PCSE WOFOST 8.1, the model was extended with N limited growth and with a layered soil-N module called SNOMIN (Soil Nitrogen module for Organic and MIneral Nitrogen); see Berghuijs et al. (2024) for a full description. Briefly, SNOMIN simulates the amounts of organic matter, organic carbon, and organic N in each soil layer per amendment. It also simulates the amounts of NH_4^+-N and NO_3^-N per soil layer. From these amounts of inorganic N and the crop root length it calculates the amount of available N in each time step. Additionally, the WATFDGW layered soil water module (Rappoldt et al., 2012) was translated from FORTRAN to Python to simulate the interactions between soil water dynamics and soil organic and inorganic N dynamics in the different soil layers. The amount of available N and the N demand of the crops are used to simulate the root N uptake and its distribution over the crop's organs. If the specific leaf N drops below a level at which the crop cannot reach its maximum CO_2 gross assimilation rate anymore, growth reduction occurs. In this study, we used PCSE WOFOST version 8.1 and label it "WOFOST" in the remainder of this manuscript. WOFOST is used with an extension to take into account that crop roots can compensate water shortage in some layers by taking up extra water from the whole soil profile (Huang et al., in preparation). This extension is based on the Jarvis model for root compensation; see also Supplemantary Text S1 for a full mathematical description of the extension (Jarvis, 1989, 2010). Unless specifically mentioned otherwise, all simulations in this study were run assuming both water and N-limited growth.

2.2. Model calibration and evaluation on experimental data set

2.2.1. Calibration and evaluation data set

The field experiments used to calibrate WOFOST have been described elsewhere in detail (Ten Den et al., 2024b). Briefly, the experimental data were collected at two locations in the Netherlands (Lelystad: 52.55°N 5.55°E, Vredepeel: 51.54° N 5.86° E) during two different growing seasons (2019 and 2020). Five cultivars were used. While the cultivar Fontane was grown at both locations, the other cultivars were grown in either Lelystad (clay soil; Innovator, Markies) or Vredepeel (sandy soil; Festien, Première). All cultivars are ware cultivars, except for Festien which is a starch cultivar. For each cultivar, the experimental factors were N fertilization regime and irrigation regime. The two levels of the irrigation regime were a partial irrigation regime (W1) and a full irrigation regime (W2). The three levels of N fertilization were no fertilization (N0), 30 % of the recommended N amount (75–85 kg N ha^{-1} (N1), and 130 % of the recommended N amount (265–375 kg N ha^{-1}) (N2). Up to six intermediate harvests were conducted during which measurements of leaves, stems, and tuber fresh and dry weight (kg DM ha^{-1}) were done. Additionally, leaf area index was determined and leaf N concentration was measured. During the final harvest, the tuber fresh weight, tuber dry weight, and tuber N concentration were determined.

2.2.2. Crop parameters and other model input data

WOFOST requires model input in the form of crop and cultivar parameters, soil and site data, and daily weather data. Supplementary Text S3 describes in detail how the various crop and cultivar parameters were determined and how the soil and site data were obtained.

A critical soil parameter of the SNOMIN module is A0SOM, which refers to the initial apparent age of the soil organic matter (in years). It is a measure of how fast soil organic matter is decomposed. Higher values of this parameter indicate that the first order decomposition rate of soil organic matter becomes lower (Janssen, 1984; Van der Burgt et al., 2006). Initial analyses with the original parameter value showed that the model strongly underestimated N uptake in the W2N0 treatments (Table S1). Therefore, the value of A0SOM had to be re-estimated for each field-year combination to match with the measured N uptake (Supplementary text S2).

2.2.3. Model evaluation

Measured and simulated values of the tuber dry weight, shoot and tuber dry weight, leaf area index, leaf N amount and tuber N amount were compared. For these comparisons, the mean bias error (MBE), the root mean squared error (RMSE) and r^2 were calculated for each experimental unit:

$$\mathrm{RMSE}_{\ell} = \sqrt{\frac{\sum_{i=1}^{n_t}\left(y_{\mathrm{meas},\ell,i} - y_{\mathrm{sim},\ell,i}\right)^2}{n_{\ell}}} \quad (1)$$

$$MBE_{\ell} = \frac{\sum_{i=1}^{n_{\ell}}\left(y_{\mathrm{meas},\ell,i} - y_{\mathrm{sim},\ell,i}\right)}{n_{\ell}} \quad (2)$$

$$r_{\ell}^2 = \frac{n_{\ell}\cdot\sum_{i=1}^{n_t}\left(y_{\mathrm{obs},\ell,i}\cdot y_{\mathrm{sim},\ell,i}\right) - \sum_{i=1}^{n_t} y_{\mathrm{obs},\ell,i}\cdot\sum_{i=1}^{n_t} y_{\mathrm{sim},\ell,i}}{\sqrt{\left(\sum_{i=1}^{n_t} y_{\mathrm{obs},\ell,i}^2 - \sum_{i=1}^{n_t} y_{\mathrm{obs},\ell,i}^2\right)\cdot\left(\sum_{i=1}^{n_t} y_{\mathrm{sim},\ell,i}^2 - \sum_{i=1}^{n_t} y_{\mathrm{sim},\ell,i}^2\right)^2}} \quad (3)$$

where n_{ℓ} is the number of observations in treatment ℓ, $y_{\mathrm{meas},\ell,\mathrm{i}}$ is the measured value with index i in treatment ℓ, $y_{\mathrm{sim},\ell,\mathrm{i}}$ is the simulated value, RMSE quantifies the overall difference between the mean and the observations. MBE quantifies the systematic bias; it is negative if the models overestimates the observations and positive in case of underestimation, r^2 is the fraction of the variation in observations that can be explained by the model.

2.3. Model evaluation on farmers' fields data set

2.3.1. Farmers' fields data set

The performance of WOFOST was evaluated with data collected from 94 farmers' fields throughout the Netherlands on which potato was grown. This data set is called the "farmers' fields data set" in the remainder of this article. A detailed description of the farmers' fields data set can be found elsewhere (Ravensbergen et al., 2024b). Here, we only describe the measurements that were used in the present study. In summary, measurements were conducted on 94 fields during the growing seasons of 2020 and 2021. Potatoes were cultivated on either clay (cultivar Innovator) or sandy soils (cultivar Fontane). On these fields, synthetic fertilizers, organic fertilizers, composts and other substrates were applied and most fields were irrigated. In both years, tuber dry weights and the N concentration of the tubers were measured at harvest. Additionally, measurements of tuber dry weight and the sum of shoot and tuber dry weight were taken at various dates within the growing season of 2021.

2.3.2. Model input data and simulations of the farmers' data set

Supplementary Text S4 describes in detail how the model input data were obtained to simulate crop growth in farmers' fields and how the simulations were run. The simulations were run assuming water- and-N limited production. Unlike the experimental dataset, the farmers' fields dataset does not include control treatments in which no fertilizer was applied. Therefore, it was not possible to determine site specific values of A0SOM. In all simulations, we therefore set parameter A0SOM equal to 10 yr which is in between the values that were estimated for Lelystad and Vredepeel.

2.4. Analysis of management options

The aim of the analysis was to explore strategies to reduce the N surplus for each of the 94 farmers' fields relative to the current situation (baseline). N surplus is defined as:

$$N_s = N_{\mathrm{i,tot}} - N_{\mathrm{o}} \quad (4)$$

where N_{o} is the total amount of N in the harvested tubers, which equals the dry matter tuber yield times the N concentration at harvest, obtained from the farmers' fields data set. $N_{\mathrm{i,tot}}$ is the *total* N input, defined as the amount of N that is added to a field through the seed tubers, N fertilization, or by atmospheric N deposition. It is calculated as:

$$N_{\mathrm{i,tot}} = N_{\mathrm{seed}} + N_{\mathrm{dep}} + \sum_{k=1} N_{\mathrm{ap},k} \quad (5)$$

where N_{seed} is the amount of N in the seed potatoes, which is assumed to be 3 kg N ha^{-1} (Silva et al., 2021). N_{dep} is the amount of N that is deposited throughout the growing season. Site specific values of N_{dep} were obtained from the Dutch National Institute of Public Health and the Environment (RIVM, 2023); see Supplementary Material Text S2.4 for more detail. $N_{\mathrm{ap},k}$ is the total amount of applied N during fertilization event *k*.

