



Agro-environmental profile of potato cultivation under water and nitrogen managements – A case study in Denmark

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ABSTRACT

Potato field management in Europe is already optimized for high production and tuber quality; however, numerous environmental challenges remain if the industry is to achieve “green economy” targets, such as less resources utilized, and less nitrate leached to the environment. Strategic co-scheduling irrigation and nitrogen (N) fertilization might increase resource use efficiency while minimizing reactive losses such as nitrate leaching. This study aimed to quantify the combined effect of irrigation and N fertilization on potato production, growth, and resource use efficiencies. A field experiment was conducted from 2017 to 2019 on a coarse sandy soil in Denmark, with a drought event occurring in 2018. Full (I_{full} , maximized), deficit (I_{def} , 70–80 % of I_{full}) and low irrigation treatments (I_{low} , minimized amount to keep crop survival), each under full (N_{full} , maximized) and variable (N_{var} , variable amount according to the crops’ needs) N fertilization were applied. The analyses results show that I_{low} limited potato growth under a drought-heat event; otherwise, potato growth was comparable between I_{full} and I_{def} treatments, with 31–32 % higher irrigation efficiency (IE) under I_{def} than under I_{full} . Nitrate leaching was variable and not significantly different among the treatments, being in general 9–13 % lower under I_{def} in absolute terms than under I_{full} . Unexpectedly, outcomes from N_{var} were statistically lower compared to those from N_{full} . Radiation use efficiencies (RUE s) from I_{low} and N_{var} were significantly lower than from I_{full} and I_{def} (14–19 %), and from N_{full} (9–11 %). N use efficiencies (NUE) were comparable between N fertilization treatments but significantly different among different irrigation treatments. Overall, this study confirms that I_{def} is the best irrigation strategy. Future efforts should focus on developing improved approaches for detecting in-season crop N status and further quantifying N requirements, as well as promoting the co-scheduled management of irrigation and N fertilization. Remote sensing approaches have great potential to assist with this.

1. Introduction

Potato (*Solanum tuberosum* L.) is one of the most important food crops worldwide, after maize (*Zea mays* L.), rice (*Oryza sativa* L.) and wheat (*Oryza sativa* L.) (FAO, 2024). The crop has high nutritional value, provides a high economic yield and can be grown under different

environmental conditions (Cabrera et al., 2019; Winnicki and Bogucka, 2017; De Jong, 2016). Potato is also a valuable industrial crop for multiple purposes, including feed production, plant-based protein, supplements and colouring, medicine, starch-based bioplastics, and textile sizing (Li et al., 2019; Priedniec et al., 2017; Semeijn and Buwalda, 2018). Ensuring adequate tuber and starch yield is thus

Abbreviations: N, nitrogen; I_{full} , full irrigation; I_{def} , deficit irrigation; I_{low} , low irrigation; N_{full} , full nitrogen fertilization; N_{var} , variable nitrogen fertilization; IE , irrigation efficiency; RUE , radiation use efficiency; NUE , nitrogen use efficiency; WUE , water use efficiency; DAE, days after emergence; SWC, soil water content; FC, field capacity; SWD, soil water deficit; FM, fresh matter; DM, dry matter; PNC, plant nitrogen concentration; PNU, plant nitrogen uptake; Sc, starch content; SY, starch yield; W_A , tuber weight in air; W_W , tuber weight in water; NIR, near-infrared; RVI, Ratio Vegetation Index; I_{par} , intercepted photosynthetically active radiation; f_{ipar} , fraction of I_{par} ; A_{ipar} , accumulated I_{par} ; ET_p , potential evapotranspiration; ANOVA, analysis of variance; ART, Aligned Rank Transform; T_{max} , daily maximum temperature; DI, Deficit Irrigation.

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essential for the entire value chain, and for achieving that, potato agronomic management needs to be optimized. However, significant environmental challenges remain that hinder the potato industry to reach environmental targets.

Firstly, the crop is cultivated mostly on sandy soils to ease harvest operation. From these soils, water easily percolates beyond the root zone (Peng et al., 2023) and transports unused nitrogen (N) through leaching to the groundwater and eventually the estuaries and the sea, causing eutrophication. Farmers sometimes apply all N fertilizer at planting due to operational simplicity (Zhou et al., 2018). This single-rate application may result in low N use efficiency (*NUE*; ratio of harvested to applied N fertilizer) as potato N requirement is low during vegetative growth and tuber initiation (the first 30–40 days after planting; Gómez et al., 2019). Low *NUE* increases the risk of leaching of unutilized mineral N or freshly mineralized organic N (Ayyub et al., 2019; Rens et al., 2018). Split application of N fertilizer at planting and again later in the vegetative stages provides time for assessing soil N mineralization, and it has been shown to increase *NUE* and reduce nitrate leaching risks (Abbasi et al., 2013; Ahmed et al., 2017; Souza et al., 2020). For example, Rens et al. (2016) reported that the plant *NUE* of full N fertilization at pre-planting was significantly lower than the *NUE* when the N fertilizer was applied at emergence and tuber initiation. Du et al. (2019) also illustrated that compared to a conventional single-dose basal application, split N application had higher *NUE* because potato plants assimilated more N during later growth stages and thereby a higher proportion of N was accumulated into roots and tubers. However, significant research and industrial challenges remain to determine the best time and amount for split application.

Secondly, potato is highly sensitive to the lack of soil moisture, i.e., drought, due to its shallow rooting depth and high water demand (Satchithanathan et al., 2014). Irrigation is essential for high production, especially on sandy soils during tuber initiation and bulking periods, with the expansion of the tuber cells accompanied by water uptake, and accumulation of nutrients and carbohydrates (Gervais et al., 2021; Ierna and Mauromicale, 2006, 2012). The sensitivity of potato to drought stress may be exacerbated by the particular characteristics of sandy soils, as these soils are less compacted and have larger pores compared to fine-textured soil types (Huang and Hartemink, 2020). Thus, crops cultivated on sandy soils are more sensitive to water transport (input: precipitation and irrigation, and output: evapotranspiration) with lower soil water holding capacity. Also, there is a higher risk of nutrient leaching because the organic matter content in the sandy soil is lower. To alleviate drought stress, farmers often over-irrigate. Moreover, drought stress often co-occurs with heat stress, experienced by the canopy at high air temperature (Hussain et al., 2019; Ostmeier et al., 2020). The cooccurrence of these two stresses could result in more severe consequences than from a single stress (Hussain et al., 2019). For example, during the 2018 European heatwave, the maximum daily temperature anomalies in Scandinavia (including Denmark, one of the largest European potato producers) reached a record-breaking +14°C (Yiou et al., 2020). This heatwave event greatly reduced potato yield. In Denmark, the production of starch potatoes in 2018 was 90 % of the average for 2015–2023, and the production of seed and table potatoes was only 68 % (Danmarks Statistik, 2025). Moreover, several studies have reported more recent summer heatwaves occurring in Europe, where the European mean surface air temperature anomalies in 2024 relative to 1991–2020 reached 1.5°C, which was much higher than the 0.8°C observed in 2018 (Copernicus Climate Change Service, 2025; Sun et al., 2025). Zhou et al. (2017a) estimated an almost 10 % yield decrease in table potatoes for each degree increase in mean seasonal temperature above 15.3°C, which in turn decreases the N-demand. There is a significant research gap on how integrated drought-heat stress affects crop physiological processes, such as photosynthesis, water use efficiency (*WUE*, the rate of biomass carbon assimilation divided by the rate of transpiration) and radiation use efficiency (*RUE*, the rate of biomass carbon assimilation per unit of intercepted global radiation)

(Gervais et al., 2021). Moreover, the effects of different co-applications of N fertilization and irrigation also remain elusive. Such knowledge is important to understand how the potato crop responds to alternative practices and to support the industry towards “green economy” targets, which include reducing carbon emissions and pollution, enhancing energy and resource efficiency, and preventing the loss of biodiversity and ecosystem services (Barbier, 2012).

Several previous studies have reported that the interaction between irrigation and N fertilization has notable impacts on plant growth, resource use efficiency and environmental consequences such as nitrate leaching for crops including potato (Badr et al., 2012; Gheysari et al., 2009; Shrestha et al., 2023; Wang et al., 2010; Xu et al., 2020). Normally irrigation and N fertilization jointly affect the growth since irrigation can markedly influence N related traits such as *NUE* and N uptake ability (Gheysari et al., 2009; Tang et al., 2021), which are directly related to crop photosynthesis. N fertilization also affects water related characteristics, such as *WUE* and water uptake ability (Badr et al., 2012), which influences the crop root distribution. However, the interactive effects of irrigation and N fertilization on potato tuber and starch production, nitrate leaching and resource use efficiencies under field conditions, especially involving extreme weather events such as drought and heat, have not yet been explored.

In this study, we aimed to address the following research questions: 1) compared to single-dose N application at planting, can split variable N fertilization increase *NUE* and reduce nitrate leaching while maintaining production? 2) can alternative irrigation treatments promote potato production when drought stress occurs? 3) how does the interaction of irrigation and N fertilization affect the potato growth, resource use efficiencies and nitrate leaching? Following these questions, we therefore hypothesised that: 1) split variable N fertilization will maintain potato production while increasing *NUE* and reducing nitrate leaching; 2) appropriate irrigation based on crop needs could alleviate drought stress when heatwave occurs while promoting *WUE*; 3) optimal co-scheduling of irrigation and N fertilization promotes growth and productivity with higher *NUE* and irrigation efficiency (*IE*, the ratio of biomass to the amount of irrigated water) and less nitrate leaching, especially for sandy soils, which have low nutrient and water holding capacity. The specific objectives were to: 1) quantify potato tuber and starch production and photosynthetic physiology in response to annual meteorological variations and treatments, 2) quantify nitrate leaching under different treatments, 3) analyse the response of resource use efficiencies to weather and treatments, and 4) recommend irrigation-fertilization co-scheduling options for optimal potato cultivation that minimize environmental impact but maintain good nutritional and production profiles.

