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Assessing the Impact of Different Irrigation Levels on Starch Potato Production

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Abstract: In the view of increasing water demands in agriculture, efficient water use is a key factor in potato production. The aim of this study was to compare two deficit (80% and 90%) and one abundant (120%) gun sprinkler irrigation levels with the longtime used irrigation level of a farmer (100%). Irrigation was supplied during the 2021 growing season on a loamy sand site in Mecklenburg–Western Pomerania, Germany. Yield and tuber quality of the high-amylopectin potato (HAPP) variety "Waxy/Henriette" were assessed in a three-grade tuber size distribution. Five economic indicators were used to assess the suitability of the investigated irrigation levels to secure economic responses. Yield and starch yield did not significantly differ between the 90% (561.1 dt ha^{-1} and 102.0 dt ha^{-1}) and the 100% irrigation levels (559.1 dt ha^{-1} and 102.3 dt ha^{-1}), with total production increasing by 2.0 dt ha^{-1} and starch production decreasing by 0.4 dt ha^{-1} at the 90% irrigation level. Tuber lesions decreased the economic responses at all irrigation levels. Potentially, 87,469 m^3 of irrigation water (125.8 m^3 ha^{-1}) could have been saved on the loamy sand starch potato sites of the local farm (695.3 ha) in 2021.

Keywords: gun sprinkler irrigation management; high-amylopectin potatoes; tuber quality; sustainable irrigation; farm level economic responses; irrigation efficiency

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1. Introduction

Agricultural production is considered to react particularly vulnerably to extreme weather conditions, and farmers need to be prepared for impairments caused by predicted changes in intra-seasonal climatic variance. In Germany, 506,500 ha were irrigated in 2019 (3% of the total agricultural area). The irrigated area increased by 36%, compared with 2009 [1]. The potato production in Germany covered an area of 258,300 ha in 2021, with increases of 3900 ha, compared to the production area in 2021. Average yield was 437.9 ha dt^{-1} (2010: 398.7 dt ha^{-1}; [1]). Irrigation is applied on most of the sites used for potato production. Starch potatoes were cultivated on 60,339 ha in 2021 (i.e., 23.4% of all potato cultivation sites) with average yields of 417.5 dt ha^{-1}. In 2010, the cultivated area was 72,100 ha, and the average yield was 407.6 dt ha^{-1}.

Hence, 27.0% of all starch potatoes in the European Union were cultivated in Germany in 2021 [2]. In many regions that have been usually characterized by rainfed agriculture, increasing water scarcity during the growing season shows the need of a demand-driven supplemental irrigation and sustainable irrigation management [3], at least for some crops.

The irrigation demand of a crop is usually defined as the water demand, i.e., the plant water consumption [4], combined with the irrigation efficiency [5]. Hence, irrigation is usually considered as replenishing the soil moisture content to provide the optimum ranges of plant available water content (PAW) for the crop [6]. The irrigability of a specific crop is characterized by the consideration of economic responses and sustainable and environmental implications [7]. Irrigation decision support systems based on soil moisture or crop evapotranspiration simulations are recognized as fundamental tools in water resource management [8] as they provide key information on the spatial and temporal variance of the irrigation demands of specific crops [9] and the economic efficiency of irrigating specific crops [10,11]. However, existing research has mainly focused on crop-level adaptation strategies, while more research is needed on measures, costs, and adaptation at the farm level and for specific cropping systems [12–14].

For potatoes (*Solanum tuberosum* L.), as a major crop in worldwide food production—ranking fifth after sugar cane, maize, wheat, and rice [15]—water management is a key factor for securing yields and for increasing tuber quality [16]. All phenological stages in potato growth are sensitive to insufficient water supply, mainly attributed to the sparse and poorly branched root system of potatoes and their low capacity of regeneration after water stress [17]. Due to their relatively small root length per unit, potato plants are generally poor conductors of water [18]. Limited photosynthesis due to stomatal closure during drought stress leads to decreasing plant growth [19], leaf growth [20], leaf area index [21], and ground coverage [22]. Moreover, insufficient water supply during emergence and tuberization leads to smaller tubers [23] or lower starch content [24]. A demand-driven water supply may also reduce the vulnerability of the plant to pest infestation [25]. Ideal conditions for potato growth are deep, well-drained, and loose soils in humid climates [26]. Ensuring an optimal water supply to the potato crop by regulating the soil water dynamics within the crop-specific optimal PAW ranges leads to highest yields [27,28], supports the phenological development [29], increases the tuber quality [30], and is hence considered to stabilize and increase potato production.

Usually, the final starch content of potatoes is composed of two types of polysaccharides: amylose and amylopectin, whose ratio determines the quality as well as the cooking and industrial product properties (e.g., thickening, viscosity [31]). Amylose is an essentially linear polymer with few branches, whereas amylopectin has a highly branched structure in which branch chains are linked to the linear chains by α-(1,6)-linkage [32,33]. New starch potato varieties were cultivated during the last decades, which only consist of amylopectin compounds. These "high-amylopectin potatoes" (HAPP) are characterized by higher viscosity and lower gelatinization temperatures than table potatoes [34]. HAPP may play an increasingly significant role in potato-based convenience food production due to their high starch content and quality [35]. However, there is a widespread problem with excessive irrigation in potato irrigation management. Farmers often believe that increasing irrigation levels is an important way to avoid yield and quality reductions [29]. This leads to wasteful water consumption in potato production. In terms of sustainable water use, the actual crop and cultivar-specific irrigation demand must be determined and integrated in compliance with the irrigation efficiency into irrigation decision support systems to ensure a demand-driven water application.

Hence, the number of studies combining yield and quality criteria with farm level economic implications of HAPP irrigation management under practice-oriented agricultural conditions is generally low. As, for example, Mandryk et al. (2017) [12] concluded, there is a research gap in integrating economic implications into irrigation decision support systems. Moreover, new insights into HAPP yield and quality response to irrigation may enable a more demand-driven and sustainable water management at the field level, which may increase the irrigability of other crops or reduce the water extraction from water bodies.

This study aims to (i) assess the optimum irrigation level for HAPP considering yield, tuber quality, and economic responses, especially whether yield and quality losses resulting from drought stress might lead to lower economic responses; (ii) investigate farm level economic implications of a variable irrigation level; and (iii) compare the optimum irrigation level with existing irrigation techniques for table potatoes, e.g., partial root-zone drying techniques, which may not be suitable for HAPP, resulting from slightly shifted optimum PAW ranges, leading to different water and irrigation demands, while considering the efficiency of gun sprinkler irrigation systems. This important information for irrigation decision support systems may enable more demand driven HAPP irrigation management.

We hypothesize that (i) HAPP are often over-irrigated in agricultural practice, as lower irrigation levels might be sufficient for securing yield, tuber quality, resulting from slightly shifted optimum PAW ranges of HAPP, and an under-estimation of the irrigation efficiency; (ii) a slightly lower irrigation level than the common irrigation of the farmer leads to maximum economic responses; and (iii) the identified optimum irrigation levels help to improve farm level irrigation management, leading to considerable water savings per growing season without significant losses in yield, tuber quality, and economic responses.

2. Materials and Methods

2.1. Study Site Characterization

The study site is part of the "AgriSens DEMMIN 4.0" research project, embedded in the DEMMIN (Durable Environmental Multidisciplinary Monitoring Information Network) test site [36]. The study was conducted during the growing season 2021 on loamy sand (27.0 ha) near the village of Bentzin, Mecklenburg–Western Pomerania, Germany (53°56′58″ N, 13°14′40″ E).

According to the IUSS Working Group WRB (2015) [37], the soil type in the study site is a homogeneous stagnic Cambi/Luvisol. The topsoil (0–30 cm) is a loamy sand [38], comprised of 797 g kg^{-1} sand, 182 g kg^{-1} silt, and 21 g kg^{-1} clay. Soil pH is 6.5 and the total organic matter content is 18 g kg^{-1}. The soil hydraulic properties (Table 1) determined in the laboratory provide suitable hydraulic conditions for potato growth with loose soil structure and good drainage.

Table 1. Soil hydraulic properties (bulk density (BD, g cm^{-3}), air capacity (AC, %), field capacity (FC, %), plant available water content (PAW, %), and saturated hydraulic conductivity (K_{sat}, cm d^{-1})) at 10 cm, 20 cm, 30 cm, and 50 cm depth of the potato ridges according to soil moisture probe measurements.