The amount of N that ends in the tubers is determined by the amount of N that is provided by the soil and the *effective N input*. The latter is defined as the amount of N in the total N input that becomes available in the year of application for crop uptake. The effective N input can be smaller than the total N input, because some N is fixed in the organic matter of amendments. This N will not be readily available in the year of application, although it might be released from the organic matter amendments in later years (Hijbeek et al., 2018). The effective N input $N_{i,eff}$ for each field was estimated as in (Silva et al., 2021):

$$N_{i,eff} = N_{seed} + N_{dep} + \sum_{k=1} \left(f_{rec,k} \bullet N_{ap,k} \right) \tag{6}$$

where $f_{rec,k}$ is the fertilizer N replacement fraction (Hijbeek et al., 2018; Silva et al., 2021) of the type of fertilizer that was applied during fertilization event *k*. It can be defined as the fraction of N in an amendment that becomes available during the growing season (kg N kg^{-1} N). It was assumed that $f_{rec} = 1.0$ for any synthetic fertilizer. For each type of organic fertilizer or manure used in this study, specific values of f_{rec} were obtained from the Netherlands Enterprise Agency RVO (RVO) (Supplementary Table S8).

Three management options were investigated to assess options to reduce N surplus (Fig. 1; see Supplementary Text S4 for detailed explanation of how the options were modelled):

1) Close the efficiency yield gap (i.e., the difference between the simulated water-and-nitrogen-limited yield and the measured actual yield (Silva et al., 2017; Berghuijs et al., 2024)). This option explores to what extent the N surplus can be lowered through increasing the N uptake due to increased yields by adjusting crop management in other aspects than irrigation or N fertilization.

2) Reduce the effective N input until a further reduction would lead to yield loss or soil mining, which was assumed to occur when NUE> 0.9 kg kg^{-1}. This option explores to what extent the N surplus can be lowered by adjusting the N input without yield loss or soil mining.

3) Adjust the effective N input to a value at which 90 % of the water-and-nitrogen-limited yield can be obtained without soil mining. This option explores the lowering of N surplus through a combination of optimizing the N uptake by increased yields and adjusting the effective N input to obtain these yields without soil mining.

For each individual field in a specific year, the N surplus was calculated from the observations (baseline) and for the three options. Such analysis (Fig. 1) for an individual field consisted of a number of steps: 1) WOFOST was run for a range of fertilizer application amounts to simulate tuber dry weight (yield) and the amount of N in the tubers (N output) at the end of the growing season; 2) for each simulated fertilizer application amount, total and effective N inputs were estimated; 3) an empirical model was fitted to the paired values of the effective N input and N output (i.e. tuber dry weight at harvest) and of the effective N input and the yield to obtain effective N-input response curves for these variables, and 4) the yield, total and effective N input, and N output for all management options were calculated and N surplus determined. The details of these calculations are described in Supplementary Text S4. For each management option, we checked for each field whether the N surplus exceeded the threshold values (i.e. 50 kg N ha^{-1} for sandy soils, 125 kg N ha^{-1} for clay soils) proposed by Ros et al. (2023)

2.5. Analysis of management options under optimized irrigation

To explore the effect of drought and oxygen stress on the nitrogen management scenarios, a similar analysis was done as described above, assuming an optimal irrigation regime. Hence, no drought or oxygen stress occurred. The ideal irrigation regime was simulated by switching off oxygen stress (crop parameter IOX was set to 0) and applying irrigation at any day between the sowing and harvest date at which the amount of water in the soil layer would otherwise drop below field

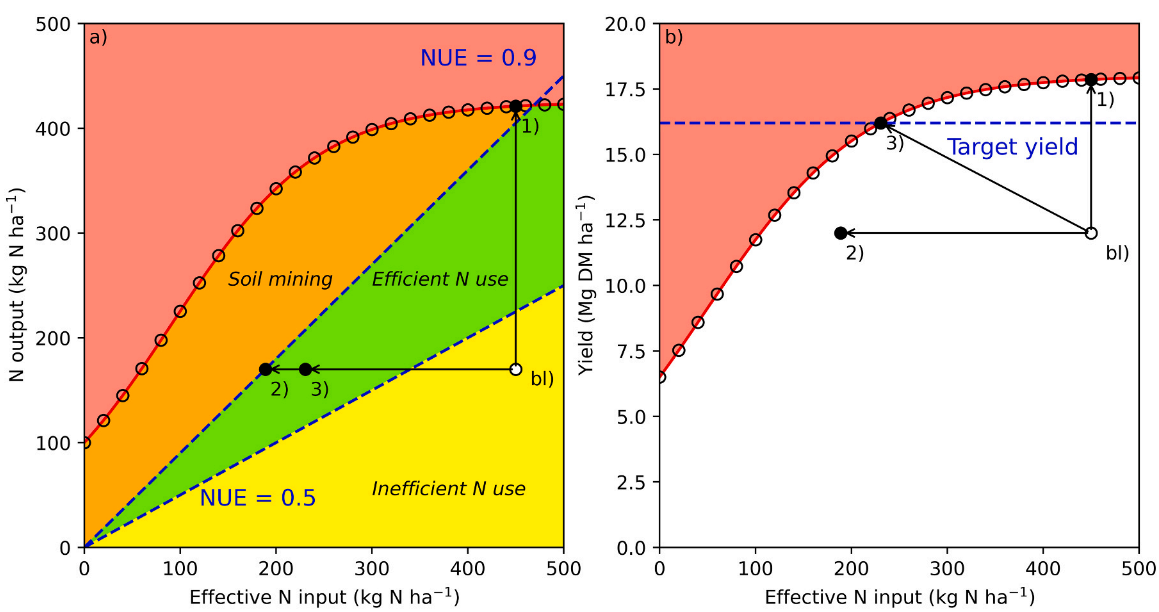

Fig. 1. Schematic overview of methodology employed for the analysis of management options. For each field, N output (a) and the yield (b) were simulated with WOFOST for different effective N input values (open circles). Subsequently, per field a logistic growth curve (red line) was fitted to the simulated N response. In the analysis of the management options, N output and yield are calculated for different management options, indicated with numbered dots. The number near the dots indicates the management option. Option 1: the efficiency yield gap is closed, i.e., the yield is increased to the level attainable with the effective N input. Option 2: N input is reduced until further reduction would result in either soil mining (i.e. when NUE > 0.9) or yield loss; Option 3: management aspects other than N or irrigation management are optimized such that 90 % of the water limited yield is achieved and N input is adjusted to attain this yield without soil mining. The open dot represents the baseline (bl; the measured effective N input, N output, and yield. The yellow area represents combinations of effective N input and N output with inefficient N use (i.e. NUE < 0.5). The green area represents combinations of effective N input and N output with efficient N use (0.5 ≤ NUE ≤ 0.9). The orange area represents combinations of effective N input and N output in with a risk of soil mining (NUE > 0.9). The red area represents combinations of effective N input and either N output or yield in which the N output or the yield are higher than the simulated values for a given effective N input.

capacity. At each irrigation event, the effective amount of applied water equalled the amount required to bring the amount of soil water back to field capacity.

2.6. Analysis of management option at the original initial age of soil organic matter

To explore the effect of adjusting parameter A0SOM from its default value of 24 y to 10 y, the three management options were investigated again. However, this time the default value of the initial age of soil organic matter was assumed in the simulations (i.e. A0SOM = 24 y).

3. Results

3.1. Model evaluation on experimental data set

Table 1 shows the values of crop parameters that were either newly introduced with the release of WOFOST 8.1 or were estimated in this study.