2. Materials and methods

2.1. Field trial and experimental design

A field experiment was conducted from 2017 to 2019 in central Denmark (56.53°N, 9.41°E) on a coarse sandy soil with 3.9 % clay, 2.3 % silt, 92 % sand, 1.4 % carbon content and pH of 6. The climate is oceanic and wet with moderate intra-annual variability. Starch potato variety ‘Oleva’ with tuber size 35–55 mm was planted at a distance of 30 cm within rows and 75–90 cm between rows, resulting in a density of 40000 potatoes ha⁻¹. The seed potatoes were planted in 15-cm high ridges in early May in a different field each year and grown until late October. The previous crops in the field every year were cereals (e.g., winter rye and winter wheat). Each year, the experiment had two N fertilization treatments (full, N_{full} ; and variable-split, N_{var}) and three irrigation treatments (full, I_{full} ; deficit, I_{def} ; and low, I_{low}) in a randomized split-plot block design with a plot size of 30 × 30 m². There were six different combinations of N fertilization and irrigation treatments, with four replicates, making 24 total treatment plots for each field in each year. The N fertilizer was mainly from pig slurry and inorganic fertilizers

(YaraBela Sulfan, Yara International, Oslo, Norway). Other fertilizers, including phosphorus, potassium, sulphate and magnesium, were applied to the field a few days after crop planting based on soil analysis, to ensure optimal conditions related to these nutrients. Ground water was used for irrigation, and the operation was implemented as overhead irrigation with a boom. The irrigation boom speed was programmed to supply the desired amount of water for plots with different irrigation treatments. The nitrate content in the irrigation water was not determined, as it was assumed to be insignificant and without influence on the treatments and results. The total amounts for N_{var} constituted 60–80 % of N_{full} , which was applied as the highest threshold prescribed by the Danish advisory service (236 kg N ha⁻¹ in 2017 and 196 kg N ha⁻¹ in 2018 and 2019). Irrigation was applied at 29–49, 30–72, and 23–51 days after emergence (DAE) in 2017, 2018 and 2019, respectively, with variable frequency depending on soil water deficit (SWD) calculated during the season. Irrigation in I_{def} was applied when measured soil water content (SWC) was at 40–50 % (25–30 mm) of field capacity (FC). The SWC at FC was determined before emergence of the potatoes, five days after the soil had been thoroughly wetted by rain and subsequently drained. The ratio of I_{def} to I_{full} ranged between 66 % and 77 %, except in 2017 which was abnormally wet and cool, and the ratio was about 90 %. Irrigation in I_{low} was applied when FC had been depleted and the amount was 6–19 % of I_{full} ; thus, this treatment could ensure plant survival even under extreme drought conditions. Summary of the field experiment management is shown in Table 1.

2.2. Soil-plant data and weather observations

SWC was measured weekly by time domain reflectometry (TDR-100 box; Campbell Scientific, Logan, UT, USA) with probes placed vertically to 60-cm depth midway between the ridge and the furrow. The obtained traces were interpreted to SWC based on an empirical model (6050XI, Jacobsen and Schjønning, 1993) and transferred to a handheld computer (Allegro, Juniper Systems, Inc. Logan, Utah, USA). SWD at a particular DAE was calculated as the difference between actual SWC and FC. The soil water solution was sampled with two porous ceramic cups (K100, UMS GmbH, Munich, Germany) installed in the middle of each plot and spaced 3–6 m apart at 1-m depth in July in 2018 and 2019 (not in 2017). The suction cups were installed in holes made with a 1-m long iron bar

with a diameter of 28 mm. Before installing the suction cups (size 22 mm), silicon meal mixed with water was added to the holes to ensure good contact between the soil and the suction cups. From September until April in the following year, the soil water was sampled every second to third week by applying 80 kPa suction to the cups two to three days prior to sampling. Nitrate concentration in the leachate was determined by standard colorimetric procedures following Best (1976), which measured absorbance of a formed soluble coloured compound at 520 nm and determined the nitrate concentration by inputting the absorbance into a calibrated equation. The compound comprised a diazonium salt produced from the reaction between nitrite which was reduced from nitrate (in the sampled soil water) with hydrazine and copper catalyst under alkaline conditions at 37 °C and sulphanilamide in acid solution with N-1-naphthylethylenediamine dihydrochloride.

Potato foliage was chemically killed by spraying diquat-bromide in mid-late September each year. The tubers were harvested in the first week of November at BBCH (Biologische Bundesanstalt, Bundessortenamt and Chemical industry) growth stages 95–96; at 106, 113 and 105 DAE in 2017, 2018 and 2019, respectively. Both the tubers and the foliage were harvested from a net harvest area of 10 m in each of four rows in the centre of each treatment plot and were weighed for fresh matter (FM). The tubers were then finely sliced, and both foliage and tubers were oven-dried at 60 °C for 48 h and weighed for foliage and tuber dry matter (DM). The whole procedure is standardized (Zhou et al., 2016) and is repeatable for other studies. The tuber size distribution was not measured as the cultivar “Oleva” is used for potato starch production. In potatoes used for starch production purposes, yield and starch content are most important, whereas tuber size is not. Dried samples were milled and analyzed for plant N concentration (PNC, %) according to the Dumas method (Elementar Analysensysteme GmbH, Germany). Plant N uptake (PNU, kg ha⁻¹) was calculated by multiplying DM with PNC. Starch content (Sc, %) was determined by weighing 5 kg of fresh potato tubers in air and then in water and DM and Sc were calculated using Maerckers table based on the following equations (Nissen, 1967):

$$\% DM = 214 * (W_A / (W_A - W_W) - 0.988) \quad (1)$$

$$Sc = \% DM - 5.75 \quad (2)$$

where W_A and W_W are tuber weight in air and water, respectively

Table 1

Summary of the field management in the study in Denmark. Annual amounts of irrigation (I) and nitrogen (N) fertilization are accompanied by subscripts for full, variable (var), deficit (def) and low treatments. DAE is days after emergence. This table is modified from Table S1 in Peng et al. (2021a).

Year	Treatment	Irrigation water (mm)	Nitrogen fertilizer (kg N ha ⁻¹)			
			Basic ^a	In-season		Total
2017	$I_{full}N_{full}$	65	236	DAE32	DAE49	DAE60
	$I_{full}N_{var}$	65	86	40	40	
	$I_{def}N_{full}$	50	236			
	$I_{def}N_{var}$	60	86	40	40	
	$I_{low}N_{full}$	10	236			
	$I_{low}N_{var}$	10	86	40	40	40 ^b
				DAE72		
2018	$I_{full}N_{full}$	205	196			
	$I_{full}N_{var}$	208	116	40		
	$I_{def}N_{full}$	146	196			
	$I_{def}N_{var}$	161	116			
	$I_{low}N_{full}$	12	196			
	$I_{low}N_{var}$	14	116			
				DAE45	DAE65	
2019	$I_{full}N_{full}$	154	196			
	$I_{full}N_{var}$	154	56	40	40	
	$I_{def}N_{full}$	103	196			
	$I_{def}N_{var}$	102	56	40	40	
	$I_{low}N_{full}$	30	196			
	$I_{low}N_{var}$	30	56	40	40	

a Basic nitrogen fertilization indicates nitrogen applied at and before planting.

b Two plots received an additional 40 kg N ha⁻¹ according to crop demand following the approach of Zhou et al. (2017b).

and the different numbers are empirical constants. Starch yield (SY , $t\ ha^{-1}$) was calculated by multiplying tuber FM with Sc .

Sap flow at 10 min resolution was recorded by SGA13-WS Dynagage sensors (Dynamax, Houston, Tx, USA) installed on four shoots in one plot of the $I_{full}N_{full}$ treatment and another plot of the $I_{low}N_{full}$ treatment, from 6 July to 6 September in 2018. The two treatments and the year were ideal for studying the effect from drought and heat stresses on the potato hydric metabolism. The sensors were connected to a CR1000 data logger (Campbell Scientific, Logan, UT, USA) running the Dynamax Flow32A-1K software. The sap flow measurements were calibrated from units of $mL\ h^{-1}$ to $mm\ h^{-1}$, which represents plant transpiration, according to the soil water balance model; for the details, see Peng et al. (2023).

Weather data including daily temperature, global radiation, and precipitation were recorded by a weather station located 200 m from the experimental field. Historical data (2000–2016) were downloaded from another weather station located 15 km away. The anomalies of the weather parameters were calculated as the differences between daily actual values and historical daily average values.

2.3. Reflectance data and canopy intercepted radiation calculation

Weekly canopy reflectance data in red, red edge and near-infrared (NIR) bands centred at 670, 730 and 780 nm, respectively, were collected from a handheld active sensor (RapidScan CS-45, Holland Scientific, Lincoln, Nebraska, USA). Ratio Vegetation Index (RVI) was calculated as the ratio of reflectance in the NIR to the red bands and RVI was used to calculate the fraction of intercepted photosynthetically active radiation (I_{par}), abbreviated as f_{Ipar} in a three-step procedure. First, RVI values were calculated from tabulated f_{Ipar} values from 0 to 1 in increments of 0.1 according to Christensen and Goudriaan (1993). Second, f_{Ipar} as a function of RVI was approximated by a power equation ($f_{Ipar} = a + b\ RVI^c$) and the coefficients a , b and c were determined by iteratively fitting this equation to the RVI values of the first step. Lastly, the daily I_{par} was calculated by multiplying f_{Ipar} estimated from the measured RVI and the optimized a , b and c coefficients, with half the daily global radiation (Monteith and Unsworth, 2013). The accumulated I_{par} ($Aipar$) was calculated by summing the daily I_{par} from crop emergence to harvest. This value was used to divide the potato DM yield at harvest and derive radiation use efficiency (RUE , $g\ DM\ MJ^{-1}$).

2.4. Estimation of soil nitrate leaching

Nitrate leaching cannot be measured directly and must be estimated. This study combined the measured soil nitrate and soil water percolation modelled by Daisy (ver. 5.92), a process-based model that simulates, among other things, plant growth and water dynamics in agroecosystems driven by daily weather and farm management data. Soil hydrology was simulated by water transport (Richard's equation) based on soil properties, measured precipitation, applied irrigation and reference evapotranspiration (Makkink equation). Further details on the model and its equations are available in Hansen et al. (2012). The model has been well parameterized for estimating growth and water balance of potato fields (Hansen et al., 2012; Heidmann et al., 2008) and required only slight manual calibration for crop production and SWC . Daisy needs data on weather, soil and crop management. Daily air temperature, precipitation and solar radiation recorded at the weather station were used as weather data inputs. Soil texture and organic matter content, and the van Genuchten-Mualem soil hydraulic parameters describing soil water retention and unsaturated hydraulic conductivity, were parameterised for coarse sandy soil according to Manevski et al. (2015). For crop data, the model contains a parameterization of potato cultivar "Oleva". Management information of recorded time/amounts of ploughing, sowing, N fertilization, irrigation and harvests were used. The model was run separately for each treatment in 2018 and 2019, from 1 April to 1 April in the following year, and calibrated according to

an integrated modelling framework (Manevski et al., 2016) with emphasis on accurate simulation of SWC and harvested DM by altering the saturated hydraulic conductivity (matching point, Ko) and the maximum leaf photosynthetic rate (Fm). The daily soil nitrate concentrations ($mg\ L^{-1} = mg\ dm^{-3}$) between measurement dates were interpolated according to an improved percolation weighted concentrations method on a daily scale, based on Lord and Shepherd (1993) in order to obtain daily nitrate leaching $[(mg\ dm^{-3}) \times (mm \times 10 = m^3\ ha^{-1}) \times 0.01 = kg\ ha^{-1}]$. Nitrate leaching was accumulated to annual values from 1 April to 31 March for 2018 and 2019. The N loss by surface runoff was disregarded due to the sandy soil type and the flat surface.