Depth	BD	AC	FC	PAW	K_{sat}
(cm)	(g cm^{-3})	(%)	(%)	(%)	(cm d^{-1})
10	1.28	29.84	21.75	17.99	297
20	1.40	26.01	21.26	16.83	165
30	1.46	24.89	21.06	16.87	148
50	1.55	22.68	18.85	15.78	83

Mean air temperature (period 1991–2020; [39]) in the study region is 9.5 °C and ranges between 0.9 °C in January and 18.6 °C in July. Average sunshine hours are 6.6 h d^{-1} and range between 2.3 h d^{-1} in December and 10.6 h d^{-1} in July. The long-term annual precipitation amount is 601.0 mm with an average annual reference evapotranspiration of 582.3 mm, with variations between 42.2 mm in February (10.2 days with precipitation) and 78.5 mm in July (12.9 days with precipitation). The long-term average precipitation during the growing season (1 April until 30 September) is 337.9 mm, ranging between 122.2 mm in 2018 and 498.2 mm in 2010. The long-term air temperature during the growing season is 14.4 °C, ranging between 12.9 °C in 1996 and 17.9 °C in 2019.

2.2. Crop Management

The medium-size HAPP *cv.* "Waxy/Henriette" was grown on the study site in 2021. Pre-sprouted seed tubers with a mean shoot length of approx. 1 cm were planted in preliminary ridges on 15 April 2021. The space between the ridges was 0.75 m and the plant spacing was 0.38 m, resulting in a plant density of 2.6 plants m^{-2} and 35,088 plants ha^{-1}. Fertilization was performed pre-planting by using 6.50 dt ha^{-1} multi-nutrient fertilizer (Horti37®, Timac AGRO, Zagreb, Croatia, consisting of 5% N, 10% P_2O_5, 22% K_2O, 3% MgO, and 37% SO_3), and pre-ridging (15 days after planting (DAP)) by using 5.00 dt ha^{-1} urea. On 2 May 2021 (17 DAP), the soil was treated once with soil herbicides (Proman®, 1.50 kg ha^{-1} Metobomuron; Belchim Crop Protection Deutschland GmbH, Burgdorf, Germany) to control weed growth. On 4 May 2021 (19 DAP), the soil was ridged to approx. 0.10 m above the tubers and the distance from top to furrow base of the ridge was approx. 0.30 m. During the growing season, the crop was treated three times (40, 88, and 97 DAP) with insecticides (Mospilan® SG, 0.25 kg ha^{-1} Acetamiprid; Cheminova Deutschland GmbH & Co. KG, FMC Agricultural Solutions, Stade, Germany) to control Colorado potato beetle (Leptinotarsa decemlineata) infestation, and twice with fungicides (Terminus®, 0.20 kg ha^{-1} Fluazinam; Cheminova Deutschland GmbH & Co. KG, FMC Agricultural Solutions, Stade, Germany) to control fungal diseases (Phytophthora infestans and Alternaria alternata), respectively. Defoliation was performed two-stage pre-harvest by chemical desiccation (Quickdown, 0.02 kg ha^{-1} Pyrafluen, Belchim Crop Protection Deutschland GmbH, Burgdorf, Germany, and Shark, 0.06 kg ha^{-1} Carfentrazone-Ethyl, FMC Agricultural Solutions, Stade, Germany) on 10 September 2021 (148 DAP), combined with traditional mechanical flailing on 21 September 2021 (159 DAP), in order to remove above-ground biomass for enabling a "dry-down" of the potato crop from environmental conditions and to minimize the spread of leafroll virus and aphid infestation. Hence, fertilization and pest management were conducted in compliance with the farmer's usual cultivation practice. Crops were harvested on 28 September 2021 (166 DAP).

2.3. Experimental Design

Four test plots with a size of 172 m × 72 m were installed from May to September 2021 within one irrigation lane in compliance with homogeneous soil conditions, and beforehand tested using disturbed topsoil (0–30 cm) samples. The experiment was designed as an open field experiment in compliance with the common practice of the local farmer. Each test plot was irrigated with one irrigation level: a moderate irrigation (100% irrigation level) according to the usual irrigation practice of the local farmer, two reduced irrigation levels (80%, 90%), and one abundant irrigation level (120%). A control plot was installed with no irrigation. The experiment was hence designed in compliance with the farmer's usual cultivation practice (Section 2.2).

Agrometeorological parameters (air temperature, precipitation, sunshine duration, radiation, air pressure, relative humidity, wind speed and direction, and derived optimal crop evapotranspiration, determined based on the energy budget on the site according to the FAO crop evapotranspiration [40]) were observed hourly over the entire irrigation lane in each test plot using smart weather sensors (Arable Mark 2, Arable Labs, Inc., Princeton, NJ, USA). Soil moisture was observed hourly in triplicate per test plot in 10 cm steps using 60 cm Sentek profile probes (Sentek Sensor Technologies, Stepney, Australia). All measurement devices were installed in full ridges on 5 May 2021 (20 DAP) and uninstalled on 16 September 2021 (154 DAP). Measured data were subjected to quality control using a nearby climate station (distance to field center = 720 m).

2.4. Irrigation Levels

All irrigation levels were defined in relation to the common irrigation level of the local farmer (100%), limited by the minimum possible gun sprinkler capacity of 15 mm. The 100% irrigation level was scheduled iteratively each irrigation day by the local farmer using ZEPHYR, a commonly applied tool for irrigation management. In ZEPHYR, a crop specific water supply recommendation is provided based on optimum PAW ranges for potatoes between 40% and 80% PAW during early growth stages and between 40% and 90% PAW during later growth stages [41]. ZEPHYR therefore does not provide the actual irrigation demand of the crop, but the soil water deficit, i.e., the water demand of the crop without regarding possible water losses due to the applied gun sprinkler irrigation efficiency. Preliminary analyses showed that the 100% irrigation level (i.e., the common irrigation level of the local farmer) partly exceeds the optimum PAW ranges used by ZEPHYR, indicating that the farmer increases the irrigation recommendation given by ZEPHYR by an additional water amount to compensate the usual applied values for gun sprinkler irrigation efficiencies of 75% [42,43]. Hence, the investigated irrigation levels were not defined by ZEPHYR itself, but in relation to the recommended irrigation level by ZEPHYR (100%, i.e., the common irrigation level of the local farmer). The 100% irrigation level usually corresponds to 20 mm during early growth stages and to 25 mm during maturation and tuberization, according to the experience and common practice of the local farmer. The irrigation levels were defined as 80%, 90%, and 120% of this 100% irrigation level and hence determined as deficits or increases compared to the local farmer. However, technical sprinkler capacities permit a minimum water application of 16 mm only, which, in turn, limited the lowest possible irrigation level to the 80% irrigation level in early growth stages.

The irrigation levels during five events were applied via a gun sprinkler irrigation system and varied between 16.6 mm and 26.3 mm per irrigation event. The in-field performance of the gun sprinkler irrigation system, as well as each irrigation event and all irrigation levels, were controlled using 7-min GPS-based speed and location data. These data and technical gun sprinkler information were used to derive the actual irrigation levels at a specific location within one irrigation lane, as the irrigation levels may be subject to intra-site-specific variances depending on the water pressure inside the irrigation pipe, which, in turn, influences the gun sprinkler irrigation system speed. The irrigation levels in each test plot increased during the growing season, in compliance with plant development. The overall irrigation levels at each harvest parcel, were 98.4 mm, 106.7 mm, 119.2 mm, and 134.4 mm. They varied between 16.6 mm and 30.5 mm per irrigation event (Table S1).

The ratio of each irrigation level (%) compared to the common irrigation level of the farmer (i.e., 100%) was calculated by dividing the actual irrigation level by the 100% irrigation level and multiplying by 100 (Table S1). The ratio of each irrigation level was used to assess the efficiency of the utilized gun sprinkler irrigation system and the dependence of sprinkler irrigation levels on external factors. Total water supply (TWS; irrigation level + precipitation) at the harvest parcels was calculated from May to September 2021. The irrigation efficiency was assessed using in situ measurements of topsoil (0–30 cm) and root zone (0–60 cm) soil moisture dynamics and the optimum ranges of PAW used in ZEPHYR.

2.5. Harvest Strategy, Yield and Quality Measurements

Four parcels (15 m) were harvested in each test plot at 166 DAP, each with 40 plants. Soil residues were gently removed from harvested tubers before yield and quality determination. Fresh tuber mass of each harvest parcel was measured in the field. Fresh tuber yield of each harvest parcel was stored under dry, dark, and cool conditions with sufficient ventilation to minimize the transpiration from the tubers. Promptly after harvesting (167 DAP), the tubers were sorted in a three-grade tuber size distribution by using a mechanical sorting machine: Size class (S_C) $1 \leq 35$ mm; 35 mm $< S_C2 \leq 55$ mm; and $S_C3 > 55$ mm. Yield of each tuber size class was weighed. Total yield was defined as the sum of yields in each tuber size class. The tuber number per plant was determined by counting all harvested tubers of each harvest parcel and tuber size class and dividing the sum by the number of harvested plants per harvest. The mean tuber weight of each tuber size class was determined by dividing the yield of each tuber size class by the tuber number.