3.1.1. Preliminary simulations and the effect of re-estimating A0SOM

Nitrogen uptake in the tubers in the W2N0 treatment was strongly underestimated when A0SOM was set at its default value of 24 y (MBE = 81 kg N ha^{-1}) (Supplementary Text S2 section 2.1; Table S1). After re-estimating the initial age of soil organic matter for each year-location combination (Table S1), the model performed much better in reproducing the amount of N in the tubers in the unfertilized treatments (MBE = 2 kg N ha^{-1}). The re-estimated value of A0SOM was used as input in the remaining simulations (Fig. 2 & Fig. 3 indicate results for Fontane on sandy soils and Innovator on clay soils, Fig S1-S4 indicate results for the other combinations of variety and soil type).

3.1.2. Preliminary simulations and the effect of re-estimating RNUPTAKEMAX

Preliminary results also showed that the amount of N at the end of the growing season in the high N-fertilization treatment with full irrigation (W2N2) was strongly overestimated (MBE = −58 kg N ha^{-1}) in most cultivars (Table S2), if RNUPTAKEMAX (maximum daily root N uptake rate; Table 1) would have been kept at its default value of 7.2 kg N ha^{-1} d^{-1}. Re-estimating RNUPTAKEMAX resulted in a value of 2.9 kg N ha^{-1} d^{-1} resulted and using this value to simulate the fields resulted in a much lower bias (MBE = 4.2 kg N ha^{-1}). The re-estimated value of RNUPTAKEMAX was used as input in the remaining simulations.

3.1.3. WOFOST performance in simulating the experimental data set

Figs. 2 and 3 and Figs S1 - S4 show time plots of measured and simulated values of dry matter (total, leaves, tuber), N (in leaves and tubers), and leaf area index (LAI). Over the whole growing season, WOFOST performed well in simulating the tuber dry weight in all treatments (Table S3) with both a high accuracy (MBE = −0.84) and precision (RMSE = 1.8 Mg ha^{-1}). It was capable of explaining most of the variation (r^2=0.92). However, WOFOST tended to overestimate the tuber dry matter at harvest. The degree of overestimation was stronger for the cultivars Premiere and Markies (MBE = 3.8 Mg DM ha^{-1}) than for the other cultivars (MBE = 2.4 Mg ha^{-1}). WOFOST performed similarly

Table 1
Crop parameters for potato adjusted in the calibrated version of WOFOST.

Parameter name	Definition	Value	Unit	Source
AMAX_REF	Maximum gross CO_2 assimilation rate under reference conditions and very high specific leaf N	33.0	kg CO_2 ha^{-1} leaf h^{-1}	Ten Den et al. (2022a)[1]
AMAX_SLP	Slope of maximum gross CO_2 assimilation rate and specific leaf N	3.24	kg CO_2 kg^{-1} N h^{-1}	Peng et al. (1995)
DVS_N_TRANSL	Development stage above which N translocation to the tubers occurs	1.0	-	Assumed
KN	Extinction coefficient leaf N with canopy depth	0.4	m^2 m^{-2}	Berghuijs et al. (2024)
NFIX_FR	Fraction of crop N uptake due to N_2 fixation	0	kg N kg^{-1} DM	Assumed[2]
NMAXLV_TB	Table function for maximum leaf N concentration as a function of development stage	$\begin{pmatrix} 0.0 & 0.06 \\ 0.4 & 0.05 \\ 0.7 & 0.045 \\ 1.0 & 0.045 \\ 2.0 & 0.04 \end{pmatrix}$	kg N kg^{-1} DM	Wolf (2012)
NMAXSO	Maximum N concentration in tubers	0.023	kg N kg^{-1} DM	(Van Evert et al., 2012)
NMAXST_FR	Ratio maximum N concentrations in stems and leaves	0.5	kg N kg^{-1} DM	Wolf (2012)
NMAXRT_FR	Ratio maximum N concentrations in stems and roots	0.5	kg N kg^{-1} DM	Wolf (2012)
NRESIDLV	Residual N fraction in leaves	0.02	kg N kg^{-1} DM	Wolf (2012)
NSLLVTB	Table function for enhancement factor leaf ageing due to N stress	$\begin{pmatrix} 0.0 & 1.0 \\ 1.1 & 1.0 \\ 1.5 & 1.5 \\ 2.0 & 1.5 \end{pmatrix}$	-	(Bouman et al., 2001)
NRESIDRT	Residual N fraction in roots	0.01	kg N kg^{-1} DM	(Wolf, 2012)
RDMCR	Maximum root length	60	cm	Boons-Prins et al. (1993)
RDRSTB	Table function for relative stem mortality as a function of development stage	$\begin{pmatrix} 0 & 0 \\ 2.0 & 0 \end{pmatrix}$	d^{-1}	Assumed[3]
REALLOC_DVS	Development stage above which reallocation starts	1.5	-	Estimated
REALLOC_LEAF_FRACTION	Fraction of leaf dry matter at development stage REALLOC_DVS that becomes available for reallocation	0	-	Estimated
REALLOC_STEM_FRACTION	Fraction of stem dry matter at development stage REALLOC_DVS that becomes available for reallocation	0.460	-	Estimated
REALLOC_STEM_RATE	Relative rate of reallocatable stem dry matter to the tubers	0.228	d^{-1}	Estimated
RNUPTAKEMAX	Maximum daily N uptake	2.9	kg N ha^{-1} d^{-1}	Estimated
RGRLAI_MIN	Maximum relative increase in LAI under high N stress during juvenile stage	0.004		Berghuijs et al. (2024)
TCNT	Time coefficient of N translocation to tubers	10	d	Wolf (2012)

[1] We assumed it equals their estimated value of AMAX at early development stages, estimated by Ten Den et al. (2022a).
[2] Potato is not a legume and does not have root nodules to fix N_2 from the atmosphere.
[3] We assumed that the observed decrease in stem dry matter is due to reallocation rather than stem mortality