2.5. Empirical calculations and statistical analyses

Daily potential evapotranspiration (ET_p) was calculated using the FAO56 Penman-Monteith equation (Allen et al., 1998) using a crop coefficient of 1.15 in the middle of the growing season. The NUE (%) was calculated as total PNU ($kg\ ha^{-1}$) at harvest divided by total N input over the entire season (N fertilization and soil N mineralization; $kg\ ha^{-1}$). The soil N mineralization including atmospheric deposition (on average, $51.8\ kg\ ha^{-1}$) at harvest was estimated from the crop average PNU from plots that did not receive N fertilization in the N-response trials in the same field each year (Peng, 2021). The IE ($kg\ mm^{-1}$) of plots which received I_{full} and I_{def} treatments was calculated by the equation:

$$IE = (DM - DM_{I_{low}}) / (IA - IA_{I_{low}}) \quad (3)$$

where $DM_{I_{low}}$ is DM in the I_{low} treatment; IA and $IA_{I_{low}}$ are the irrigation amounts applied to the target plot and the plot received I_{low} treatment.

For evaluating treatment effects on the potato variables, linear mixed-effect models were built using the *lmer* function from 'lme4' package (Bates et al., 2015) in R with the irrigation, nitrogen fertilization and year set as fixed effects:

$$V = I_i + N_j + Y_k + I_i \times N_j + I_i \times Y_k + N_j \times Y_k + I_i \times N_j \times Y_k + 1|r + e \quad (4)$$

where V represents the dependent variable, either FM , DM , PNU , PNC , Sc , SY , nitrate leaching, $Aipar$, RUE , NUE or IE ; and I_i , N_j , and Y_k indicate fixed effect of irrigation ($i = 3$, three irrigation levels, except for IE , which was analysed only for I_{full} and I_{def}), N fertilization ($j = 2$, two N fertilization levels), and year ($k = 3$, three years, except for nitrate leaching, which was analysed only for 2018 and 2019); r is replicate i.e. block treated as a random effect; e is unexplained variation. Most analyses were conducted for both tuber and total biomass (foliage plus tuber), except Sc and SY which were only calculated for tubers. The outliers of each dependent variables were detected based on the inter-quartile range (IQR); however, outliers were not removed as the outliers were most likely derived from specific treatments (e.g., extremely high PNC under $I_{low}N_{var}$ in 2018) and the removal would significantly affect the analysis results. The Shapiro test was used to test the residual normality, and the Bartlett test was applied to test the variance homogeneity. The *Rand* function was used to test the random effect in the model. Logarithm, exponential, power, or inverse transformation methods were used for adjusting the variables if they did not pass the tests. If the linear mixed-effect model passed the assumption test, the analysis of variance (ANOVA) was implemented on the model to distinguish the significant difference between treatments (irrigation and N fertilization) and years. The model was updated by removing non-significant components (either the effects or interactions) in Eq. 4. After updating, the pairwise comparisons of the significant effects and interactions were expressed by the Least Square mean (L.S. means) values obtained by the *lsmeans* function for the updated model (from the "lsmeans" package in R; Lenth, 2016) using the 'Tukey' option at 95 % significance level ($P < 0.05$), together with specific letters of each treatment levels determined by the *cld* function (from the "multcomp" package in R; Hothorn et al., 2008). If a specific model did not pass the

assumptions (normal residual distribution or variance homogeneity) even after data transformation, the non-parametric Aligned Rank Transform (ART) modelling was implemented using the *art* function (from the “ARTool” package in R; Kay, Wobbrock, 2021). All analyses were implemented in the R environment (ver. 4.1.1; R Core Team, 2021).

3. Results

3.1. Weather condition, soil water deficit and plant transpiration

Mean daily temperature and global radiation during the growing season (0–120 DAE) in 2018 were 17.3°C and 18 MJ m⁻² respectively, which were higher than the corresponding values of 14.7°C and 13.5 MJ m⁻² in 2017 and 15.8°C and 14.8 MJ m⁻² in 2019, and also higher than the historical (2000–2016) seasonal values of 14.1°C and 16.2 MJ m⁻². Compared to the historical seasonal average precipitation of 320 mm, 2018 was markedly drier with 251 mm, while 2017 and 2019 accumulated 396 and 451 mm, respectively (Fig. S1). The average anomalies of the mean daily temperature, daily global radiation and daily precipitation during the growing season were 0.6°C, -2.6 MJ m⁻² and 1.2 mm in 2017; 3.2°C, 1.8 MJ m⁻² and -0.02 mm in 2018; and 1.7°C, -1.4 MJ m⁻² and 1.6 mm in 2019 (Fig. S2). The comparison indicates that the increasing degree of temperature in 2018 was much higher than 2017 and 2019. The global radiation was lower in 2017 and 2019 than historical data, but was higher in 2018, and *vice versa* for precipitation. Hydrological drought (low precipitation), agronomic drought (low SWC for several consecutive days) and heat wave (high temperature and

radiation) were all features of the growing season in 2018.

The SWD from I_{low} treatment was 23–44 %, 29–72 %, 10–102 % higher than SWD from I_{def} and I_{full} treatments in 2017, 2018 and 2019, respectively, varying with N fertilization treatment (Fig. 1). This clearly shows the limiting effect of I_{low} treatment on the potato growth regardless of N fertilization. Moreover, SWD between I_{full} and I_{def} was similar among all years regardless of N fertilization, which was expected for this coarse sandy soil. The relatively large gap occurred at 42–77 DAE (03 July–07 August) in 2018 when SWD from I_{def} was 50 % (for N_{full}) and 16 % (for N_{var}) higher than the values from I_{full}. During DAE 37–49 (10 July – 22 July) in 2019 for N_{full}, the SWDs from I_{def} were 45 % higher than the values from I_{full}.

Potato plant transpiration (calibrated from sap flow measurements) ranged 0.39–5.68 mm d⁻¹ and 0–2.81 mm d⁻¹ for I_{full} and I_{low}, respectively, under N_{full} during the growing season in 2018 (Fig. 2). The dynamics indicate that in I_{low}, transpiration was considerably lower than in I_{full} (on average 60 %) during 45–105 DAE. Compared to ET_P, potato plant transpirations from I_{full} and I_{low} treatments were on average 17 % and 68 % lower. This reflects the higher SWD from I_{low} in 2018 shown in Fig. 1 (drought stress). The higher amount of irrigation (140 mm) in I_{full} compared to I_{low} (15 mm) contributed to the differences in SWD (Fig. 1) and plant transpiration in the potato. The observations show that under a heatwave, if the irrigation was not or insufficiently applied, water availability and plant physiological activities (e.g. transpiration and photosynthesis) were reduced to a large degree.

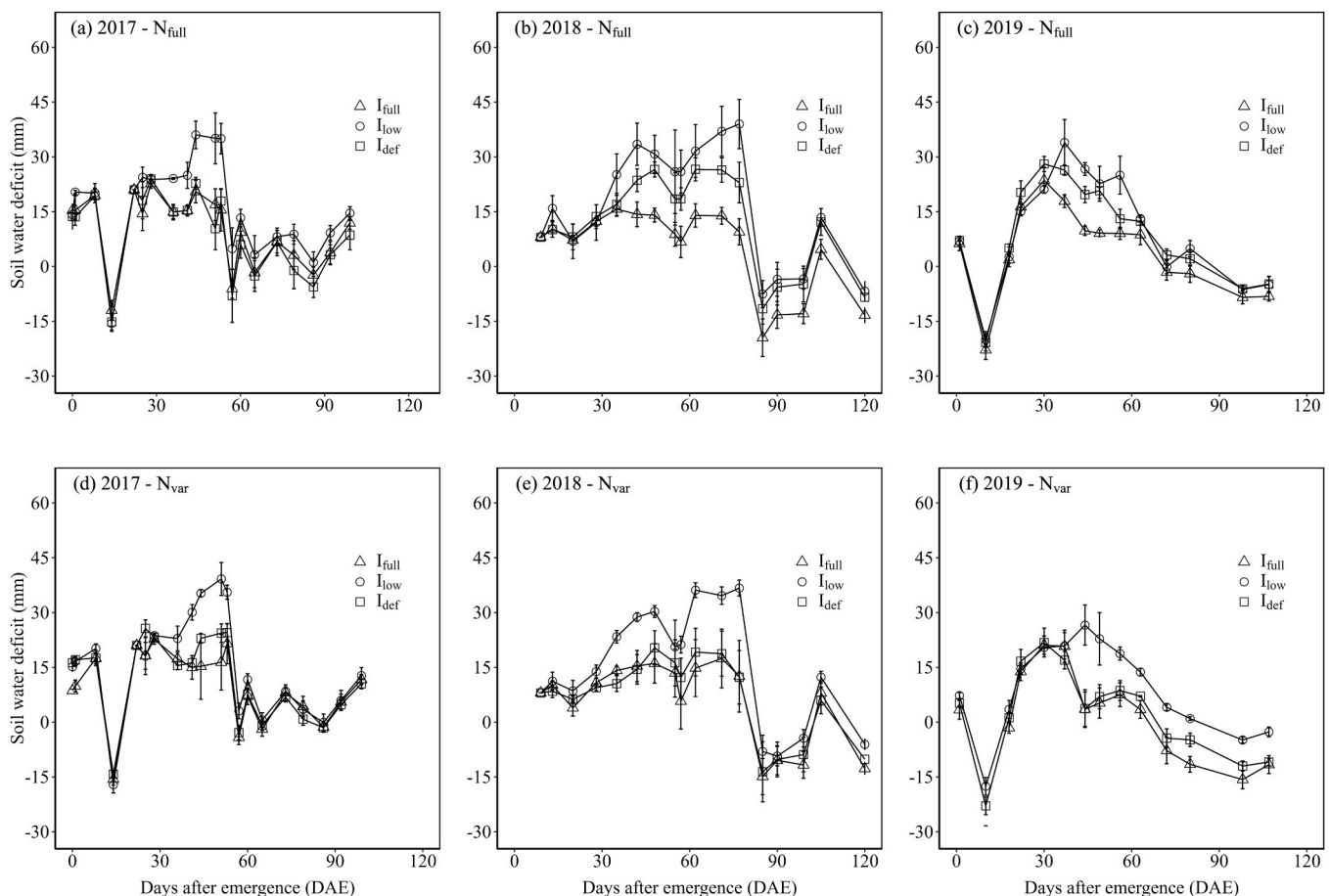


Fig. 1. Soil water deficit (SWD) for different irrigation treatments (full irrigation, I_{full}; deficit irrigation, I_{def}; and low irrigation, I_{low}) under full and variable nitrogen (N) fertilization treatments (N_{full} and N_{var}) during the growing seasons in 2017–2019. Error bars indicate the standard error of each irrigation treatment at each time point.