After sorting, yield per tuber size class of all harvest parcels in each test plot was randomly mixed to generate an adequate subsample size for quality measurements. Hence, 15 subsamples were used for each quality measurement (5 irrigation levels including the non-irrigated control plot $\times$ 3 tuber size classes). All subsamples were again carefully washed, air-dried, and stored under dry, dark, and cool conditions with sufficient ventilation to avoid post-ripening or late blight.

Dry matter content was measured in triplicate (each 0.5 kg) after drying cut tubers. To avoid tuber boiling, the cut tubers were dried first at 65.0 °C for 24 h and afterwards at 105.0 °C for 24 h.

Starch content (percentage of starch, g kg^{-1}) of average, non-damaged tubers was measured in duplicate (each 5.0 kg) using the specific gravity based immersion weighing principle [44]. The specific gravity was determined by determining the underwater weight of the subsample at a controlled water temperature of 17.5 °C:

$$\text{weight in water} \times (\text{weight inn air} - \text{weight in water})^{-1} \tag{1}$$

Whenever required, single tubers were cut to make the total weight exactly 5.0 kg. The immersion weighing principle is used in a standardized Reimann–Parov immersion hydrostatic balance scale according to Eckert (1975) [45]. Several studies proved that there is a robust correlation between the specific gravity of potato tubers with the starch content [46,47]. The immersion weighing principle is hence a commonly applied method for starch content [48,49] or dry matter content [50] determination, and, moreover, implemented in the United states standards for grades of potato processing by the United States Department of Agriculture (USDA) [51]. Starch yield (starch content × crop yield) was calculated in dt ha^{-1}.

A nine-grade classification from 1 (not affected) to 9 (strongly affected) [52] was used for assessing internal and external tuber quality lesions of 20 randomly selected tubers. External quality criteria were: common scab infestation [53] (divided into humpback scab, flat scab, and deep scab), growth cracks [54], and the ratio of green tubers [55]. Internal tuber quality criteria included incidences of iron staining and net necrosis [56]. For the determination of dry matter content, the starch content measurements, and the assessment of internal and external tuber quality, a separate subsample was chosen.

2.6. Economic Indices and Responses

Five different economic indices were calculated for each tuber size class and total yield for assessing the economic productivity of the different irrigation levels at each harvest parcel. The selected indices are divided into economic (Equations (2) and (4)) and ecologic (Equations (5) and (6)) indices, and are generally independent from external factors, as yield (and tuber quality) is related to the amount of a specific input. They are hence suitable to assess the profitability of a specific cropping system.

First, the total production value [57,58] was calculated for each harvest parcel and tuber size class. Yield was related to the beforehand determined production costs (Table 2) and the starch potato price on the day of harvest of 16.60 USD dt^{-1} [59] (Equation (2)).

Table 2. Variable and fixed production costs in potato production during the field experiment 2021 [60].

Production Segment	Calculation	Costs (USD ha^{-1})	
water and energy for irrigation	variable (mm) × 1.76 USD mm^{-1}	80%	171.17
		90%	185.57
		100%	207.46
		120%	233.79
labor [1]	40 h ha^{-1} × 17.6 USD h^{-1}	704.00	
fuel [1]	fixed costs	872.00	
fertilization [1]	fixed costs	213.00	
agrochemicals [1]	fixed costs	330.60	
seed tubers	35,088 tubers ha^{-1} × 0.06 kg tuber^{-1} × 0.35 USD kg^{-1}	736.85	

[1] on-farm information from the local farmer.

Second, the TPV_{total} (USD ha^{-1}) was adjusted to reduced tuber quality (Table 3), resulting in the $TPV_{reduced}$ [61] (Equation (3)). Multiple occurrences of quality lesions or missed thresholds were summed for the respective tuber size class or irrigation level.

Table 3. Tuber quality thresholds and reduction (percentage) of the total production value (TPV_{total}).

Tuber Quality Criterion	Threshold	Reductions of the TPV_{total}
dry matter content	195.0 g kg^{-1}	10%
starch content [1]	170.0 g kg^{-1}	0.77 USD kg^{-1} reduced starch yield (dt ha^{-1}) [2]
deep scab [3]	20% of all tubers	10%
growth cracks [3]	20% of all tubers	10%
tuber greening	10% of all tubers	10%
iron staining	10% of all tubers	10%
net necrosis	1% of all tubers	full rejection

[1] reduced from 180.0 g kg^{-1} to 170.0 g kg^{-1} due to the purity and quality of produced starch. [2] current global market value for potato starch (September 2021; [59]). [3] leading to starch impurity [62].

Third, the benefit to cost ratio (BCR, Equation (4); [63,64]) was calculated for assessing the economic efficiency of the used potato production system [58] by dividing the $TPV_{reduced}$ (Equation (3)) by the production costs (Table 2).

$$TPV_{total}\ (\text{USD ha}^{-1}) = \text{yield (dt ha}^{-1}) \times 16.60\ \text{USD dt}^{-1} - \text{production costs (USD ha}^{-1}) \quad (2)$$

$$TPV_{reduced}\ (\text{USD ha}^{-1}) = TPV_{total}\ (\text{USD ha}^{-1}) - \text{tuber quality reductions (USD ha}^{-1}) \quad (3)$$

$$\text{BCR (-)} = TPV_{reduced}\ (\text{USD ha}^{-1}) \times \text{production costs (USD ha}^{-1})^{-1} \quad (4)$$

Fourth, the irrigation water productivity (IWP, Equation (5) [65]) was calculated for assessing the irrigation efficiency [66,67]. Fifth, the water productivity (WP, Equation (6)) was calculated for assessing the crop's yield response to TWS, as water savings are often related to an increase in WP [68,69].

$$\text{IWP (dt mm}^{-1}) = \text{yield (dt ha}^{-1}) \times \text{irrigation level (mm)}^{-1} \quad (5)$$

$$\text{WP (dt mm}^{-1}) = \text{yield (dt ha}^{-1}) \times \text{total water supply (mm)}^{-1} \quad (6)$$

The case study of the local farm in Mecklenburg–Western Pomerania (total cultivated area: 1600 ha), on whose site the experiment was conducted, was used for a farm level calculation of possible water savings and economic responses of the economically best irrigation level. In 2021, 895.9 ha (55.9% of the total cultivated area) of the local farm were used for starch potato production. We assume that all cultivated starch potato varieties, all of which are genetic clones of the investigated HAPP *cv.* "Waxy/Henriette" are reacting equally to variable irrigation levels and water supply in yield, tuber quality, and economic responses. According to the German Soil Estimation [70], 695.3 ha (i.e., 77.6%) of the sites used for starch potato production in 2021 are loamy sands.

2.7. Statistical Analyses

The open-source software "RStudio" (Version 1.4; Rstudio Team, Boston, MA, USA), as an integrated development environment for R (Version 4.1.1), was used for statistical analyses. Yield and tuber quality were assessed for normal distribution (Shapiro–Wilk test) and variance homogeneity (Levene's test). One-way analyses of variance (ANOVA) were performed to assess differences between yield, tuber quality, and economic responses of the irrigation levels. The Tukey honestly significant difference test was applied to determine differences in group means at a significance level of $p \leq 0.05$.

Polynomials were used to assess the relationships between variable irrigation levels and yield, tuber quality, and economic responses. Yield, tuber quality, and economic values were related to the actual irrigation level at the harvest parcel. The polynomials are based on 16 grid points as there were four replicates (i.e., harvest parcels) per irrigation level. The local maximum of each fitted polynomial was used to determine the maximum profitable irrigation level (MPI). The lowest profitable irrigation level (LPI) of each parameter was determined using local turning points lower than the MPI of the fitted polynomials. Partially, the LPI was shifted in response to tuber quality and economic thresholds.

3. Results

3.1. Weather Conditions

Mean daily air temperature during the 2021 growing season was 17.0 °C, ranging between T_{min} = 5.5 °C and T_{max} = 32.9 °C (Figure 1).