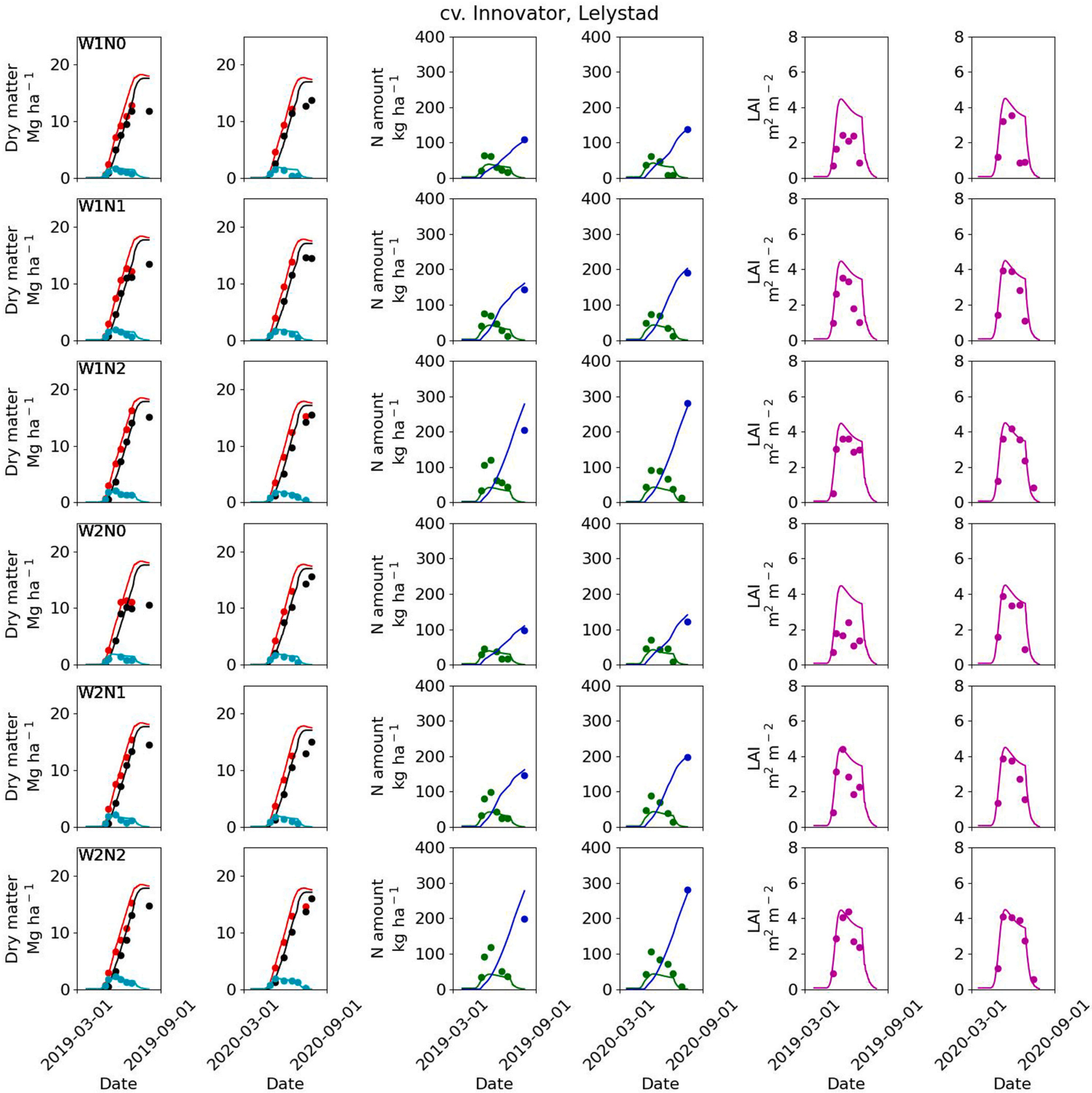

Fig. 2. Average measured (dots) and simulated crop variables (curves) for all treatments for Innovator grown in Lelystad. The crop variables consist of tuber dry weight (black), sum of shoot and tuber dry weights (red), leaf dry weight (cyan), leaf N amount (green), tuber N amounts (blue), and leaf area index (magenta).

well in reproducing the observed dry matter of the combined tubers and shoots (Table S4).

Overall, WOFOST reproduced the N uptake by the tubers with a small bias (MBE = 1.5 kg N ha^{-1}) (Table S5). However, the accuracy strongly varied between the different cultivars (MBE between −35 kg N ha^{-1} and 36 kg N ha^{-1}). WOFOST underestimated the amount of N in the leaves (MBE = 14 kg N ha^{-1}) and the degree of this underestimation increased with increased applied N (Table S6). The leaf area index was reproduced with a RMSE of 1.3 m^2 m^{-2} and a MBE of −1.1 m^2 m^{-2}. The degree of overestimation was stronger for low N fertilization levels than high fertilization levels (Table S7).

3.2. *Model evaluation on farmers' fields data set*

Fig. 4 compares measured and simulated tuber dry matter for each combination of cultivar and growing season. The model reproduced the tuber dry weight with r^2 = 0.85, MBE = -2.13 Mg ha^{-1}, and RMSE = 0.15 Mg ha^{-1} for the farmers' fields data set. It performed better in simulating the observations for 2021 than for 2020 (Fig. 4, Figs S5-S8) In 14 out of 93 fields, the simulated final tuber dry weights were lower than the measured values. In only three of these cases, the final simulated tuber dry weight was lower than 80 % of the measured tuber dry weight. In the majority of cases, 85 %, simulated yields exceeded observed yields as may be expected because the does not capture growth reducing factors, i.e., due to weeds, pests and diseases.

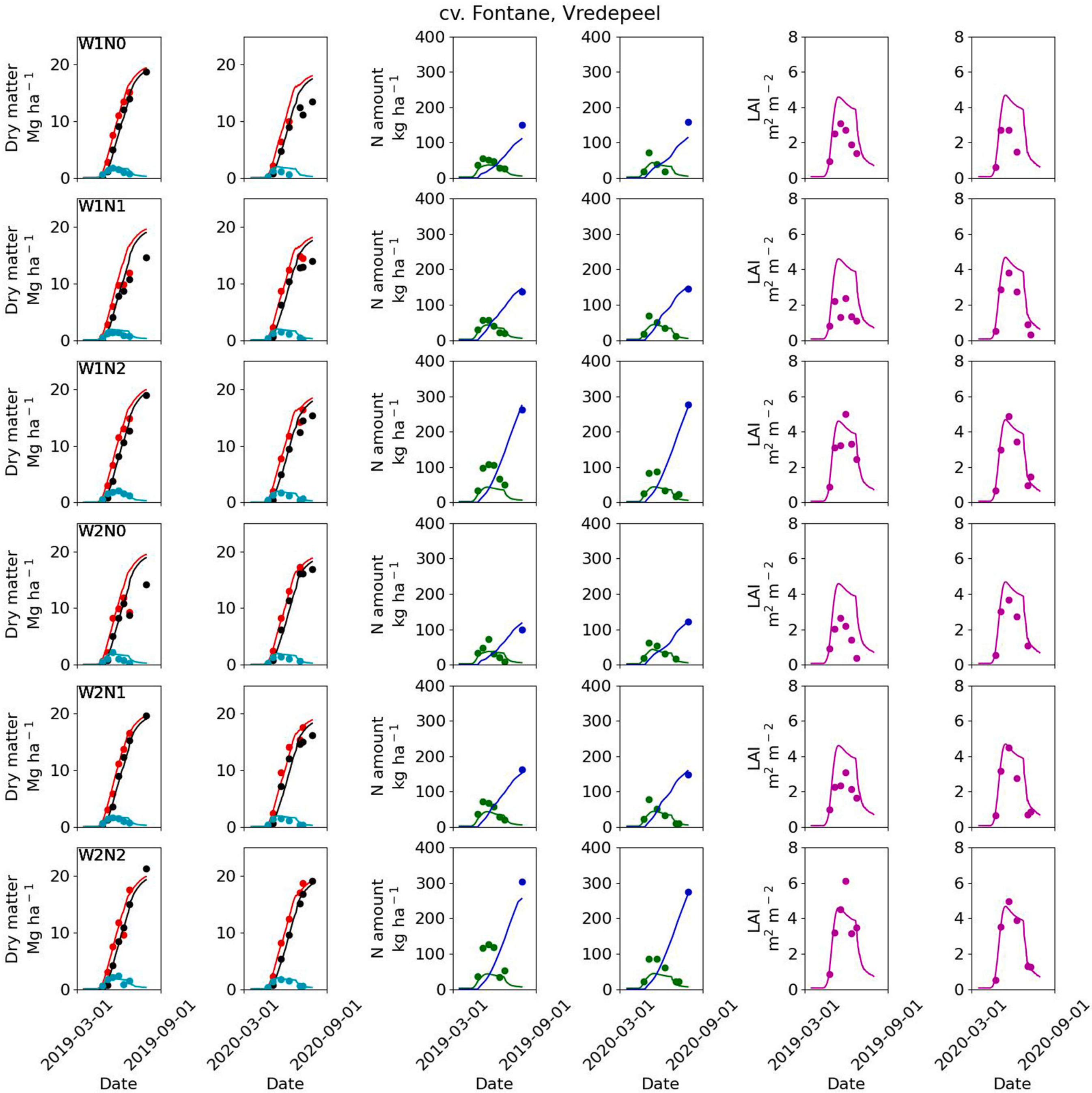

Fig. 3. Average measured (dots) and simulated (curves) crop variables for all treatments for Fontane grown in Vredepeel. The crop variables consist of tuber dry weight (black), sum of shoot and tuber dry weights (red), leaf dry weight (cyan), leaf N amount (green), tuber N amounts (blue), and leaf area index (magenta).