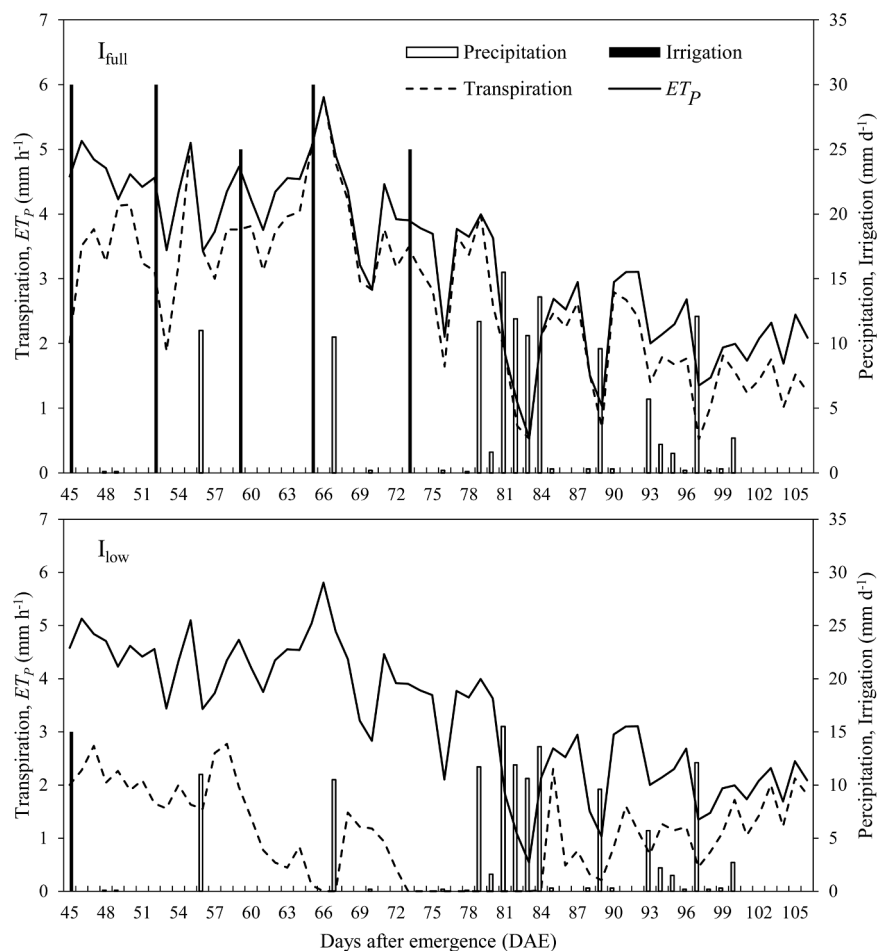


Fig. 2. Plant transpiration calibrated from sap flow measurements for full irrigation (I_{full}) and low irrigation (I_{low}) treatments under full nitrogen (N_{full}) fertilization during the growing season in 2018. The ET_p is potential evapotranspiration.

3.2. Intercepted radiation and harvested biomass

The dynamics of f_{ipar} under different irrigation and N fertilization managements are shown in Fig. 3. The f_{ipar} values ranged from 0.03 to 0.98 for all years, but over the whole season were 16–19 % lower in 2018 and 2019 compared to 2017. There was no apparent difference in f_{ipar} among irrigation treatments in 2017 and this was also the case between I_{full} and I_{def} in 2018 and 2019. However, f_{ipar} in I_{low} was on average 9–15 % lower than the other irrigation treatments, with larger variation in N_{var} in 2018 and 2019. Compared to the SWD curves in Fig. 1, it is apparent that the periods with low f_{ipar} in I_{low} coincides with the periods with high SWD during 2018 and 2019, while this was not the case for I_{def} in any of the years or for I_{low} during 2017. This implies limited growth under I_{low} due to drought stress in 2018 and 2019. The f_{ipar} from N_{var} was on average 3–12 % lower than N_{full} in all years with bigger differences (10–12 %) in 2018 and 2019. In 2018, f_{ipar} increased in I_{low} from DAE 77 (07 August 2018) following the precipitation (see Fig. S1) in late August and early September, showing recovery and regrowth of the plants after the cooccurrence of drought and heat stresses.

The ANOVA (Table 2) indicates that the irrigation and N fertilization treatments, and year had significant effects on the Aipar and biomass (FM and DM). The group-wise mean values comparisons show that I_{low} resulted in significantly lower (9–27 % depending on different variables) Aipar and biomass than those under I_{full} and I_{def} , between which no significant difference was observed, which hinted that I_{low} prohibited the potato growth. N_{var} made the Aipar and biomass significantly lower (8–20 % depending on different variables) than those under N_{full} , which

indicated that N_{var} could not match the Aipar and biomass from N_{full} . The Aipar was highest in 2018, followed by 2017 and 2019, with annual average values of 632, 553 and 489 MJ m⁻² in each year, and the annual differences of Aipar across years were significant. The biomass across the three years reduced progressively from 2017 to 2019: total FM and DM values were, on average, 79 and 18 t ha⁻¹ in 2017, 51 and 11 t ha⁻¹ in 2018, and 43 and 11 t ha⁻¹ in 2019, respectively. The biomass in 2017 was significantly higher than 2018 and 2019 (33–46 % depending on different variables), between which there was no significant difference except that the total FM in 2018 was significantly higher (16 %) than in 2019. Since the main potato biomass was tubers, the comparisons of tuber FM and DM between different treatments and years were overall similar to total FM and DM (Table 2). The exceptions occurred for tuber DM, which was lower in 2018 compared to 2017 and 2019.

The interaction of irrigation and year had significant effects on Aipar, tuber FM, and total and tuber DM. There was a significant interaction of nitrogen and year on Aipar. The interactions of irrigation and N fertilization, N fertilization and year, irrigation, N fertilization and year did not show significant effects on the biomass (Table 2).

The significant effects from interactions of irrigation and year, and N fertilization and year on Aipar were mainly derived from the significant differences among different treatment groups in 2018 and 2019, in which the Aipar under I_{full} and I_{def} was significantly higher (10–18 %) than that under I_{low} . Likewise, the Aipar from N_{full} was significantly higher (10–12 %) than that from N_{var} in 2018 and 2019 (Fig. 4).

The significant effects from interactions of irrigation and year on tuber FM (Fig. 5a), total DM (Fig. 5b) and tuber DM (Fig. 5c) were due to the significantly lower (20–53 %) values under I_{low} than those under I_{full}

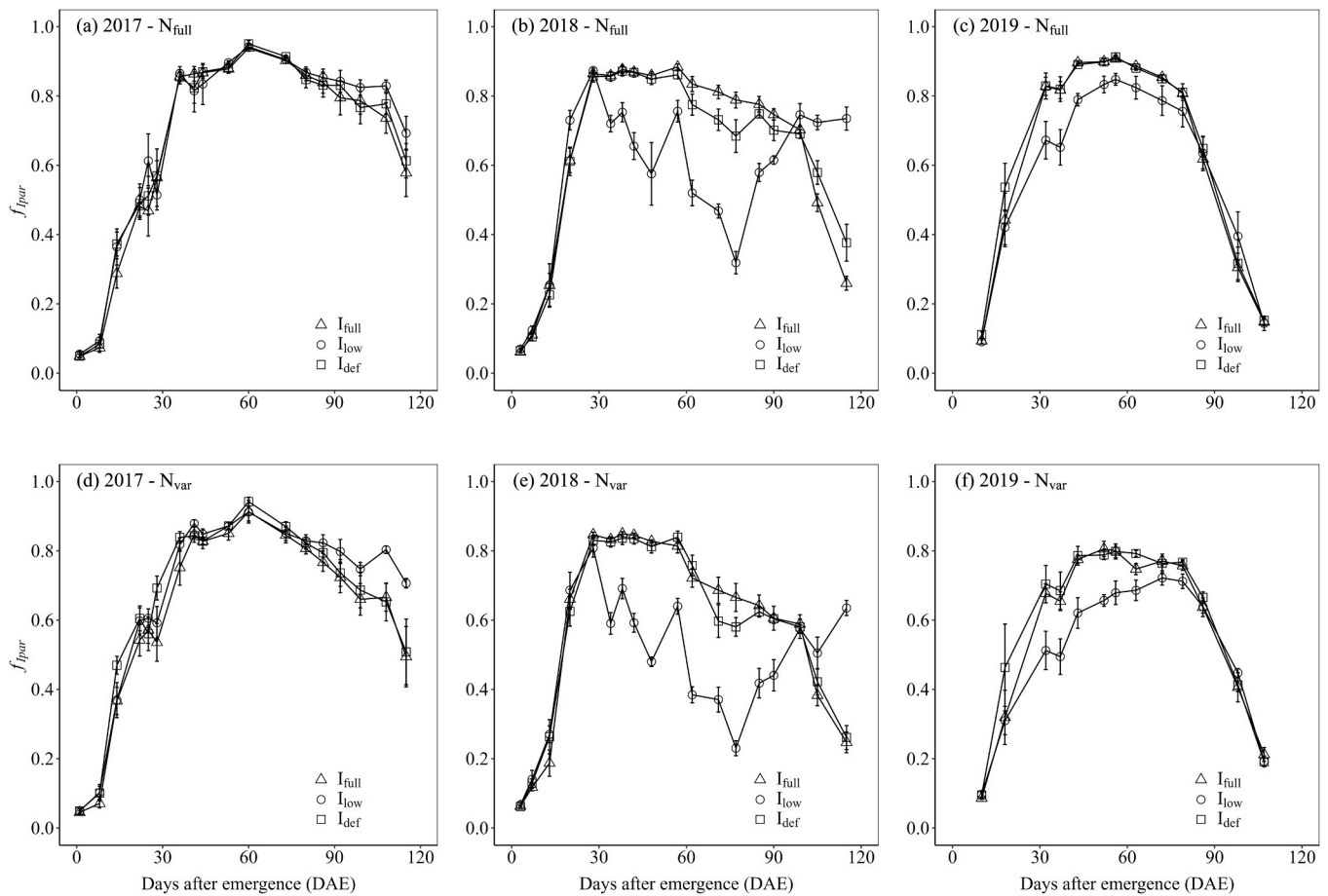


Fig. 3. Fraction of intercepted photosynthetically active radiation (f_{ipar}) for potato canopies during the growing seasons from 2017 to 2019 as affected by irrigation levels of full, low and deficit (I_{full} , I_{low} and I_{def}) and full and variable nitrogen (N_{full} and N_{var}) fertilization rates. Error bars indicate the standard error of each irrigation treatment at each time point.