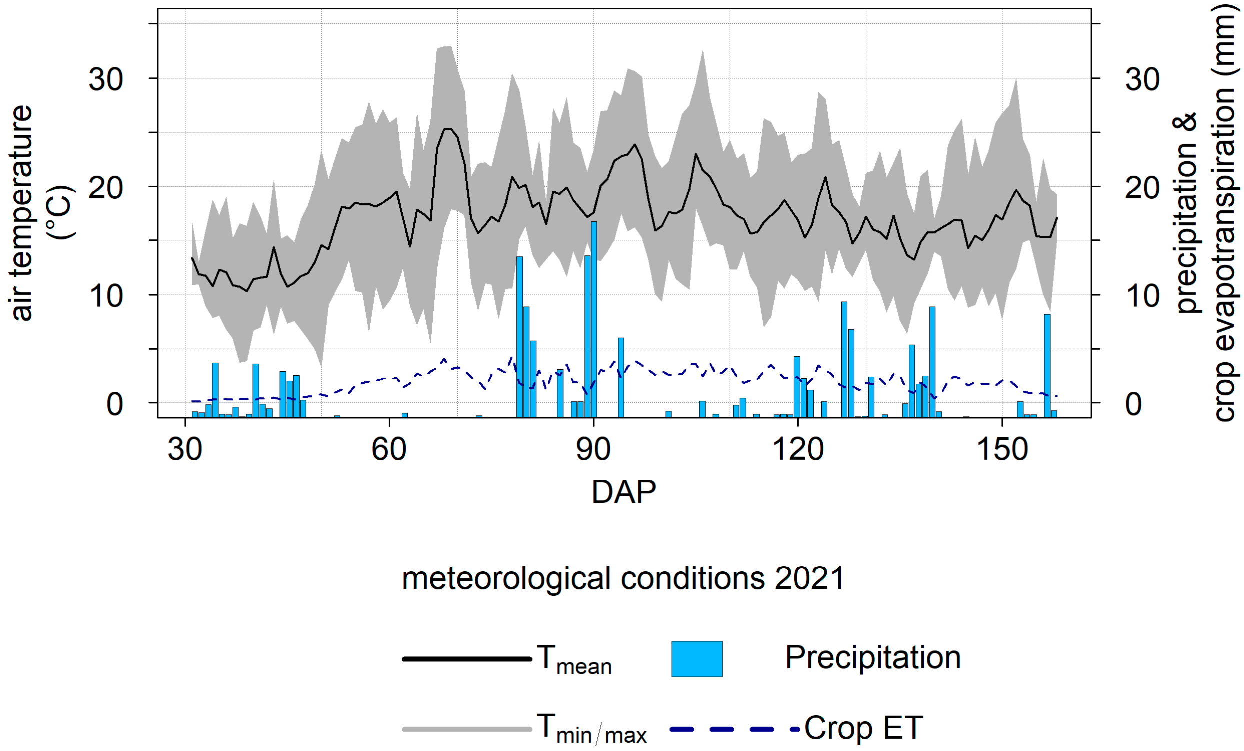

Figure 1. Measured agrometeorological data during the 2021 growing season (12 May 2021, until 16 September 2021): DAP = days after planting; T_{mean} = mean daily air temperature (°C); T_{min} = minimum daily air temperature (°C); T_{max} = maximum daily air temperature (°C); Crop ET = in situ derived crop evapotranspiration (mm) determined based on the energy budget on the site according to the FAO crop evapotranspiration [40]. Crops were planted on 15 April 2021. Data were measured in four replicates on the study site and validated using a nearby climate station. Measurement devices were installed over the entire irrigation lane on 5 May 2021 (20 DAP) and uninstalled on 16 September 2021 (154 DAP).

Total in situ measured sunshine duration from 5 May 2021, until 12 September 2021, was 1388.1 h, with an average daily sunshine duration of 10.6 h d^{-1}, ranging between 0 h d^{-1} on 29 August 2021, and 13.1 h d^{-1} on 2 June 2021 and 28 June 2021. Total precipitation was 255.1 mm, slightly exceeding the long-term precipitation amount of 252.5 mm during the growing season of the potato crop (5 May–16 September, period 1991–2019, [39]). Daily precipitation ranged between 0.1 mm (23 August) and 24.1 mm (10 July). There were 114 days with no precipitation (83.8%). Precipitation occurred irregularly during the growing season with 84.2% of precipitation after 74 DAP (28 June). Early growth stages were dry with an overall precipitation of 40.5 mm. Total in situ measured crop evapotranspiration was 349.9 mm during the growing season (2.6 mm d^{-1}), with daily evapotranspiration rates ranging between 0.2 mm (13 May) and 6.2 mm (28 June). Hence, the total water deficit during the 2021 growing season was 97.4 mm.

3.2. Water Supply

According to the irrigation levels at each harvest parcel derived from 7-min GPS-based sprinkler speed and location data, TWS (precipitation + irrigation) at the harvest parcels was 255.1 mm at the 0% irrigation level, 353.5 mm at the 80% irrigation level, 361.8 mm at the 90% irrigation level, 374.3 mm at the 100% irrigation level, and 389.5 mm at the 120% irrigation level (Table S1). However, due to technical gun sprinkler properties resulting in high spatial and temporal variance, the average irrigation levels in each test plot differed from the irrigation levels at the locations of the harvest parcels.

Compared to the TWS, the crop evapotranspiration during the growing season 2021 revealed short-time drought stress at all irrigation levels immediately before the first irrigation event (Figure 1). The TWS on 20 July 2021 (one day after the last irrigation event) exceeded the cumulative crop evapotranspiration by 63.0 mm at the 120% irrigation level and by 45.1 mm at the 80% irrigation level. With maturity and beginning of crop defoliation (15 August 2021), the difference between TWS and cumulative crop evapotranspiration was −7.3 mm at the 80% irrigation level, 1.1 mm at the 90% irrigation level, 13.6 mm at the 100% irrigation level, and 28.8 mm at the 120% irrigation level, indicating the sufficiency of a slightly reduced irrigation level to meet the water demand of the crop.

The in situ measured root zone (0–60 cm) soil moisture dynamics were between 20% PAW and 70% PAW at the 80% irrigation level, between 40% PAW and 90% PAW at the 90% irrigation level, between 40% PAW and field capacity (20.73 Vol.%) at the 100% irrigation level, and between 50% PAW and 110% PAW at the 120% irrigation level. Moreover, in topsoil (0–30 cm), the soil moisture was between 5% and 60% PAW at the 80% irrigation level, between 30% and 95% PAW at the 90% irrigation level, between 40% PAW and field capacity (21.30 Vol.%) at the 100% irrigation level, and between 50% and 110% PAW at the 120% irrigation level.

3.3. Total Yield and Tuber Size Distribution

Irrigation significantly affected the total yield as there were significant differences between different irrigation levels (Figure 2).

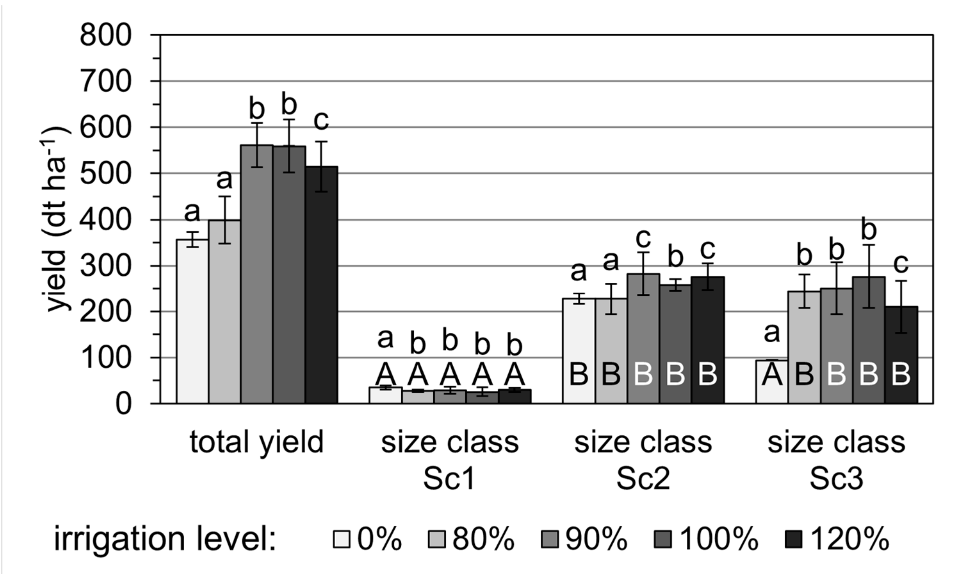

Figure 2. Total yield (dt ha^{-1}) per irrigation level (grey scale; 0% = 0 mm, 80% = 98.4 mm, 90% = 106.7 mm, 100% = 119.2 mm, 120% = 134.4 mm) as a sum of all tuber size classes and per tuber size class (S_C1: ≤35 mm; 35 mm < S_C2 ≤ 55 mm; S_C3: >55 mm) with standard deviation at 5% probability ($p \leq 0.05$). Lower case letters indicate statistically significant differences ($p \leq 0.05$) between irrigation levels within one tuber size class or total yield, respectively. Upper case letters indicate statistically significant differences ($p \leq 0.05$) between tuber size classes within one irrigation level.

Significantly ($p \leq 0.05$) highest total yields were obtained at the 90% (561.1 dt ha^{-1}) and the 100% irrigation levels (559.1 dt ha^{-1}). Total yield was significantly lowest at the 0% (356.4 dt ha^{-1}) and the 80% irrigation levels (398.4 dt ha^{-1}). At higher irrigation levels (120%), total yield was significantly reduced (514.3 dt ha^{-1}) compared to the 90% and 100% irrigation levels.