3.3. *Analysis of management options*

3.3.1. *Default irrigation regime*

Figs. 5–6 compare the yields, effective N inputs, N outputs, N surpluses, yield increase relative to the baseline and the effective N input reduction between the baseline and the examined management options. The N surplus calculated from the observations (baseline; bl) varied from −26 kg N ha^{-1} to 347 kg N ha^{-1} for Fontane on sandy soil and from 60 kg N ha^{-1} to 752 kg N ha^{-1} for Innovator on clay soil. The median N surpluses were 137 kg N ha^{-1} for Fontane and 212 kg N ha^{-1} for Innovator. For Fontane this is 87 kg N ha^{-1} above the proposed threshold for sandy soils to stay below critical nitrate concentration levels in the groundwater (Ros et al., 2023) and for Innovator also 87 kg N h^{-1} above the threshold for clay soils. The median yields that were obtained for Fontane and Innovator were, respectively, 13.3 Mg ha^{-1} and 11.8 Mg ha^{-1}.

For management option 1, the efficiency yield gap was closed without changing the baseline N fertilization regimes. This resulted in considerably higher median yields for both Fontane (16.9 Mg ha^{-1}) and Innovator (16.2 Mg ha^{-1}) than in the baseline. The median N surpluses decreased for both cultivars; for Fontane to 32 kg N ha^{-1} and for Innovator to 68 kg N ha^{-1}. In both cases, these values are below the threshold proposed by Ros et al. (2023) (50 kg N ha^{-1} for sandy soils, 125 kg N ha^{-1} on clay soils). However, while there were only two fields (both with Fontane) with negative N surpluses in the baseline, there were 31 fields with negative N surpluses in management option 1. These negative

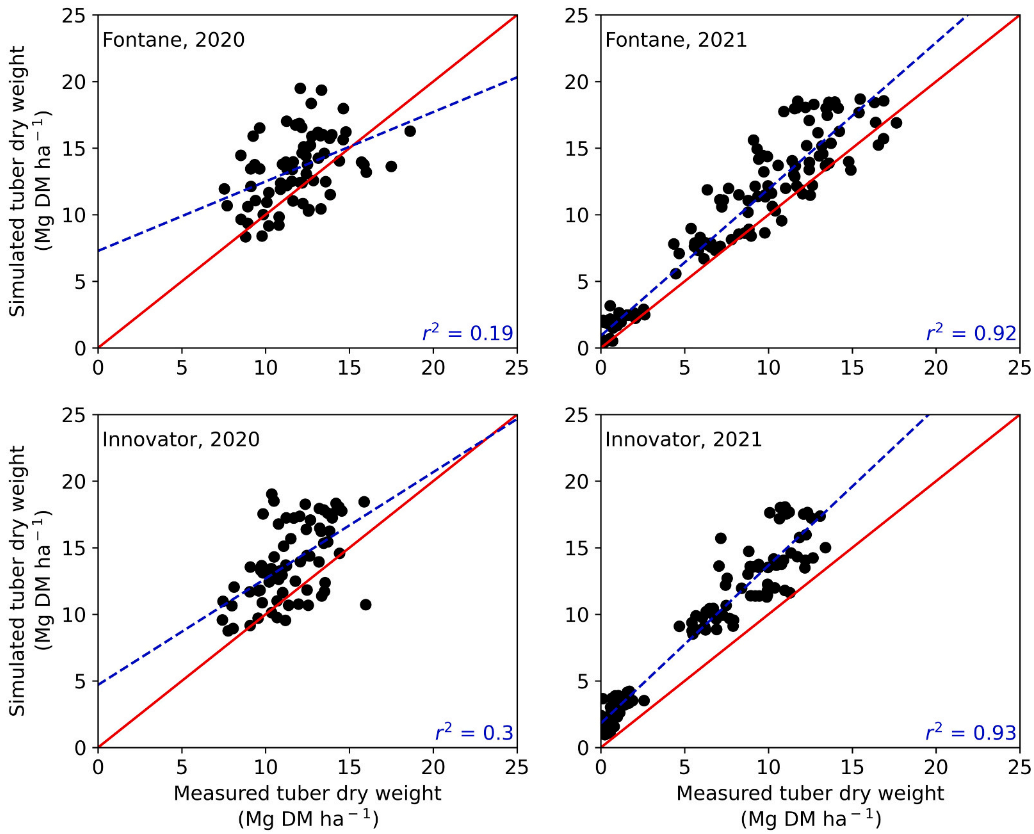

Fig. 4. Simulated versus measured tuber dry weight grouped per growing season and cultivar. The red line represents the 1:1 line. The blue dashed line is a linear regression model fitted to the measured and simulated values (with r^2 values in the lower right corner).

surpluses were as low as −130 kg N ha^{-1} for Fontane and −101 kg N ha^{-1} for Innovator. Moreover, there was also a considerable number of fields (14 for Innovator, 18 for Fontane) of which the N surpluses were still above the thresholds from Ros et al. (2023). The highest N surplus for Fontane was 212 kg N ha^{-1} for Fontane and 551 kg N ha^{-1} for Innovator.

For management option 2, the effective N input was reduced until a level at which a further reduction would result in either yield loss or soil mining. For this scenario, the median N input level was reduced to 189 kg N ha^{-1} for Fontane and 203 kg N ha^{-1} for Innovator. For Fontane, N input ranged from 18 to 247 kg N ha^{-1} and for Innovator from 132 to 263 kg N ha^{-1}. The N input reductions relative to the baseline for these cultivars were respectively 71 kg N ha $^{-1}$ and 138 kg N ha^{-1}. However, for cultivar Fontane, N input increased in seven fields. On each of these seven fields, there was not enough N applied on these fields to prevent soil mining in the baseline. There were no negative N surpluses in this management option and the median N surplus of Innovator (47 kg N ha^{-1}) was below the recommended threshold from Ros et al. (2023) for clay soil. However, this was not the case for the N surplus of Fontane (65 kg N ha^{-1}) that exceeded the threshold value for sand soils.

For management option 3, the target yield was 90 %, and N input was adjusted in such a way that both this yield can be obtained and that there was no soil mining. The median yields increased substantially to 15.4 Mg ha^{-1} for Fontane and 14.6 Mg ha^{-1} for Innovator. For almost all fields, management option 3 had the same effective N input and N output as management option 2. Only for five fields (all Fontane), there were small differences between the effective N inputs and N outputs in management options 2 and 3. Because of this, the median N surplus was the same as for management option 2 for both cultivars. These results suggest that the effective N input that is required to obtain a NUE of 0.9 (requirement for both management options 2 and 3) is almost always also enough to obtain 90 % of the water-limited yield (management option 3).

3.3.2. Optimal irrigation regime

All management options were explored again for irrigation regimes that were optimized to eliminate water and drought stress. For all investigated management options, the median yields were equal (management option 2; it assumes no yield loss, but also no yield increase) or higher (management options 1 and 3) than without optimized irrigation regimes (Figs. 5–6).

For Fontane, the yields in management option 1 varied between 16.4 and 19.8 Mg ha^{-1} and for Innovator between 16.3 and 19.01 Mg ha^{-1}. These yield ranges are a considerably smaller than the ranges for the same management options under the farmers' reported irrigation regime. Optimized irrigation resulted in higher median yields (Fontane: 18.6 Mg ha^{-1}, Innovator: 17.7 Mg ha^{-1}). Similarly, management option 3 resulted in higher median yields (Fontane: 16.7 Mg ha^{-1}, Innovator: 16.0 Mg ha^{-1}) and narrower yield ranges (Fontane: 14.9 – 18.0 Mg ha^{-1}, Innovator: 14.6 – 17.1 Mg ha^{-1}) than under the farmers' reported irrigation regime.

Just like with the farmers' irrigation regime, management options 2 and 3 with optimized irrigation resulted in almost the same effective N input and N output. For Fontane, the median N input under optimized irrigation for both management options 2 and 3 slightly increased from 189 to 185 kg N ha^{-1}. The median N output slightly decreased from xx to 167 kg N ha^{-1}, probably because the simulated optimized irrigation regime resulted in slightly more N leaching. As a result, management options 1, 2, and 3 resulted in median N surpluses of 45 kg N ha^{-1} in management option 1 and 62 kg N ha^{-1} in management options 2 and 3. For Innovator, both the effective N input and N output and, therefore, N surplus remained the same as under the farmers' irrigation regime for all management options. However, unlike management options 1, there were no negative N surpluses for these management options.