Table 2

Summaries of P values of the analysis of variance (ANOVA) and group-wise least square mean values of each significant main effect for linear mixed-effect models exploring the effects from treatments (irrigation (I) and nitrogen (N) fertilization) and years (Y) on the accumulated intercepted photosynthetically active radiation (Aipar), total and tuber fresh matter (FM) and dry matter (DM) of potato at the final harvest.

Effect	Group	Aipar (MJ m^{-2})		Total FM (t ha^{-1})		Tuber FM (t ha^{-1})		Total DM (t ha^{-1})		Tuber DM (t ha^{-1})	
		P	Mean	P	Mean	P	Mean	P	Mean	P	Mean
I	I_{full}	< 0.001	572 b	< 0.001	59 b	< 0.001	50 b	< 0.001	14 b	< 0.001	13 b
	I_{def}		581 b		62 b		51 b		15 b		13 b
	I_{low}		521 a		51 a		40 a		11 a		10 a
N	N_{full}	< 0.001	581 b	< 0.001	63 b	< 0.001	51 b	< 0.001	15 b	< 0.001	13 b
	N_{var}		534 a		52 a		44 a		12 a		11 a
Y	2017	< 0.001	553 b	< 0.001	79c	< 0.001	61 b	< 0.001	18 b	< 0.001	16 b
	2018		632 c		51 b		41 a		11 a		9 a
	2019		489 a		43 a		39 a		11 a		10 a
I $\times$ N		NS		NS		NS		NS		NS	
I $\times$ Y		< 0.001		NS		< 0.001		< 0.01		< 0.001	
N $\times$ Y		< 0.01		NS		NS		NS		NS	
I $\times$ N $\times$ Y		NS		NS		NS		NS		NS	

Note: NS indicates not significant. The group-wise means values and letters showing significant levels were obtained for each significant effect (I, N, or Y) individually.

and I_{def} in 2018 and 2019, when drought and heat stresses occurred in the summer season.

3.3. Nitrogen and starch content

Similar to effects on Aipar and biomass, the irrigation and N

fertilization treatments, and year had significant effects on the total and tuber PNU and PNC, and tuber SY and S_C , except that the N fertilization did not have a significant effect on the tuber S_C (Table 3). Regarding the group-wise comparisons, the total PNU under I_{low} was significantly lower (12 %) than that under I_{def} , but not statistically different to that under I_{full} . This pattern was different to tuber PNU, which was

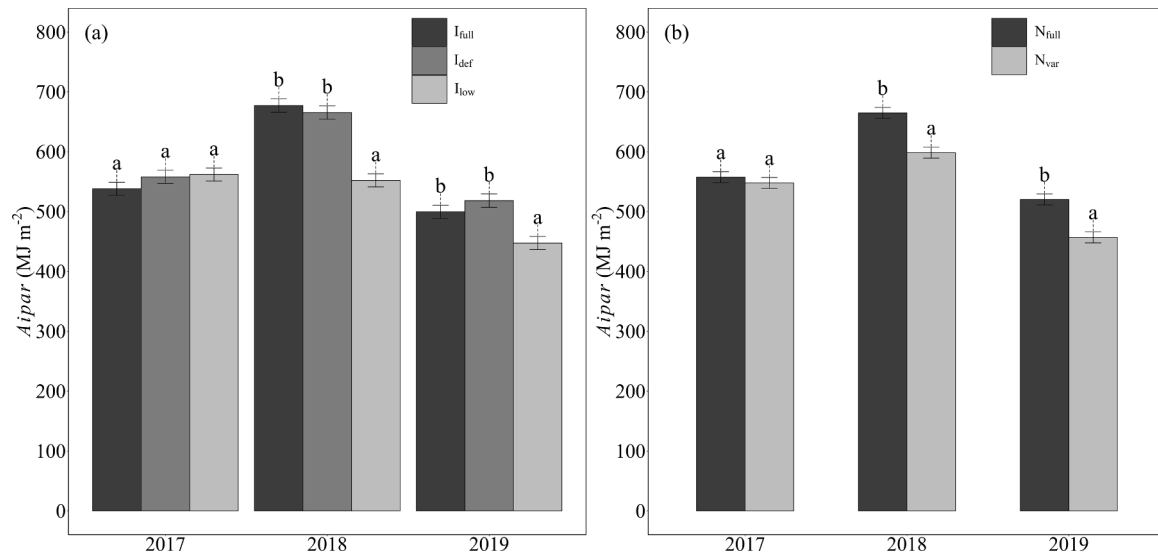


Fig. 4. Accumulated intercepted photosynthetically active radiation ($Aipar$, $MJ\ m^{-2}$) among treatment groups of irrigation (a) and nitrogen (N) fertilization (b) in each year. Low, def, full and var refer to low, deficit, full and variable treatment, respectively. Error bars indicate the standard error of treatment groups in each year. Different letters above bars indicate significant difference among different group from treatments (irrigation or N fertilization) in each single year at $P < 0.05$.

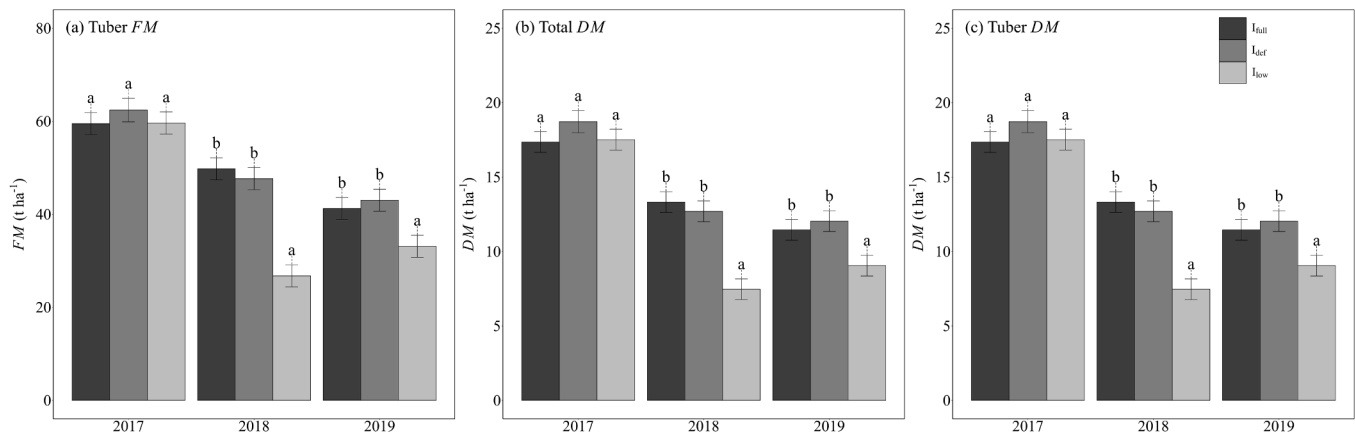


Fig. 5. Tuber fresh matter (FM , $t\ ha^{-1}$, a), and total and tuber dry matter (DM , $t\ ha^{-1}$, b and c) for different irrigation groups in each year. Low, def, and full refer to low, deficit, and full treatment, respectively. Error bars indicate the standard error of different groups in each year. Different letters above bars indicate significant difference among different irrigation treatment groups in each single year at $P < 0.05$.

significantly lower (14–17 %) under I_{low} compared to those under I_{full} and I_{def} . Both total and tuber PNU s under N_{var} were significantly lower (20–22 %) than those under N_{full} . The total and tuber PNU s were, on average, 246 and 200, 144 and 111, and 125 and 113 $kg\ ha^{-1}$ in 2017, 2018 and 2019, respectively. The values in 2017 were significantly higher (41–49 %) than those in 2018 and 2019. The total PNU in 2018 was significantly higher (13 %) than that in 2019, whereas tuber PNU in 2018 was not statistically different to that in 2019. The total and tuber PNC s under I_{low} were significantly higher (13–17 %) than those under I_{full} and I_{def} . N_{var} made total and tuber PNC s significantly lower (6 %) than that under N_{full} . The annual average values of total and tuber PNC s were, 1.38 and 1.28, 1.37 and 1.26, and 1.15 and 1.12 $kg\ ha^{-1}$ in 2017, 2018 and 2019, respectively. The total and tuber PNC s in 2017 and 2018 were not statistically different, and significantly higher (11–17 %) than those in 2019. Similar to the biomass and tuber PNU , the tuber Sc and SY under I_{low} were significantly lower (5–25 %) than those under I_{full} and I_{def} . Unlike the non-significant effect from N fertilization on tuber Sc , the tuber SY under N_{full} was significantly higher (15 %) than that under N_{var} . The tuber Sc values in 2017, 2018, and 2019 were, on average, 18.3, 16.2 and 17.8 %. The tuber Sc in 2017 was not statistically different to that in 2019, and both were significantly higher (9–11 %) than that in 2018.

The tuber SY values were, on average, 11.03, 6.88 and 7.01 $t\ ha^{-1}$ in 2017, 2018, and 2019, respectively. The tuber SY in 2017 was significantly higher (36–38 %) than that in 2018 and 2019, which were not statistically different from each other (Table 3).

The tuber Sc had a negative relationship with tuber PNC , mainly due to increased scatter of the data points in 2018 (higher tuber PNC and lower Sc at I_{low} , and *vice versa* at I_{full} and I_{def} treatments, similar to 2017 and 2019; Fig. 6a). Under drought conditions, the potato tuber bulking process was limited, therefore the tuber Sc was lower, and PNC was correspondingly higher due to low biomass (concentration effect). Tuber SY and FM were significantly positively correlated with each other, showing the importance of starch content in the final tuber FM (Fig. 6b).