There were significant differences in yield of each tuber size class between the irrigation levels. Yield of tuber size class S_C1 was significantly highest at the 0% irrigation level (35.1 dt ha^{-1}). No significant differences were found in yield of tuber size class S_C1 between all other irrigation levels. Yield of tuber size class S_C2 was significantly highest at the 90% irrigation level (282.1 dt ha^{-1}) and the 120% irrigation level (275.0 dt ha^{-1}), respectively. Significantly lowest yield of tuber size class S_C2 was obtained at the 0% (227.6 dt ha^{-1}) and 80% (227.0 dt ha^{-1}) irrigation levels. Yield of tuber size class S_C2 at the 100% irrigation level was 257.5 dt ha^{-1}. Yield of tuber size class S_C3 was significantly highest at the 80% (243.8 dt ha^{-1}), 90% (249.9 dt ha^{-1}), and the 100% (276.0 dt ha^{-1}) irrigation levels. There was a significant decrease at the 120% irrigation level (209.8 dt ha^{-1}) compared to the 100% irrigation level. The significantly lowest yield was obtained at the 0% irrigation level (93.8 dt ha^{-1}).

Furthermore, yield at the irrigation levels partly differed significantly between the tuber size classes. At the 0% irrigation level, significantly highest yield was obtained in tuber size class S_C2. No significant differences were found for yield in tuber size classes S_C1 and S_C3. At all other irrigation levels, significantly lowest yield was obtained in tuber size class S_C1, and no significant differences were found between yield of tuber size classes S_C2 and S_C3.

The total tuber number per plant was significantly highest at the 90% irrigation level (18.2) and significantly lowest at the 0% (16.6) and the 80% (16.8) irrigation levels (Table 4). No significant differences were found between the 100% (17.6) and the 120% (17.4) irrigation levels. The number of tubers in tuber size class S_C1 was significantly highest at the 0% (5.1) and the 80% (5.6) irrigation levels and significantly lowest at the 100% (3.6) irrigation level. No significant differences were found between the 90% (4.4) and the 120% (4.4) irrigation levels. In tuber size class S_C2, no significant differences were found between the 0% (9.7), 90% (9.1), 100% (9.4), and 120% (9.4) irrigation levels in terms of tubers per plant. The tuber number was significantly lowest at the 80% irrigation level (8.2). In tuber size class S_C3, the tuber number per plant was significantly highest at the 90% (4.7) and the 100% (4.6) irrigation levels, and significantly lowest at the 0% (1.8) irrigation level. The tuber number at the 80% and the 120% irrigation levels were 3.0 and 3.6, respectively, with no significant differences. Furthermore, significant differences were found at the 0% irrigation level between all tuber size classes. At all other irrigation levels, no significant differences were found between the number of tubers in tuber size classes S_C1 and S_C3 (Table 4). Pearson's correlation coefficient showed that there are significant statistical relationships between total yield and total number of tubers (K = 0.90, p = 0.036) and between yield of tuber size class S_C3 and number of tubers in this tuber size class (K = 0.98, p = 0.003) (not shown).

The mean tuber weight did not differ significantly between all irrigation levels (Table 4), although it was slightly higher at the 100% and the 120% irrigation levels, compared to all other irrigation levels. In tuber size class S_C1, no significant differences were found in the mean tuber weight. In tuber size class S_C2, the mean tuber weight was significantly higher at the irrigated harvest parcels, compared to the 0% irrigation level. In tuber size class S_C3, the mean tuber weight was significantly highest at the 100% (0.17 kg) and the 120% (0.17 kg) irrigation levels, and significantly lowest at the 80% (0.13 kg) irrigation level. No significant differences were found between the 0% (0.15 kg) and the 90% (0.15 kg) irrigation levels. The mean tuber weight differed significantly between tuber size classes at all irrigation levels, except the 0% irrigation level. No significant differences between tuber size classes S_C1 and S_C2 were found here (Table 4).

Table 4. Quality parameters for starch potato production per irrigation level for total yield and per tuber size class (S_C1: $\leq$35 mm; 35 mm < $S_C2 \leq$ 55 mm; S_C3: >55 mm). The irrigation levels were: 0% = 0 mm, 80% = 98.4 mm, 90% = 106.7 mm, 100% = 119.2 mm, 120% = 134.4 mm. Lower case letters indicate statistically significant differences ($p \leq 0.05$) between irrigation levels within one tuber size class or total yield, respectively. Upper case letters indicate statistically significant differences ($p \leq 0.05$) between tuber size classes within one irrigation level. Statistical testing was not applied for the tuber number per plant and for tuber greening, as these criteria were determined based on all harvested tubers of one irrigation level, and for internal (iron staining) tuber quality parameters, as a nine-grade classification from 1 (not affected) to 9 (strongly affected) was applied for measurements.

Tuber Quality Criterion			Irrigation Level				
			0%	80%	90%	100%	120%
tuber number	(-)	S_C1	5.1 aA	5.6 aA	4.4 bA	3.6 cA	4.4 bA
		S_C2	9.7 aB	8.2 bB	9.1 aB	9.4 aB	9.4 aB
		S_C3	1.8 aC	3.0 bA	4.7 cA	4.6 cA	3.6 bA
		total	16.6 a	16.8 a	18.2 b	17.6 c	17.4 c
mean tuber weight	(kg)	S_C1	0.02 aA	0.01 aA	0.02 aA	0.02 aA	0.02 aA
		S_C2	0.06 aA	0.08 bB	0.09 bB	0.08 bB	0.08 bB
		S_C3	0.15 aB	0.13 bC	0.15 aC	0.17 cC	0.17 cC
		total	0.08 a	0.08 a	0.08 a	0.09 a	0.09 a
dry matter content	(g kg^{-1})	S_C1	246.9 aA	236.3 bA	237.9 bA	242.8 abA	250.7 aA
		S_C2	256.3 aB	255.1 aB	256.1 aB	259.1 aB	256.7 aB
		S_C3	259.5 aB	257.8 aB	253.7 aB	255.1 aB	254.7 aB
		total	253.8 a	249.3 a	250.9 a	254.8 a	254.7 a
starch content	(g kg^{-1})	S_C1	170.0 aA	168.0 aA	158.0 bA	170.0 aA	160.0 bA
		S_C2	174.5 aB	176.0 aB	181.0 bB	180.5 bB	173.3 aB
		S_C3	177.5 aC	178.5 aC	182.5 bC	186.5 bC	175.0 aC
		total	173.4 a	173.8 a	175.6 a	179.9 b	170.2 c
starch yield	(dt ha^{-1})	S_C1	6.0 aA	4.6 bA	4.6 bA	4.4 bA	4.7 bA
		S_C2	39.7 aB	40.0 aB	51.1 cB	46.5 bB	47.7 bB
		S_C3	16.7 aC	25.7 aB	46.3 cB	51.5 cB	36.7 bB
		total	62.3 a	70.3 a	102.0 c	102.3 c	89.1 b
common scab	(1–9)	S_C1	1.5	1.5	1.5	1.8	2.0
		S_C2	1.5	2.5	2.7	2.2	2.5
		S_C3	2.0	2.0	1.8	2.3	2.0
		total	1.7	2.0	2.2	2.1	2.3
iron staining	(1–9)	S_C1	1.0	1.0	1.0	1.0	2.0
		S_C2	1.0	1.0	2.0	1.0	2.0
		S_C3	1.0	2.0	1.0	1.0	2.0
		total	1.0	1.2	1.5	1.0	2.0
tuber greening	(%)	S_C1	8.3	10.6	15.3	10.2	10.3
		S_C2	7.4	3.6	10.5	11.2	7.1
		S_C3	6.2	2.0	5.3	0.0	0.0
		total	21.9	16.2	31.1	21.4	17.4

3.4. Tuber Quality

No significant differences were found in the total dry matter content between irrigation levels, although it differed significantly between tuber size class S_C1 and larger tuber sizes at all irrigation levels (Table 4).