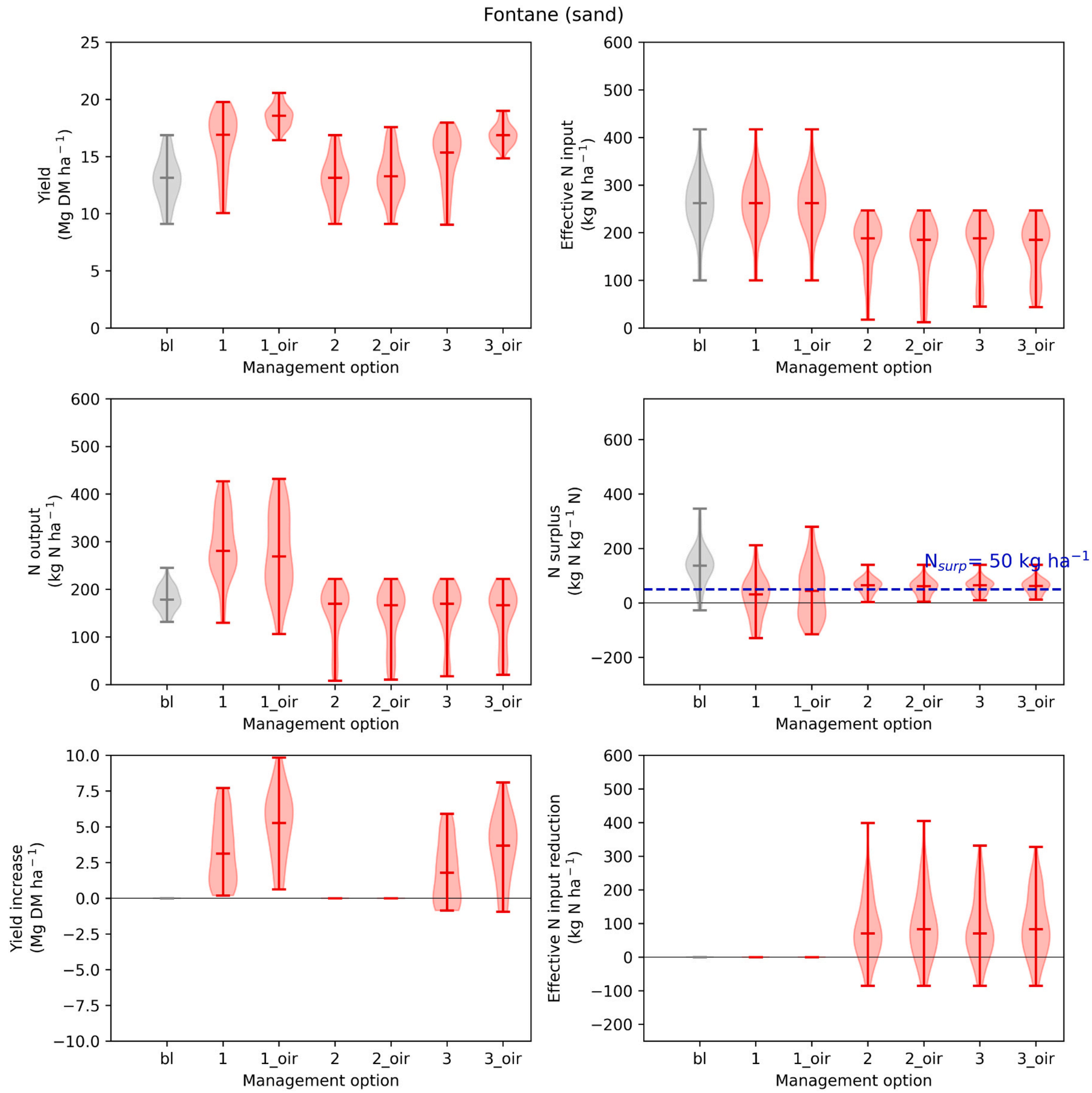

Fig. 5. Distribution of yield, effective N input, N output, N surplus, yield increase, and reduction of effective N input for 47 fields of Fontane; horizontal dashes show maximum, median and minimum values. The displayed management options are the baseline situation (bl), closing the efficiency yield gap (management option 1), adjusting effective N input to a level below which either yield loss or soil mining occurs (management option 2), and adjusting the effective N input to a level in which 90 % of the water-limited yield can be obtained without soil mining (management option 3). The results of the analysis are shown for both the farmers' reported irrigation regime and an optimized irrigation regime ("_oir). The blue dashed line represents the threshold value of the N surplus according to Ros et al. (2023) for sandy soils.

3.3.3. High initial age soil organic matter

The results of the management option analysis for the default value of A0SOM (i.e. A0SOM = 24 y) can be found in Supplementary Figures S10-S12 and described in Supplementary Text S5. In summary, changing the value of A0SOM from 10 y to 24 y had almost no effect on the yields for any of the management options. However, it did affect the N surpluses for each management option. For management options 1–3, it respectively reduced the median of the N surplus to 68, 47, and 47 kg N ha^{-1} for Innovator. For Fontane, it changed to 78, 35 and 45 kg N ha^{-1} for Fontane. This would mean that the median N surplus for Fontane for management options 2 and 3 would be below the threshold values, while it was initially above (both 63 kg N ha^{-1}). However, it did not change the general trends for management option 1 compared to assuming A0SOM = 10 y. Also if A0SOM = 24 y, a substantial number of fields for management option 1 had a negative N surplus which indicates soil mining (Fontane: 7 fields, Innovator: 6 fields) or exceeded the N surplus threshold values (Fontane: 32 fields, Innovator: 18 fields). It also did not change the trends in management options 2 and 3 that almost no fields with Innovator exceeded the threshold values (2 fields for both options), while a substantial number of fields did so for Fontane (19 for management option 2, 21 for management option 3).

4. Discussion

4.1. WOFOST's performance in reproducing yields in field experiment

WOFOST was calibrated on data from the experimental data set from Ten Den et al. (2024b) collected in 2020 and evaluated with data from 2019 in the same data set. After calibration, WOFOST was able to reproduce the dry matter production, its partitioning and the leaf area index. The model also performed well in simulating the N uptake in the leaves and tubers (Figs. 2–3, Fig S1-S4, Table S8). However, preliminary simulations showed that WOFOST could not explain the observed high N