The interaction of irrigation and year had significant effects on the total and tuber PNC , and tuber SY and Sc , but did not show significant effects on the total and tuber PNU . The interactions of irrigation and N fertilization, N fertilization and year, irrigation, N fertilization and year did not show significant effects on the PNU , PNC , SY , and Sc (Table 3).

The significant effects from the interaction of irrigation and year on the total and tuber PNC s were derived from the fact that the PNC under I_{low} were significantly higher (33–37 %) than those under I_{full} and I_{def} in 2018 specifically (Fig. 7a, b). The significantly lower (16–17 %) tuber Sc

Table 3
Summary of *P* values of the analysis of variance (ANOVA) and group-wise mean values of the significant main effects for linear mixed-effect models exploring the effects from treatments (irrigation (I) and nitrogen (N) fertilization) and years (Y) on the total and tuber plant nitrogen uptake (PNU), and plant nitrogen concentration (PNC), and tuber starch yield (SY) and content (SC) of potato at the final harvest, as well as the soil nitrate leaching.

Effect	Group	Total PNU (kg ha ⁻¹)			Tuber PNU (kg ha ⁻¹)			Total PNC (%)			Tuber PNC (%)			Tuber SC (%)			Tuber SY (t ha ⁻¹)			Soil nitrate leaching (kg N ha ⁻¹)		
		<i>P</i>	Mean	<i>P</i>	<i>P</i>	Mean	<i>P</i>	<i>P</i>	Mean	<i>P</i>	<i>P</i>	Mean	<i>P</i>	<i>P</i>	Mean	<i>P</i>	<i>P</i>	Mean	<i>P</i>	<i>P</i>	Mean	<i>P</i>
I	I _{full}	< 0.05	173 ab	< 0.001	< 0.001	147 b	< 0.001	< 0.001	1.21 a	< 0.001	< 0.001	1.16 a	< 0.001	< 0.001	17.7 b	< 0.001	< 0.001	8.93 b	NS	NS	8.93 b	NS
	I _{def}		182 b			151 b			1.23 a			1.15 a			17.8 b			9.12 b				
	I _{low}		161 a			126 a			1.46 b			1.34 b			16.8 a			6.87 a				
N	N _{full}	< 0.001	193 b	< 0.001	< 0.001	157 b	< 0.001	< 0.001	1.34 b	< 0.001	< 0.01	1.25 b	< 0.001	NS	18.3 b	< 0.001	< 0.001	8.97 b	NS	NS	8.97 b	NS
	N _{var}		150 a			126 a			1.26 a			1.18 a			16.2 a			7.64 a				
Y	2017	< 0.001	246c	< 0.001	< 0.001	200 b	< 0.001	< 0.001	1.38 b	< 0.001	< 0.001	1.28 b	< 0.001	< 0.001	17.8 b	< 0.001	< 0.001	11.03 b	NS	NS	11.03 b	NS
	2018		144 b			111 a			1.37 b			1.26 b			16.2 a			6.88 a				
	2019		125 a			113 a			1.15 a			1.12 a			17.8 b			7.01 a				
I × N		NS		NS	NS		NS	NS		NS	NS		NS	NS		NS	NS		NS	NS		NS
I × Y		NS		NS	NS		NS	< 0.001		< 0.001	< 0.001		< 0.001	< 0.001		< 0.001	< 0.001		NS	NS		NS
N × Y		NS		NS	NS		NS	NS		NS	NS		NS	NS		NS	NS		NS	NS		NS
I × N × Y		NS		NS	NS		NS	NS		NS	NS		NS	NS		NS	NS		NS	NS		NS

Note: NS indicates not significant. The group-wise means values and letters showing significant levels were obtained for each significant effect (I, N, or Y) individually.

under I_{low} compared to those under I_{full} and I_{def} in 2018 was the reason why the interaction of irrigation and year had an overall significant effect on tuber SC. Likewise, the significantly lower (20–55 %) tuber SY under I_{low} compared to those under I_{full} and I_{def} in 2018 and 2019 resulted in a significant effect from the interaction of irrigation and year on the tuber SY.

3.4. Soil nitrate leaching

There were no significant differences in nitrate leaching among the different treatments and years ($P > 0.05$ for all effect variables and interactions, Table 3), which can also be seen from pairwise comparisons (Fig. 8). Under the same irrigation treatment, nitrate leaching from N_{full} was 2–32 % higher than the values from N_{var} (depending on year and irrigation, and the largest difference occurred for the I_{def} treatment), which implies that N_{var} could reduce nitrate leaching to a certain extent. The exception was that leaching from I_{full}N_{var} was 18 % higher than I_{full}N_{full} in 2018.

I_{low} produced the lowest nitrate leaching, 4–34 % than the values from I_{full} and I_{def}. The nitrate leaching from I_{full} was in general 9–13 % higher than the values from I_{def}, except that in 2018 under N_{full}, the nitrate leaching from I_{def} was 32 % higher than the values from I_{full}.

Regarding the combined effects from irrigation and N fertilization, the nitrate leaching from both I_{low}N_{full} and I_{low}N_{var} was on average 21 % lower than other combinations in two years. Under I_{full} and I_{def}, the nitrate leaching from I_{def}N_{var} was 12–39 % lower than other combinations in each year. The exception is that in 2018 the value from I_{def}N_{var} was 7 % higher than I_{full}N_{full}, but the difference was minor compared to the differences with other treatments.

3.5. Resource use efficiency analyses

The total and tuber RUEs were significantly affected by irrigation, N fertilization and year (Table 4), similar to the results for biomass (Table 2). The N fertilization had no significant effect on the total and tuber NUE and IE, whereas the irrigation and year showed significant impacts on them. In details, the total and tuber RUEs from I_{low} and N_{var} were significantly lower than those from I_{full} and I_{def} (14–19 %), and those from N_{full} (9–11 %). The total and tuber RUEs in 2017, 2018 and 2019 were, on average, 3.22 and 2.83, 1.74 and 1.46, as well as 2.21 and 2.06 g MJ⁻¹, respectively. The annual total and tuber RUE differences were significant: the values in 2017 were highest, progressively followed by those in 2019 and 2018.

The total and tuber NUEs from I_{def} were not statistically different to those from I_{full} but significantly higher (11–18 %) than those from I_{low}. The total NUE from I_{full} was not statistically different to that from I_{low}, however, the tuber NUE from I_{full} was significantly higher (14 %) than that from I_{low}. The total and tuber NUEs in 2017, 2018 and 2019 were 92 and 79, 68 and 52, and 57 and 52 %, respectively. The total NUE in 2017 was highest, progressively followed by 2018 and 2019, and the annual differences were significant. The tuber NUE in 2017 was significantly higher (34 %) than that in 2018 and 2019, which were not significantly different to each other.

The total and tuber IEs from I_{def} were significantly higher (31–32 %) than those from I_{full}. The total and tuber IEs were 17.2 and 17.1, 30.3 and 31.8, and 24.2 and 22.8 kg ha⁻¹ mm⁻¹ in 2017, 2018 and 2019, respectively. The total and tuber IEs in 2018 were highest, which were not statistically different to those in 2019, but significantly higher (43–46 %) than those in 2017 (Table 4).

The effect from the interaction of irrigation and year on the tuber RUE was significant, which was mainly derived from the significantly lower (40–42 %) values from I_{low} compared to those from I_{full} and I_{def} particularly in 2018 (Fig. 9); however, other interactions did not show significant impacts on the resources use efficiencies (Table 4).

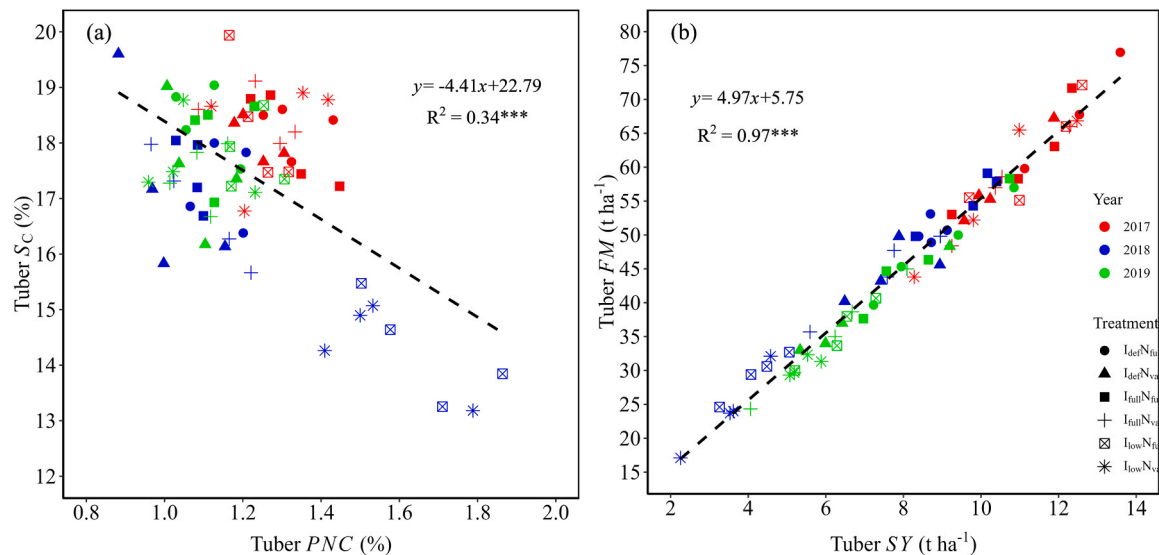


Fig. 6. The linear fit between tuber starch content (Sc ,%) and tuber nitrogen concentration (PNC ,%), as well as the linear fit between tuber fresh matter (FM , $t\ ha^{-1}$) and tuber starch yield (SY , $t\ ha^{-1}$). The black dashed lines are the linear fit regression lines. *** denotes significance at $Pp < 0.001$.

4. Discussion

4.1. Effects from irrigation, N fertilization and their combinations on potato production

The overall high N fertilization amount and cool and wet weather were the main reasons why the tuber and total potato production were higher in 2017 than in 2018 and 2019. The unexpected less mineralized N from the soil in 2019 (less than 20 % compared to 2018, Peng, 2021) was the main reason why the biomass was lower in 2019.

In this study, the potato Aipar and biomass from N_{var} were significantly lower than those from N_{full} ; moreover, the NUE s from N_{var} were not statistically different to those from N_{full} (Table 4). These findings do not agree with previous studies which showed that a split N fertilization strategy maintains potato production with less N input and higher NUE (Ahmed et al., 2017; Souza et al., 2020). This highlights the shortcoming of methods proposed by Zhou et al. (2017b) as it only detects plant N deficiency, but it could not quantify the exact N requirements. Determining the timing and precise amounts of the split applications remain a challenge due to the effect on both production and environmental flows such as nitrate leaching. Remote sensing of potato canopies shows potential due to its time efficiency, non-destructive nature, and high spatio-temporal accuracy (Peng et al., 2021a).