The total starch content significantly differed between the 100% (179.9 g kg^{-1}) and 120% (170.2 g kg^{-1}) irrigation level and all other irrigation levels. Starch content of tuber size class S_C1 was significantly highest at the 0% (170.0 g kg^{-1}), 80% (168.0 g kg^{-1}), and 100% (170.0 g kg^{-1}) irrigation levels, and significantly lowest at the 90% (158.0 g kg^{-1}) and 120% (160.0 g kg^{-1}) irrigation levels. In tuber size classes S_C2 and S_C3, starch content was significantly highest at the 90% (181.0 g kg^{-1} and 182.5 g kg^{-1}) and 100% (180.5 g kg^{-1} and 186.5 g kg^{-1}) irrigation levels. Nevertheless, there are also differences between the 90% and the 100% irrigation levels, but the differences are not significant. No significant differences were found in starch content of tuber size classes S_C2 and S_C3 between all other irrigation levels (Table 4). Total starch yield significantly differed between pairs of irrigation levels, due to differences in yield between the irrigation levels (Table 4). Total starch yield was significantly highest at the 90% (101.9 dt ha^{-1}) and the 100% (102.3 dt ha^{-1}) irrigation levels, and significantly lowest at the 0% (62.3 dt ha^{-1}) and the 80% (70.3 dt ha^{-1}) irrigation levels. Total starch yield at the 120% irrigation level was 89.1 dt ha^{-1}. Starch yield of tuber size class S_C1 was significantly highest at the 0% irrigation level with 6.0 dt ha^{-1}. No significant differences were found for starch yield in tuber size class S_C1 between all other irrigation levels. Starch yield of tuber size class S_C2 was significantly highest in the 90% irrigation level (51.1 dt ha^{-1}), and significantly lowest at the 0% (39.7 dt ha^{-1}) and the 80% (40.0 dt ha^{-1}) irrigation levels. Starch yield in tuber size class S_C2 at the 100% and the 120% irrigation levels was 46.5 dt ha^{-1} and 47.7 dt ha^{-1}, respectively, with no significant differences. In tuber size class S_C3, significantly highest starch yield was obtained at the 90% (46.3 dt ha^{-1}) and the 100% (51.1 dt ha^{-1}) irrigation levels. Lowest starch yields in tuber size class S_C3 were obtained at the 0% (16.7 dt ha^{-1}) and the 80% (25.7 dt ha^{-1}) irrigation levels. Starch yield of tuber size class S_C3 at the 120% irrigation level was 36.7 dt ha^{-1} (Table 4).

Starch content and yield also both significantly differed between different tuber size classes. Starch content was significantly highest in tuber size class S_C3 and significantly lowest in tuber size class S_C1, at all irrigation levels. At the 0% irrigation level, starch yield differed significantly between all tuber size classes. At all other irrigation levels, there were significant differences between tuber size classes S_C1 and S_C2, but no significant differences between tuber size classes S_C2 and S_C3 (Table 4).

The Incidence of external and Internal tuber lesions was generally low at all Irrigation levels (Table 4). Incidences of common scab lesions slightly differed between the irrigation levels. Tubers of tuber size class S_C2 were more affected with common scab than other tuber size classes. Incidences of deep scab infestation or growth cracks were not detected. Incidences of iron staining were highest at the 120% irrigation level. The ratio of green tubers varied with the irrigation level, with the highest ratio of 31.1% at the 90% irrigation level. The ratio of green tubers was higher at the 0% irrigation level (21.9%) than at the 80% (16.2%), 100% (21.4%), and 120% (17.4%) irrigation levels. Net necrosis or late blight were not detected on any tubers.

3.5. Economic Indices and Responses

Usually, economic responses of a specific agricultural production system are subject to strong, even intra-seasonal, fluctuations due to varying prices. Hence, a generalization and transferability is difficult to implement. However, production costs are usually divided into fixed (e.g., labor, fuel, agrochemicals), and variable (e.g., water and energy for irrigation) production costs. Hence, production costs (and economic responses) are usually impacted by fluctuations in energy costs. The production costs were highest for fuel (872.78 USD ha^{-1}) and lowest for irrigation (Table 2).

The total TPV_{total} and $TPV_{reduced}$ were significantly highest at the 90% (6274.55 USD ha^{-1} and 5595.74 USD ha^{-1}) and the 100% (6216.39 USD ha^{-1} and 5877.61 USD ha^{-1}), respectively (Table 5). Significantly lowest TPV_{total} and $TPV_{reduced}$ were obtained at the 0% (3083.25 USD ha^{-1} and 2620.07 USD ha^{-1}) and the 80% (3590.40 USD ha^{-1} and 2919.38 USD ha^{-1}) irrigation levels. The total TPV_{total} at the 120% irrigation level was 5444.68 USD ha^{-1}. Hence, significantly highest losses of economic responses due to reduced tuber quality (i.e., the difference between the TPV_{total} and the $TPV_{reduced}$) were obtained at the 80% (671.02 USD ha^{-1}, 18.7%), 90% (678.81 USD ha^{-1}, 10.8%), and 120% (622.59 USD ha^{-1}, 11.4%) irrigation levels (Table 5). The losses were significantly lowest at the 100% irrigation level (338.78 USD ha^{-1}, 5.5%). At the 0% irrigation level, the economic losses were 463.18 USD ha^{-1} (15.0%). Moreover, significantly higher yields, and hence TPV_{total}, at the 90%, 100%, and 120% irrigation levels, compared to the 0% and 80% irrigation levels, led to less relative implications of the economic losses due to reduced tuber quality. According to the tuber quality (Section 3.4), the economic losses partly differed between tuber size classes. At the 0%, 90%, and 120% irrigation levels, significant differences were found between tuber size classes S_C1 and S_C2, and no significant differences were found between tuber size classes S_C2 and S_C3. Economic losses at the 80% irrigation level differed significantly between all tuber size classes. At the 100% irrigation level, the economic losses differed significantly between tuber size class S_C2 and the other tuber size classes (Table 5).

Table 5. Economic indices and responses at different irrigation levels for total yield and per tuber size class (S_C1: ≤35 mm; 35 mm < S_C2 ≤ 55 mm; S_C3: >55 mm). The irrigation levels were: 0% = 0 mm, 80% = 98.4 mm, 90% = 106.7 mm, 100% = 119.2 mm, 120% = 134.4 mm. Lower case letters indicate statistically significant differences ($p \leq 0.05$) between irrigation levels within one tuber size class or total yield, respectively. Upper case letters indicate statistically significant differences ($p \leq 0.05$) between tuber size classes within one irrigation level. TPV_{total} = total production value without tuber quality losses (USD ha^{-1}). $TPV_{reduced}$ = reduced total production value due to tuber quality losses (USD ha^{-1}). BCR = benefit to cost ratio (-). IWP = irrigation water productivity (dt mm^{-1}). WP = water productivity (dt mm^{-1}). The IWP was not calculated for the non-irrigated control plot.

Economic Indices			Irrigation Level				
			0%	80%	90%	100%	120%
TPV_{total}	(USD ha^{-1})	S_C1	310.47 aA	252.90 aA	332.87 aA	291.69 aA	318.39 aA
		S_C2	1960.79 aB	2033.75 aB	3146.65 bB	2843.08 cB	2896.04 cB
		S_C3	811.99 aA	1303.75 bB	2795.03 cB	3081.62 cB	2230.25 cB
		total	3083.25 a	3590.40 a	6274.55 b	6216.39 b	5444.68 c
$TPV_{reduced}$	(USD ha^{-1})	S_C1	301.43 aA	190.84 aA	264.50 aA	254.39 aA	224.70 aA
		S_C2	1756.58 aB	1822.24 aB	2823.85 bB	2550.64 bB	2598.30 bB
		S_C3	562.06 aA	906.30 bA	2507.39 cB	3072.58 cB	1999.09 cB
		total	2620.07 a	2919.38 a	5595.74 b	5877.61 b	4822.09 c
losses	(USD ha^{-1})	S_C1	9.04 aA	62.06 bA	68.37 bA	37.30 cA	93.69 dA
		S_C2	204.21 aB	211.51 aB	322.80 bB	292.44 bB	297.74 bB
		S_C3	249.93 aB	397.45 bC	287.64 aB	9.04 cA	231.16 aB
		total	463.18 a	671.02 b	678.81 b	338.78 c	622.59 b
BCR	(-)	S_C1	1.07 aA	0.92 aA	1.67 bA	1.80 bA	1.26 cA
		S_C2	0.96 aA	1.05 aA	1.84 bA	1.80 bA	1.56 bB
		S_C3	0.75 aA	0.82 aA	1.84 bB	2.01 cB	1.56 bB
		total	0.92 a	0.96 a	1.83 b	1.90 b	1.55 c
IWP	(dt mm^{-1})	S_C1	-	0.28 aA	0.28 aA	0.22 aA	0.22 aA
		S_C2	-	2.31 aB	2.69 bB	2.17 aB	2.05 aB
		S_C3	-	1.46 aC	2.38 bB	2.31 bB	1.56 aB
		total	-	1.89 a	2.48 b	2.19 a	1.78 a
WP	(dt mm^{-1})	S_C1	0.14 aA	0.08 aA	0.08 aA	0.07 aA	0.08 aA
		S_C2	0.89 aB	0.64 bB	0.78 aB	0.69 bB	0.71 bB
		S_C3	0.37 aA	0.41 aB	0.69 bB	0.74 bB	0.54 aB
		total	0.68 a	0.52 b	0.72 a	0.70 a	0.61 b