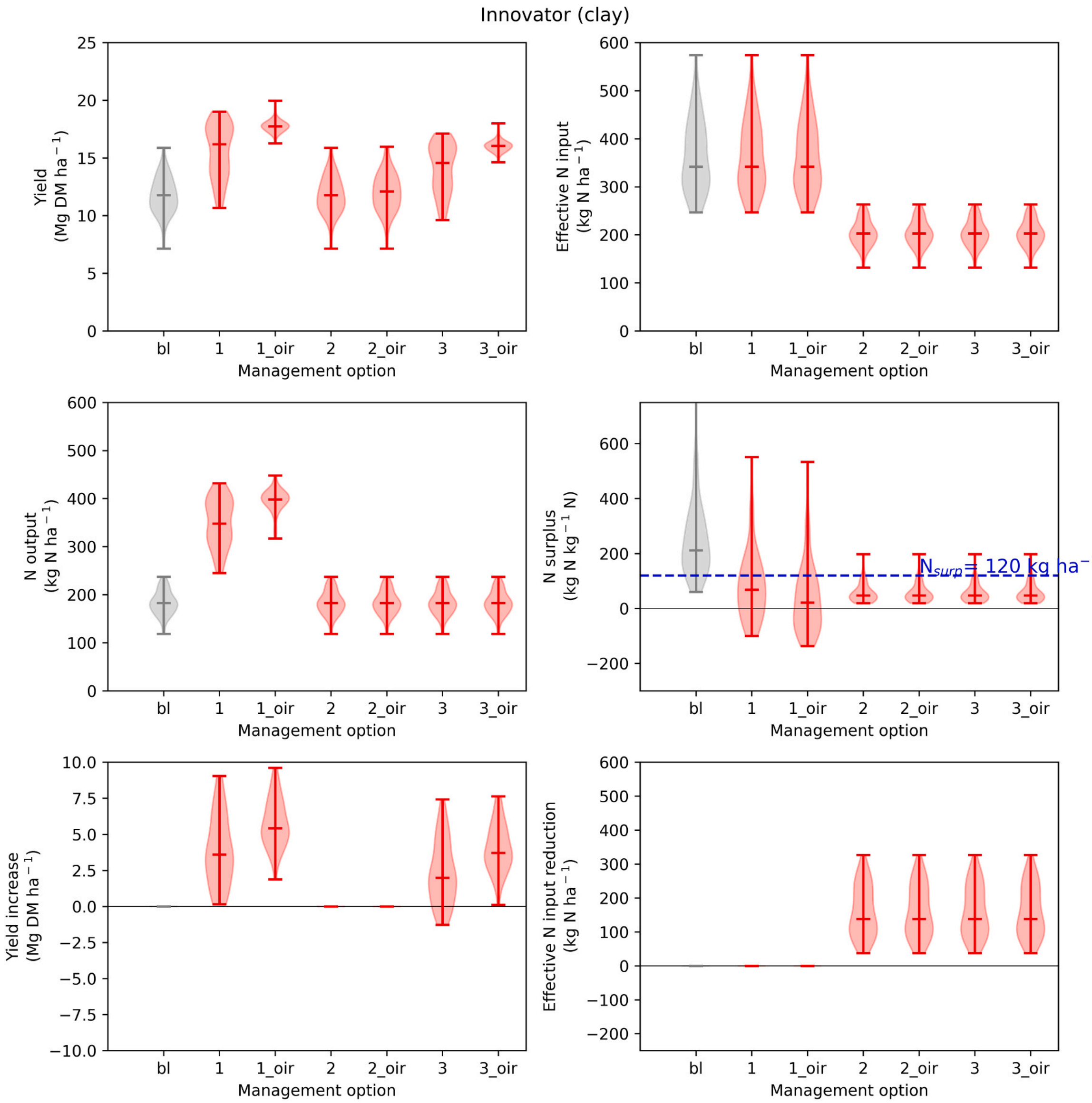

Fig. 6. Distribution of yield, effective N input, N output, N surplus, yield increase, and reduction of effective N input for 47 fields of Innovator; horizontal dashes show maximum, median and minimum values. The displayed management options are the baseline situation (bl), closing the efficiency yield gap (management option 1), adjusting effective N input to a level below which either yield loss or soil mining occurs (management option 2), and adjusting the effective N input to a level in which 90 % of the water-limited yield can be obtained without soil mining (management option 3). The results of the analysis are shown for both the farmers' reported irrigation regime and an optimized irrigation regime ("_oir). The blue dashed line represents the threshold value of the N surplus according to Ros et al. (2023) for clay soils.

uptake in the treatments without N fertilization (W1N0, W2N0) (Table S1). This suggested that SNOMIN (Berghuijs et al., 2023), the soil N module to which WOFOST was coupled, underestimated the amount of N that became available from the mineralization during the decomposition of organic matter. One parameter that determines the decomposition of soil organic matter is the so-called initial age of soil organic matter A0SOM (y) (Janssen, 1984). A higher value of A0SOM corresponds to a lower first-order decomposition rate of organic matter and, therefore, a lower mineralization rate (Heinen and De Willigen, 2005). We re-calibrated this parameter for each year-location combination and found that the value for A0SOM should indeed be considerably lower (8–14 y; Table S1) than the default value of this parameter (24 y) (Van der Burgt et al., 2006). The difference in A0SOM is possibly due to the fact that A0SOM lumps the contribution of the decomposition of all organic matter applications from recent growing seasons and soil organic matter that was already present in the soil. While A0SOM in our study was estimated for a single growing season, Van der Burgt et al. (2006) estimated this parameter from a data set of which the field management was known for several years (Mirschel et al., 2007). Therefore, Van der Burgt et al. (2006) did not lump the effects of recent growing seasons into the estimate and may have obtained a higher value for A0SOM than in our study. It is also possible that the soils from Münchenberg in Eastern Germany in the 1990s (Mirschel et al., 2007) for which Van der Burgt et al. (2006) estimated A0SOM, were not representative for the Netherlands in recent years. After re-estimating the value of A0SOM, the amounts of N in the tubers at harvest in the treatments without fertilization were no longer systematically underestimated.

The model underestimated the amount of N in the leaves (MBE = 14 kg N ha^{-1}). This could have been caused by various factors. One factor was that it was unknown what the initial amount of inorganic N was at sowing, which made it challenging to initialize the amouts of NO_3^--N and NH_4^+-N in SNOMIN. A second factor was that it was unknown at all moments in the growing season what the total N uptake was. The N uptake in the haulm was not measured and the amount of N in the tubers only at the end of the growing season. This could have resulted in an uncertain estimate of the daily maximum rate of N uptake RNUPTAKEMAX and, consequently, the amount of N in the leaves. Also, the various parameter values that were adopted from the LINTUL-4 model (Wolf, 2012) may have contributed to the underestimation of the amount of N in the leaves. It is also possible that the default value (Table 1) of the table function for the maximum N concentration in the leaves (NMAXLV_TB) contains too low N concentrations for various development stages or that the fraction of the maximum N concentration in the stems and in the leaves (NMAXST_FR) is too high. Also, too high values of parameter NMAXSO or too low values of parameter TCNT that affect reallocation of N from the leaves to the storage could have resultated in an underestimation of the leaf N amount. However, it is hard to verify which of these parameters may have to be recalibrated. We recommend further calibration of WOFOST on fields in which the amount of N at sowing, the total N uptake, and the partitioning of N to different organs are known throughout the growing season.

4.2. WOFOST's performance in reproducing yield in farmers' fields

WOFOST performed considerably better in simulating the observations for 2021 in terms of r^2 (0.92 for Fontane, 0.93 for Innovator) than for 2020 (0.19 for Fontane, 0.3 for Innovator) (Fig. 4, Figs S5-S8). This difference in performance can be explained by the fact that tuber weight measurements were taken in 2021 at five (Innovator) or six (Fontane) different moments in time, while the tuber weight measurements in 2020 were taken at only three moments in time. Moreover, tuber weight measurements from 2020 were conducted in a relatively short period late in the growing season (early August - early October), while the measurements from 2021 covered a longer part of the growing season (mid-June - late September). Since there were both more measurements through time available for 2021 and the period that was covered by these measurements was also longer, there was more variation in the observations that could be explained by WOFOST, which increased its performance.

WOFOST often overestimated the final tuber dry weights This is to be expected because the model does not capture yield reducing factors (pests, diseases, etc.) which may have played a role in farmers' field. Yet, in 13 out of 94 fields yield was underestimated. This underestimation is surprising as WOFOST assumes that the (potential) yield is determined by the sowing date, radiation, and temperature (De Wit et al., 2019; Van Ittersum et al., 2013) and that growth limitation relative to the potential production only occurs due to water stress (De Wit et al., 2019; Van Ittersum et al., 2013) or due to N stress (Berghuijs et al., 2024). A possible explanation for underestimations of yields in some fields are uncertainties in the Van Genuchten parameters (Van Genuchten, 1980), obtained from the BOFEK soil map (Heinen et al., 2022), that were used to parametrize the layered soil water balance (Rappoldt et al., 2012). This problem could be tackled in further experiments by parametrizing the layered soil water module from measured water retention curve, instead of reconstructing these water retention curves from data obtained from a soil map. Another possible explanation is that the layered soil water balance does not consider capillary rise from water from the subsoil. Ten Den et al. (2024a) found that the older WOFOST version 7.2 systematically underestimated water-limited yields. They suggested that this might have been caused by the fact that the single layered soil water module, that was used in WOFOST 7.2, does not consider capillary rise of water from the subsoil into the rootable soil. Furthermore, WOFOST 7.2, does not consider recirculation; the upward movement of water within the rootable soil. Indeed, Kroes et al. (2018) showed by simulation with the SWAP soil water model (Kroes et al., 2017), that both capillary rise and recirculation can have a considerable effect on the simulated yields due to the increased amount of available water during the growing season. They also showed that the simulated yields become more accurate if these processes are included in the model. This problem was partially tackled, because the version of WOFOST 8.1 used in this study is coupled to a layered soil water module that does consider recirculation (Berghuijs et al., 2024; Rappoldt et al., 2012). However, the layered soil water module in PCSE still does not consider capillary rise of water from the subsoil, which may need to be incorporated in future research.