Under I_{low} , the biomass in 2018 was significantly lower than that under I_{full} and I_{def} in 2018 and 2019. The reason might be that under the I_{low} treatment, the tuber enlargement was constrained in the bulking stage and could not be recovered later since the bulking process was paused during the drought in the summer season in 2018 and 2019. Jefferies and Mackerron (1989) reported similar results in a study in Scotland, that tuber yields in drought treated potatoes were 37–44 % of irrigated potatoes. Several studies have reported that drought stress limits crop growth and reduced biomass (Alqudah et al., 2011; Joshi et al., 2016; Lamaoui et al., 2018; Lobell et al., 2013). The mechanism is that drought stress reduces the photosynthetic rate and CO_2 fixation due to stomatal closure, which leads to less accumulated production (Mafakheri et al., 2010). With prolonged dehydration, plant leaves roll and wilt, which results in weakness and even death (Sahoo et al., 2013) and thus lower f_{ipar} . A parallel study focused on the remote sensing data based evapotranspiration estimation found that the measured stomatal conductance values from I_{low} were all lower than $0.4\ mol\ m^{-2}s^{-1}$ and most of them were below $0.2\ mol\ m^{-2}s^{-1}$ (see Fig. 7 from Peng et al., 2023) from which the photosynthetic water use efficiency started to

decline dramatically thus the crop growth was inhibited (Liu et al., 2005). Moreover, in 2018, the potatoes were also exposed to heat stress – there were 8 days with daily maximum temperature (T_{max}) higher than $29^{\circ}C$ in which the photosynthesis was paused, and 109 out of 119 days during the growing season with the T_{max} higher than $17.2^{\circ}C$ which is the optimal T_{max} (for details, see Peng et al. 2021b). The concurrent occurrence of drought and heat stress could lead to more severe consequences than single stresses by affecting the photosynthesis, osmolyte accumulation, antioxidation and nutrient uptake (Hussain et al., 2019; Ostmeier et al., 2020). Thus, breeding drought and heat tolerant potato cultivars would be useful for mitigation of these stresses (Lamaoui et al., 2018; Martínez et al., 2021; Obidiegwu et al., 2015; Zaki and Radwan, 2022).

In this study, the interaction of irrigation and N fertilization did not have significant effects on the biomass and N status (Tables 2 and 3), which indicates that overall, the effects from either irrigation or N fertilization did not depend on the level of each other. This finding is different from the results reported by Ierna and Mauromicale (2018) and Satognon et al. (2021) but is in line with the results presented by Fandika et al. (2016) for biomass and Gheysari et al. (2009) for PNU . The reason might be the experimental design of the current study, in which the difference between the two N fertilization rates was not big enough compared to some other studies, which included several N fertilization rates with relatively big differences (Ierna and Mauromicale, 2018). The rather small difference and less gradients in N fertilization rates might have made the overall effect from irrigation less sensitive to the N fertilization treatment. In the study of Fandika et al. (2016), a similar experimental design (three irrigation levels, which were no irrigation, partial irrigation and full irrigation; two N fertilization levels, which were low and high N fertilization rates) was applied and the effect from the interaction of irrigation and N fertilization on the biomass was also not significant.

4.2. Nitrate leaching from potato fields under wet and dry meteorological conditions

The leached nitrate under $I_{full}N_{full}$ in 2018 was lower than the amount in the same combined treatment in 2019. Moreover, the nitrate leaching from $I_{full}N_{full}$ was also lower than other combined treatments except I_{low} in 2018. A possible reason is that the potato plants from $I_{full}N_{full}$ treatment plots in 2018 utilized more N than plants from other treatments under a heatwave to alleviate the heat stress derived from

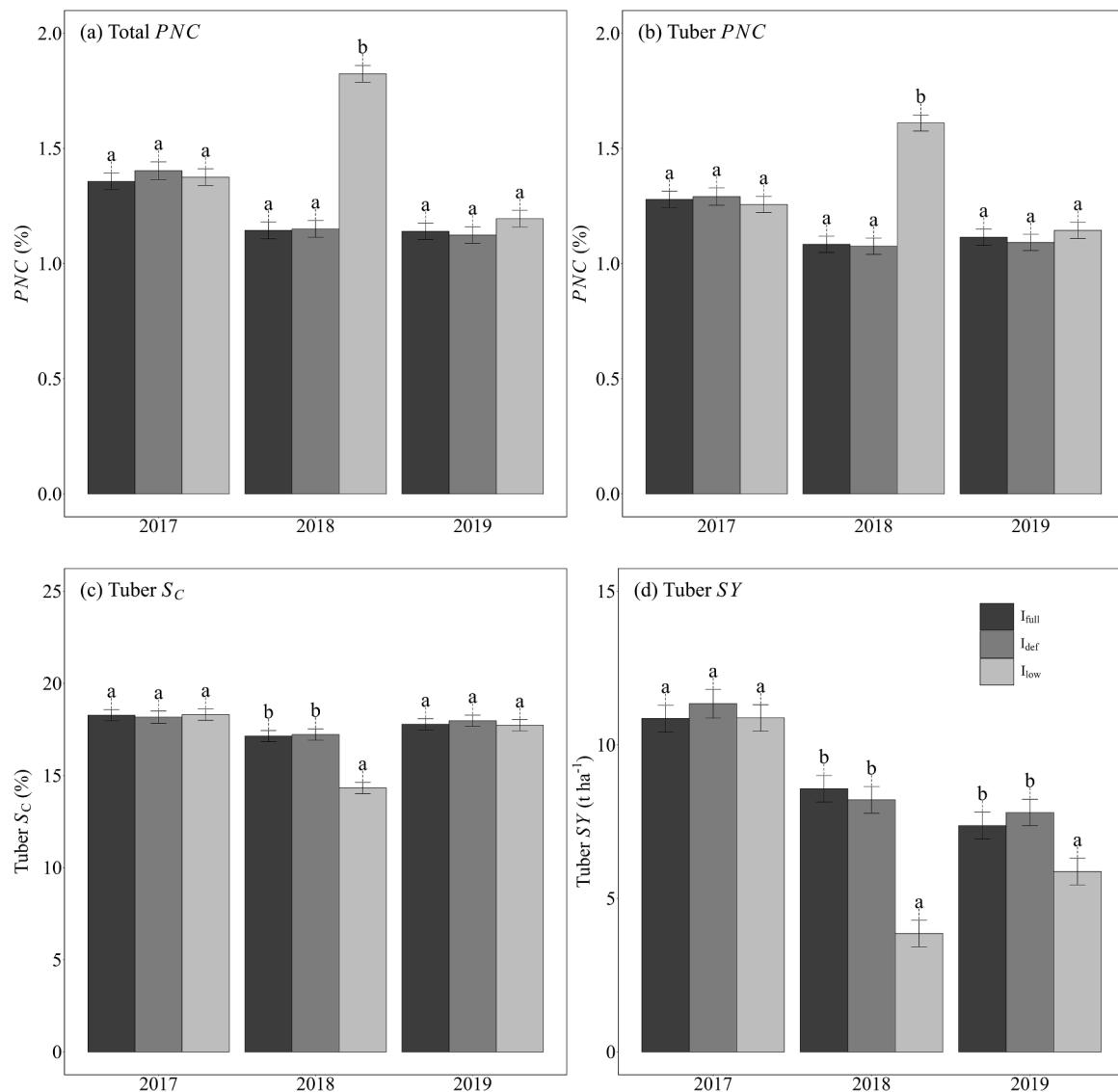


Fig. 7. Total and tuber plant nitrogen concentration (PNC, %, a and b), tuber starch content (S_C, %, c) and tuber starch yield (SY, t ha⁻¹, d) among different irrigation groups in each year. Low, def, and full refer to low, deficit, and full treatment, respectively. Error bars indicate the standard error of different groups in each year. Different letters above bars indicate a significant difference among different groups in each single year at $P < 0.05$.

higher temperature as the resource inputs (N and water) were maximum, thus less N was leached. Several studies have revealed that with ample water provided, sufficient N supply can alleviate the negative effects from heat stress on crop photosynthesis; and the reason is that the N assimilation capacity was improved thus the chlorophyll content was increased and several physiological activities (such as Rubisco, phosphoenolpyruvate carboxylase, osmoregulation and antioxidation) were enhanced (Guo et al., 2024; Ostmeier et al., 2020; Ru et al., 2023). Nitrate leaching is a complex process and can be affected by several factors, such as applied N fertilizer, applied irrigation, soil N mineralization, leaching depth, crop growth stage, crop N uptake as well as field management including rotations (Gheysari et al., 2009; Jiang et al., 2022).

In both years, the nitrate leaching from I_{low} treatments tended to be lower than in the I_{full} and I_{def} treatment no matter the N fertilization regimes. Ten Damme et al. (2022) reported that in general, non-irrigated treatments of grain crops and oilseed rape leached more nitrate than the irrigated treatments, especially when droughts occurred during the growing season. This is not in agreement with the results from the current study, particularly for the nitrate leaching in 2018 when serious

drought happened during the growing season. A possible reason might be that in this study, due to the alleviation of the drought stress derived from lower temperature and more precipitation during the later season in 2018, the potato especially the foliage part started to regrow to a large extent (from 80 DAE, see Fig. 3) and due to the regrowth process, N was taken up from the soil later in the season. As this happened so late, the foliage parts were not mineralized during the winter so the N was retained in the soil.

If only taking 2019, which was a more normal year, into consideration, the nitrate leaching from I_{full} was in general higher than I_{def}. This implies that usually I_{def} could reduce the nitrate leaching as less water was applied to the field, which is in line with several previous studies which showed that excessive irrigation resulted in considerable higher amount of nitrate leaching in sandy soils with low water-holding capacity (Gehl et al., 2005; Zotarelli et al., 2007). On the other hand, except I_{full}N_{full} in 2018, under the same irrigation treatment, the amount of leached nitrate from N_{full} was higher than N_{var}, which indicates that the N_{var} treatment could reduce N leaching (Fig. 8). It is supported by several other studies that split-N application can reduce N leaching (Rosen and Bierman, 2008; Zhou et al., 2018).