The total BCR was significantly highest at the 90% (1.90) and the 100% (1.83) irrigation levels. It was significantly lowest at the 0% (0.92) and the 80% (0.96) irrigation levels, respectively. The 120% irrigation resulted in a significantly lower total BCR compared to the 90% (−0.28) and 100% (−0.35) irrigation levels (Table 5). In tuber size class S_C1, the BCR was significantly highest at the 90% and the 100% irrigation levels, and significantly lowest at the 0% and the 80% irrigation levels. At the 120% irrigation level, the BCR of tuber size class S_C1 was 1.26. The BCR in tuber size class S_C2 differed significantly between the 0% and the 80% irrigation levels, compared to all other irrigation levels. In tuber size class S_C3, the BCR was significantly highest at the 100% irrigation level, and significantly lowest at the 0% and the 80% irrigation levels. The BCR in tuber size class S_C3 at the 90% and the 120% irrigation levels were 1.84 and 1.56, respectively, with no significant differences. Between tuber size classes, no significant differences were found for the BCR at the 0% and the 80% irrigation levels. At the 90% and the 100% irrigation levels, the BCR in tuber size classes S_C1 and S_C2 differed significantly from the BCR in tuber size class S_C3. At the 120% irrigation level, the BCR in tuber size classes S_C2 and S_C3 differed significantly from the BCR in tuber size class S_C1.

Total IWP was significantly highest at the 90% irrigation level (2.48 dt mm^{-1}). No significant differences were found between all other irrigation levels (Table 5). The total IWP of the 80%, 100%, and 120% irrigation levels were 2.19 dt mm^{-1}, 1.89 dt mm^{-1}, and 1.78 dt mm^{-1}, respectively. The IWP was not determined for the 0% irrigation level. In tuber size class S_C1, no significant differences were found in the IWP between the irrigation levels. In tuber size class S_C2, the IWP was significantly highest at the 90% irrigation level (2.69 dt mm^{-1}). No significant differences were found between all other irrigation levels. In tuber size class S_C3, no significant differences were found for the IWP between the 90% (2.38 dt mm^{-1}) and the 100% (2.31 dt mm^{-1}) irrigation levels, or between the 80% (1.46 dt mm^{-1}) and the 120% (1.56 dt mm^{-1}) irrigation levels. Moreover, the IWP differed significantly between all tuber size classes at the 80% irrigation level and in tuber size class S_C1, compared to tuber size classes S_C2 and S_C3, at all other irrigation levels.

The WP also accounted for precipitation during the growing season. The total WP was significantly highest at the 0% (0.68 dt mm^{-1}), 90% (0.72 dt mm^{-1}), and 100% (0.70 dt mm^{-1}) irrigation levels, with no significant differences between these irrigation levels. Significantly lower total WP were obtained at the 80% (0.52 dt mm^{-1}) and 120% (0.61 dt mm^{-1}) irrigation levels. In tuber size class S_C1, no significant differences were found between all irrigation levels. In tuber size class S_C2, the WP was significantly highest at the 0% irrigation level (0.89), with no significant differences between all other irrigation levels. In tuber size class S_C3, significantly highest WP returned at the 90% (0.69 dt mm^{-1}) and the 100% irrigation levels (0.74 dt mm^{-1}). The WP furthermore differed significantly between tuber size class S_C1 and the other tuber size classes at all irrigation levels, except the 0% irrigation level, in which the WP did not differ significantly between tuber size classes S_C1 and S_C3 (Table 5).

Applying the 90% irrigation level with the used gun sprinkler system to all sites of HAPP production of the selected local farm in Mecklenburg–Western Pomerania, Germany, could have led to possible water savings of 125.8 m^3 ha^{-1} on all loamy sand starch potato sites in 2021 (87,469 m^3 for all loamy sand starch potato sites in 2021). Total produced yield was predicted to increase by 2.0 dt ha−1 (139.5 t), while starch yield is predicted to decrease by 0.4 dt ha^{-1} (25 t). Starch yield of tuber size class S_C2 is predicted to increase by 4.6 dt ha^{-1} (318.5 t). The TPV_{total} increases by 58.16 USD ha^{-1} (40,438.65 USD), although yield of tuber size class S_C3 is predicted to decrease by 26.1 dt ha^{-1} (1813.9 t, Table 6).

Table 6. Possible water savings (m^3), changes in yield (t) and starch yield (t), and economic indices and responses (total production value and total production value with regard to tuber quality losses, USD) of farm level 80% and 90% irrigation levels using the local farm in Mecklenburg–Western Pomerania, Germany (1600 ha), on which 695.3 ha were of loamy sand and used for starch potato cultivation in 2021. Differences Δ were calculated in comparison to the common irrigation of the local farmer (100%, 828,797.60 m^3 at the farm level in 2021).

Yield & Economic Criteria			Irrigation Level	
			Δ (80%)	**Δ (90%)**
irrigation water	(m^3)	S_C1	+9420	+544
		S_C2	+7911	−9015
		S_C3	−162,370	−78,997
		total	−145,040	−87,469
yield	(t)	S_C1	+139.1	+245.7
		S_C2	−2123.2	+1710.8
		S_C3	−9192.4	−1813.9
		total	−11,176.6	+139.5

Table 6. *Cont.*

Yield & Economic Criteria			Irrigation Level	
			Δ (80%)	Δ (90%)
starch yield	(t)	S_C1	+19.5	+17.4
		S_C2	−454.0	+318.5
		S_C3	−1794.6	−360.9
		total	−2229.1	−25.0
total production value (with regard to tuber quality losses)	(USD)	S_C1	−26,970.70 (−44,181.29)	+28,632.45 (+7063.66)
		S_C2	−562,727.10 (−506,456.20)	+211,072.23 (+189,966.95)
		S_C3	−1,271,836.89 (−1506,220.38)	−199,266.03 (−412,976.41)
		Total	−1,825,855.65 (−2,056,857.87)	+40,438.65 (−215,945.80)

Furthermore, a total of 208.6 m^3 ha^{-1} of irrigation water could have been saved by a farm level application of the 80% irrigation level (145,040 m^3 for all loamy sand starch potato sites in 2021). However, yield would have been decreased by 160.7 dt ha^{-1} (11,176.6 t) and starch yield would have been decreased by 32.1 dt ha^{-1} (2229.1 t), respectively. Hence, TPV_{total} is predicted to decrease by 2625.99 USD ha^{-1} (1,825,850.84 USD, Table 6).

3.6. Maximum and Lowest Profitable Irrigation Levels

Both the MPI and LPI are varying depending on specific quality and economic criteria. For instance, the MPI and LPI for total yield are 126.8 mm (106%) and 92.8 mm (78%, Figure 3A).

The MPI and LPI for dry matter content are 150.0 mm (125%) and 95.9 mm (80%, Figure 3B). Starch enrichment is maximally profitable at an irrigation level of 108.3 mm (91%) and least profitable at 84.5 mm (71%, Figure 3C). The MPI and LPI for starch yield are 23.7 mm (104%) and 89.7 mm (75%, Figure 3D). The overall MPI is 104.1 mm (TWS = 359.2 mm, 87%), resulting in a water deficit of 24.1 mm for the meteorological conditions in 2021 (crop evapotranspiration = 349.9 mm, Figure 1). The overall LPI is 70.7 mm (TWS = 325.8 mm, 59%). Yield is predicted to decrease by 62.8 dt ha^{-1}, when reducing the irrigation level from the MPI to the LPI (Table 7).

Only negligible losses were predicted for dry tuber mass (−2.9 g kg^{-1}). Starch yield is predicted to decrease by 11.4 dt ha^{-1} (Table 7), mainly attributed to lower yields.

Table 7. Predicted changes in tuber quality when reducing the statistically maximum profitable irrigation level to the statistically lowest profitable irrigation level, for all tuber size classes.