4.3. Effective strategies to reduce the nitrogen surplus

In previous work, it was reported that the average N surplus of ware potatoes in the period 2015–2017 was 57 kg N ha^{-1} on sandy soil and 84 kg N ha^{-1} on clay soil (Silva et al., 2021). In contrast, in our study the average baseline N surpluses of the ware potato cultivars Fontane (144 kg N ha^{-1}) and Innovator (270 kg N ha^{-1}) were considerably higher (see also Ravensbergen et al. 2024a). Unlike the N surpluses calculated in previous work (Silva et al., 2021), these values were much higher (on average 2.57 times as large) than the thresholds suggested by Ros et al. (2023). A possible reason for the differences in N surplus is that our study includes all N applications from the autumn of the year before the planting date until the harvest date, while Silva et al. (2021) only considered the N applications applied during the growing season.

The analysis of the management options (Figs. 5 - 6) aimed to explore strategies to reduce N surpluses in Dutch potato farming. Each of the investigated options resulted in lower N surpluses. For both Fontane and Innovator, adopting management option 1 would reduce the median N surplus to values below the threshold values proposed by Ros et al. (2023), even though there was still a considerable number of fields with both Fontane and Innovator where these thresholds were exceeded. The substantial increase in yields make this option attractive in the short term. However, implementing management option 1 also resulted in soil mining on various fields. This makes it an unattractive option for the longer term. It also requires that farmers know what the yield limiting factors are (Ravensbergen et al., 2023), which may not always be the case, such they can close the yield gap. And even if a full closure of the yield-gap would be feasible, it may still be economically unattractive to do so due to increased management costs.

Interestingly, both management options 2 and 3 resulted in the same median N surplus and also the ranges of N surplus over the different fields were almost the same. This result demonstrates that, in almost all fields, the adjustment of the effective N input to prevent soil mining results in an effective N input that is also sufficient to achieve 90 % of the water-limited yield. For Fontane, both options brings the median N surplus (65 kg N ha^{-1}) close but still above to thresholds value proposed by Ros et al. (2023) for sandy soils and for Innovator (48 kg N ha^{-1}) well below the threshold value for clay soil. Both management options are more attractive than management option 1 from an environmental perspective. They both strongly reduce the N surplus and negative N surpluses, which indicate soil mining, did not occur. Of all management options, management 3 is the most attractive for farmers in the long run, because it increases the yield while both high N surpluses and soil mining are prevented. However, the challenge of adopting this option, compared to management option 2, is that achieving the target yield requires that farmers know what the yield limiting and reducing factors other than irrigation and N fertilization regimes are (Ravensbergen et al., 2023). This may not always be the case and may also differ across growing seasons.

It has been shown that water stress due to either lack of water or lack of oxygen due to surplus water can considerably reduce potato yields in the Netherlands. Farmers can thus substantially increase their yields by optimizing irrigation regimes and other measures like improving drainage (Ravensbergen et al., 2024b). This is also shown in our study where the yields of an optimized irrigation regimes were higher than both the yields reported by the farmers and the yield calculated for the different management options without optimized irrigation. The effective N input was hardly affected by the improved irrigation regime and, except for management option 1 for Fontane, the N output was not affected either. These results suggest that improved irrigation will generally not change the N surplus. Nevertheless, it does result in a more agronomically effective N use, as the same amount of applied N results in higher yields.

It is remarkable that management option 1 has often considerably higher N output than management options 2 and 3. This may be explained by the differences in the way that N output is calculated for the different options. Management option 1 assumes, just like in the WOFOST simulations, that the efficiency yield gap is closed. Therefore, it is assumed that the N output for this scenario equals the N output simulated by WOFOST. In contrast, this is not possible in scenario 2 and 3 because WOFOST assumes a closed efficiency yield gap, which is not the case for these management options. Therefore, the measured N output was used to calculate the N surplus for these management options (Supplementary Text S4).

The management option analysis was done for two single growing seasons (2020 and 2021). This provides information about how N surplus can potentially be reduced within a single growing season of potato without soil mining. However, it does not show how the N surplus will develop in the long term. In order to do so, a similar analysis needs to be done for full crop rotations. Such an analysis requires that WOFOST is calibrated for all crops within the rotation under N-limited growth conditions. Such a calibration, which includes N-limited growth, has been done in previous work for winter wheat (Berghuijs et al., 2024) and potato (this study), but not for other crop species. In future research, WOFOST should be therefore calibrated and evaluated under N-limited conditions for crop species other than winter wheat or potato to allow an analysis of management options over a full crop rotation.

5. Conclusion

WOFOST performed well in reproducing the leaf area index, dry matter production and partitioning, and the N uptake by the leaves of our experimental data from 2019 and 2020. It also reproduced the N uptake by the tubers at harvest with a small mean bias, but a higher uncertainty than for other variables.

We then evaluated WOFOST for 94 individual fields in a farmers' field data set that was obtained in the growing seasons 2020 and 2021. WOFOST performed reasonably well in explaining the variation in tuber dry weight throughout the growing season, but it occasionally underestimated yields, in particular in 2020.

Next, we examined different management options with the aim to reduce the N surplus on the farmers' field. We found that closing the efficiency yield gap (management option 1) on both clay and sandy soils is often not enough to prevent both soil mining *and* to reach N surpluses below the threshold values from Ros et al. (2023). Thirty one of the fields N surpluses above the threshold values from Ros et al. (2023). Meanwhile, in another 31 % of the fields, the N surplus was negative which suggests soil mining. Thus, adjustments of the N input needed to be considered too. Two other management options were therefore explored. Both assumed that N input was adjusted such that the NUE does not exceed 0.90 kg kg^{-1} (to prevent soil mining). One of the options assumed that N input was kept high enough to prevent yield loss (management option 2) while the other option also assumed optimization of management and of N input such that 90 % of the water-limited yield could be obtained (management option 3), Both options yielded very similar N surpluses on almost all fields. This indicates that the N input to prevent soil mining is also sufficient for most fields to obtain 90 % of the water-limited yield. The results of management options 2 and 3 further showed that the baseline N surplus can be substantially be reduced in most fields, even though this still frequently leads to N surpluses above threshold values on sandy soils. We conclude that 1) adjusting the effective N inputs is a more effective way of reducing the N surplus than closing the efficiency yield gap and that 2) it is almost always feasible to reduce the N surplus below threshold values without soil mining or yield loss for potatoes grown on clay soil by reducing the effective N input and 3) that reducing the N input without yield loss or soil mining does also substantially reduce N surpluses on sandy soils, although not always to below the threshold values. For most of the investigated fields, we would therefore recommend a reduction of the effective N input.

Further research should focus on further calibrating the WOFOST parameters that affect the N partitioning to various organs in potato. Also future research is needed on calibrating WOFOST for other crop species grown under N-limited growth conditions. This would allow to investigate management options to reduce N surpluses for an entire crop rotation and not just single growing seasons in which potato is grown.

Declaration of Competing Interest

The authors have nothing to declare

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.fcr.2026.110396.

Data availability

Data will be made available on request.

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