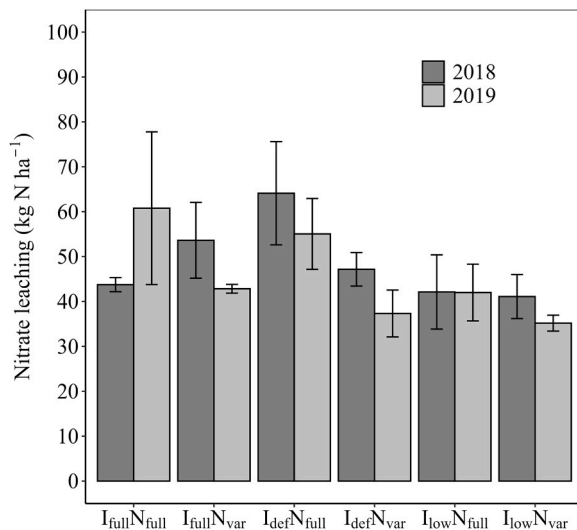


Fig. 8. Annual nitrate leaching (kg N ha^{-1}) amounts from the potato field experiments in 2018 and 2019 in Denmark. Error bars are the standard errors of treatment combinations ($n = 4$).

In this study, the ceramic suction cups were installed in the field to collect soil water solution and measure rootzone nitrate concentration, which was widely used by other studies to determine nitrate leaching (Weihermüller et al., 2007; Wolf et al., 2023). However, several challenges remain as usually it is difficult to get samples with enough volume in coarse sandy soils when dry conditions occur because less soil water is available (Zotarelli et al., 2007). Trying other approaches such as drainage lysimeters and soil cores or their combinations might be able to overcome this shortcoming. It is also challenging to estimate water flux and interpolate the nitrate concentrations between measurement days with high accuracy (Vogeler et al., 2020). Finding appropriate models for water fluxes estimation and nitrate concentration interpolation is therefore important.

4.3. Resource use efficiencies of potato under different treatments

The variation of *RUE* over years was high, which was a result of the contrasting biomass and *Aipar* (Tables 2, 4). Global radiation and temperature are often correlated on a seasonal basis, so the curtailed production may be both due to higher temperatures and lower fraction of diffuse radiation, which was controlled by the annual climatic

conditions. This finding agrees with the conclusion from Garbulsky et al. (2010), who found that the annual variation of crop *RUE* was mainly related to the energy balance and water availability following the climatic gradient. This points to a weakness in simple *RUE* models and the need to adjust them for climatic conditions.

In this study, the analysis revealed that the total *NUEs* from *N_{var}* were statistically similar to that from *N_{full}* (Table 4). Less applied N fertilizer led to proportionally lower biomass and *PNU*, thus *NUE* was unchanged. This is not in line with several other studies which reported that split N fertilizer applications according to potato growth needs improved N fertilizer use efficiency (Datta et al., 2015; Rens et al., 2015; Uddin et al., 2017; Zotarelli et al., 2015). The possible reason could be that in this study the amount of the applied N fertilizer under *N_{full}* was the highest threshold. The amount of the applied N from the high-level N fertilization treatments by other studies was likely not that high, thus it might be easier for other studies to get an improved *NUE* by applying split N fertilizer applications.

In this study, the *IE* values from *I_{def}* were generally higher than the values from *I_{full}* (Fig. 7e). It has been reported by several previous studies that deficit irrigation (DI, approx. 70 % of full irrigation) can increase *WUE* and save water (Ferreira and Soriano, 2006; Karam et al., 2014; Wang et al., 2009). DI can activate the production of root-based chemical signals (abscisic acid) which enable the crop to maintain the physiological response to drought stress and enhance the guard cell signal transduction network; and these abilities can decrease water loss from transpiration, maintain high leaf water potential and osmotic regulation of leaf-turgor pressure, optimize stomatal control that improves the photosynthesis to transpiration ratio, and decrease evaporative surface areas that reduces soil evaporation, thus the *WUE* and *IE* are improved (Chai et al., 2016; Jensen et al., 2010). In the current study, the irrigated water amounts of *I_{def}* treatments were proportional to *I_{full}* treatments, which was determined by *SWC* and *SWD*. This method is useful and accurate for small-scale fields, but it would be challenging for large-scale field application. Remote sensing based evapotranspiration modelling from thermal imaging technology is a useful and applicable approach for large-scale crop drought condition detection and DI determination (Antoniuk et al., 2021; Nieto et al., 2019; Peng et al., 2023).

It was reported by several previous studies that the combination of DI and split N fertilization could increase *NUE* and *WUE* for several crops, including potato (Di Paolo and Rinaldi, 2008; Gheysari et al., 2009; Ierna et al., 2011; Tang et al., 2021; Xing et al., 2022). In this study, it was confirmed that *I_{def}* could greatly increase the *IE* compared to *I_{full}*; however, the *NUE* from *N_{var}* was not statistically different compared to

Table 4

Summary of *P* values of the analysis of variance (ANOVA) and group-wise mean values of the significant main effects for linear mixed-effect models exploring the effects from treatments (irrigation (I) and nitrogen (N) fertilization) and years (Y) on total and tuber radiation use efficiency (*RUE*), nitrogen use efficiency (*NUE*) and irrigation efficiency (*IE*) of potato at the final harvest.

Effect	Group	Total <i>RUE</i> (g MJ^{-1})		Tuber <i>RUE</i> (g MJ^{-1})		Total <i>NUE</i> (%)		Tuber <i>NUE</i> (%)		Total <i>IE</i> ($\text{kg ha}^{-1} \text{mm}^{-1}$)		Tuber <i>IE</i> ($\text{kg ha}^{-1} \text{mm}^{-1}$)	
		<i>P</i>	Mean	<i>P</i>	Mean	<i>P</i>	Mean	<i>P</i>	Mean	<i>P</i>	Mean	<i>P</i>	Mean
I		< 0.001		< 0.001		< 0.05		< 0.001		< 0.05		< 0.05	
	I _{full}		2.48 b		2.23 b		72 ab		63 b		19.5 a		19.6 a
	I _{def}		2.52 b		2.24 b		76 b		66 b		28.6 b		28.5 b
	I _{low}		2.16 a		1.88 a		68 a		54 a				
N		< 0.001		< 0.001		NS		NS		NS		NS	
	N _{full}		2.53 b		2.22 b								
	N _{var}		2.25 a		2.01 a								
Y		< 0.001		< 0.001		< 0.001		< 0.001		< 0.05		< 0.05	
	2017		3.22c		2.83c		92 c		79 b		17.2 a		17.1 a
	2018		1.74 a		1.46 a		68 b		52 a		30.3 b		31.8 b
	2019		2.21 b		2.06 b		57 a		52 a		24.2 ab		22.8 ab
I × N		NS		NS		NS		NS		NS		NS	
I × Y		NS		< 0.05		NS		NS		NS		NS	
N × Y		NS		NS		NS		NS		NS		NS	
I × N × Y		NS		NS		NS		NS		NS		NS	

Note: NS indicates not significant. The group-wise means values and letters showing significant levels were obtained for each significant effect (I, N, or Y) individually.

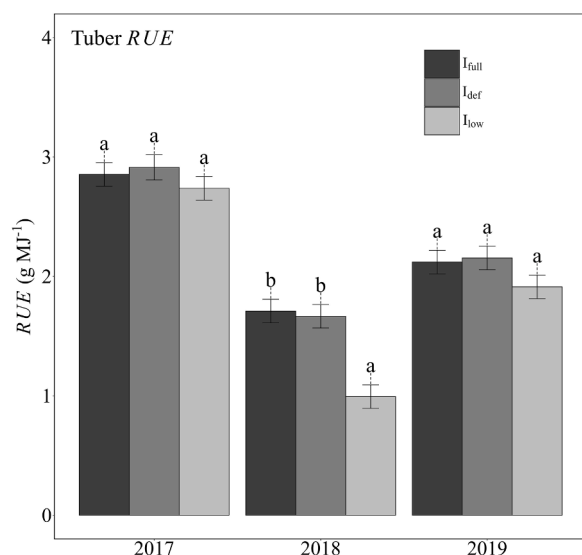


Fig. 9. Tuber radiation use efficiency (RUE , g MJ⁻¹) among different irrigation groups in each year. Low, def, and full refer to low, deficit, and full treatment, respectively. Error bars indicate the standard error of different groups in each year. Different letters above bars indicate significant difference among different groups in each single year at $P < 0.05$.

that from N_{full} , which was mainly derived from significantly lower biomass and PNU under N_{var} compared to those under N_{full} . Nevertheless, it should not be concluded that the combination of I_{def} and N_{var} is not the best choice for potato growth, since there is previous evidence in several other studies that it is the best combination from the perspective of resource use efficiencies (Badr et al., 2012; Gheysari et al., 2009). From this study, the results highlight the need for more precise and applicable quantification of in-season crop N requirements.

In this study, the effects of irrigation, nitrogen and year on several different variables including resources use efficiencies were analysed. Several other studies implemented similar experiments and data analysis (Fandika et al., 2016; Ierna and Mauromicale, 2018) with different treatments such as different doses of irrigation and N rates. Unlike most of these studies, we also analysed the treatment effects on the nitrate leaching. From the perspective of nitrate leaching and environmental protection, $I_{def}N_{var}$ tended to have lower N losses to the environment than fully N-fertilized and fully irrigated plots. However, the current study still does not address several key points, such as how to determine the optimal timing and doses of N topdressing (more directly than Zhou et al. 2017b) and irrigation, which should be in focus in the future.

5. Conclusion

The low irrigation (I_{low}) treatment significantly inhibited potato growth compared to higher irrigation levels (I_{full} or I_{def}), which indicates the important role of irrigation during a heatwave. I_{def} performed as good as I_{full} both under these stress conditions and without them. N_{var} could not produce comparable biomass (FM and DM) and N content compared to the legally allowed maximum N fertilization amount (N_{full}). The split N_{var} treatment reduced N leaching compared to N_{full} treatment, on the other hand, I_{def} treatment produced less N leaching compared to I_{full} under the usual circumstances (e.g., 2019 with less drought stress). To ensure effective application of the combination of irrigation and N fertilization from both agronomic and environmental perspectives, future efforts should focus on developing improved approaches for in-season crop N status detection and quantification of N fertilization requirements, as well as promoting the co-scheduling of $I_{def}N_{var}$. Remote sensing approaches are promising for optimising and accomplishing this.

CRedit authorship contribution statement

Junxiang Peng: Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Kiril Manevski:** Writing – review & editing, Supervision, Methodology, Investigation, Data curation, Conceptualization. **Kirsten Kørup:** Writing – review & editing, Supervision, Methodology, Investigation, Data curation. **Mathias Neumann Andersen:** Writing – review & editing, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **David Parsons:** Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.eja.2025.127874.

Data availability

Data will be made available on request.

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