Tuber Quality			Irrigation Level		Difference Δ
			Maximum Profitable	Lowest Profitable	
tuber number		S_C1	7.7	7.7	0.0
		S_C2	9.6	9.3	−0.3
		S_C3	4.6	4.3	−0.3
		total	21.9	21.3	−0.6
dry matter content	(g kg^{-1})	S_C1	248.9	238.3	−10.6
		S_C2	257.9	254.6	−3.3
		S_C3	259.5	255.5	−4.0
		total	255.4	249.5	−5.9
starch content	(g kg^{-1})	S_C1	170.4	170.2	−0.2
		S_C2	179.4	175.4	−4.0
		S_C3	182.3	180.1	−2.2
		total	175.8	173.9	−1.9

Table 7. *Cont.*

Tuber Quality			Irrigation Level		Difference Δ
			Maximum Profitable	Lowest Profitable	
starch yield	(dt ha^{-1})	S_C1	5.8	5.5	−0.3
		S_C2	49.5	44.2	−5.3
		S_C3	36.0	30.1	−5.9
		total	91.3	79.8	−11.5

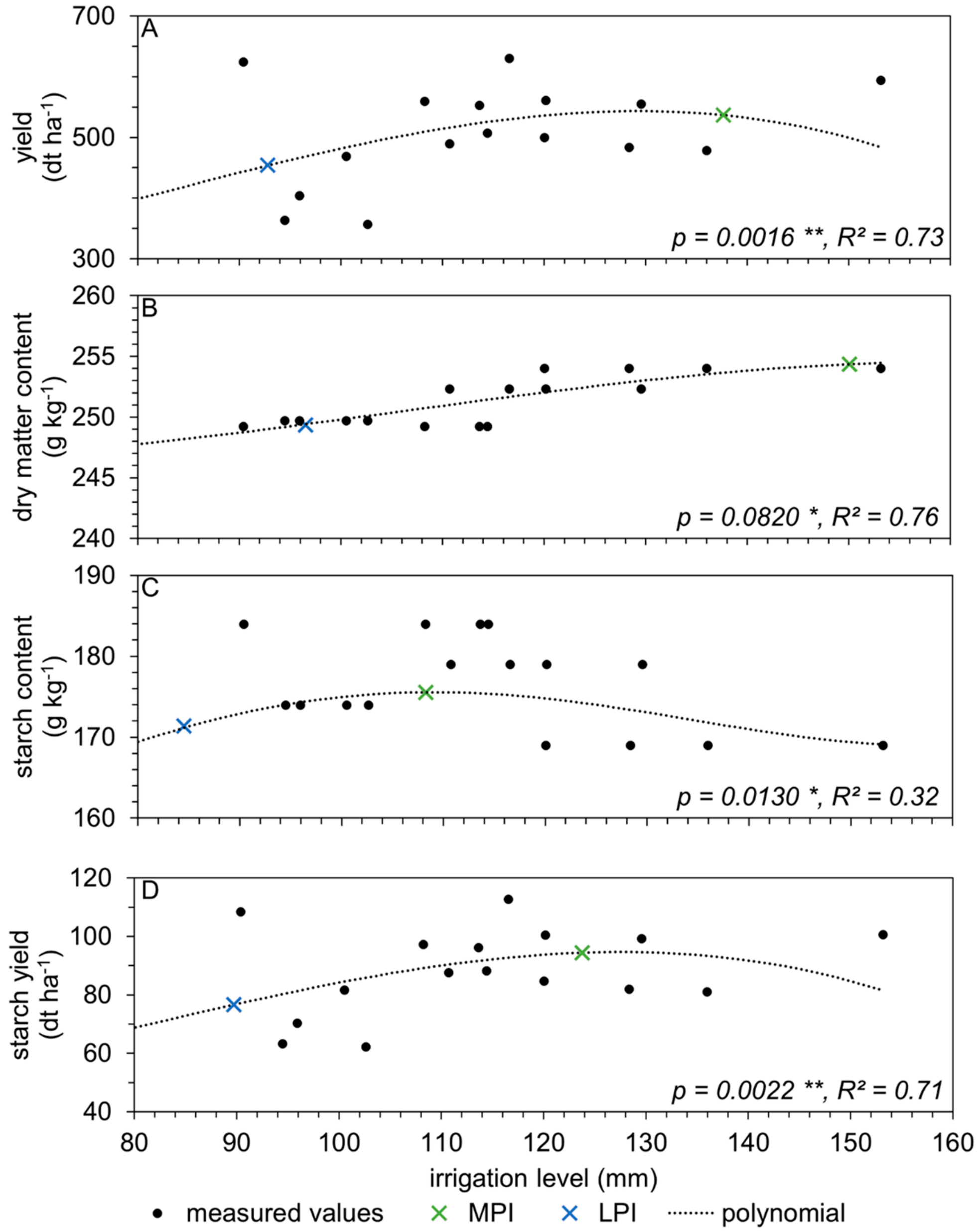

Figure 3. Yield and tuber quality of each harvest parcel (four harvest parcels per test plot) as a function of the irrigation level (mm). (**A**): total yield (dt ha^{-1}); (**B**): dry matter content (g kg^{-1}); (**C**): final starch content (g kg^{-1}); (**D**): total starch yield (dt ha^{-1}). Green dashed lines indicate the maximum profitable irrigation level (MPI). Blue dashed lines indicate the lowest profitable irrigation level (LPI), with regard to tuber quality thresholds. Level of statistical significance of each polynomial is indicated by * $p \leq 0.05$, ** $p \leq 0.01$. According to the polynomial order, there are local minima at higher irrigation levels than the MPI. These were not used for the LPI, as it must be lower than the MPI.

4. Discussion

4.1. Weather Conditions

Weather conditions during the 2021 growing season were appropriate for potato growth. Air temperature lower than 10.0 °C or higher than 30.0 °C could lead to a reduction of biomass allocation to tubers and thus lower yields [71]. Air temperature fell below 10.0 °C on 23 days or rose above 30.0 °C on 9 days during June 2021 (Figure 1) and thus exceeded optimum conditions, which might have led to tuber quality losses [72]. Yield is furthermore sensitively related to photoperiods with potential losses at a daily sunshine duration of more than 12 h [73]. Average daily sunshine duration during the growing season was 10.6 h d^{-1}, with more than 12 h d^{-1} on 20 days. Total precipitation during the 2021 growing season was 255.1 mm and failed to meet the 349.9 mm evaporative demand derived from in situ measured meteorological data (Section 3.1). The early season water deficits (40.5 mm before 28 June) may have caused yield and quality losses but were compensated by irrigation (Table S1).

4.2. Water Supply

TWS exceeded the in situ estimated crop evapotranspiration at all irrigation levels, leading to unproductive water losses of 3.6 mm at the 80% irrigation level, 11.9 mm at the 90% irrigation level, 24.4 mm at the 100% irrigation level, and 39.6 mm at the 120% irrigation level (Table S1). Hence, balancing out the in situ measured precipitation of 255.1 mm and the crop evapotranspiration of 349.9 mm, the optimum irrigation level should be 94.8 mm, corresponding to 79.5% of the irrigation level applied by the farmer.

In situ measurements of root zone (0–60 cm) soil moisture dynamics revealed that the 100% and the 120% irrigation levels exceeded both the commonly applied thresholds of optimal PAW ranges in potato irrigation management between 40% and 80% PAW during early growth stages and between 40% and 90% PAW during later growth stages [16,74], as well as the derived irrigation levels of ZEPHYR. The PAW ranges of the 90% irrigation level are in line with the optimum PAW ranges applied for the 100% irrigation level in ZEPHYR. These deviations indicate an increase of at least 10% in the irrigation levels by the local farmer, compared to the irrigation recommendation given by ZEPHYR, to incorporate the irrigation efficiency [42,43]. The topsoil (0–30 cm) furthermore indicated that the irrigation levels exceeded the optimum PAW ranges of ZEPHYR by 15% at the 90% irrigation level, by 20% at the 100% irrigation level, and by 30% at the 120% irrigation level.

Hence, the differences between demand-driven and actual irrigation levels highlight the need to increase the irrigation efficiency both technically and in terms of planning. Other soil moisture-based, water saving irrigation strategies, e.g., partial root zone drying techniques, are also well established for table potato production [75]. In this study, the PAW ranges of the 80% irrigation level are comparable to partial root zone drying irrigation levels [68,74]. Based on the significant yield losses observed in this study, partial root zone drying techniques must be doubted for successful HAPP production and require further investigation.

4.3. Total Yield and Tuber Size Distribution

Irrigation levels slightly below the commonly applied irrigation level by the farmer (i.e., 90%) were found sufficient for securing HAPP yield. The tuber size distribution is usually influenced by the number of tubers per plant [76], which was significantly highest at the 90% irrigation level (Table 4). Irrigation led to a significant increase of tubers in tuber size class S_C3, mainly attributed to the well documented drought sensitivity of potato crops during tuber formation [77]. However, no direct relationship was found between the irrigation level and the mean tuber weight, indicating that water supply mainly influences the tuberization of the potato plant but less the tuber growth.

The results for the HAPP *cv.* "Waxy/Henriette" are in line with previous studies conducted for several table potato varieties with different maturity times, e.g., "Cara" [78], "Folva" [68], "Santana" [79], and "Unica" [80]. However, the irrigation efficiency is not regarded in the observed irrigation levels. Although deficit irrigation levels have not yet been confirmed for HAPP, our results underscore a general trend that deficit irrigation levels to a certain degree and under average meteorological conditions are sufficient to produce a high, if not optimal, yield and tuber formation.

4.4. Tuber Quality

The tubers' starch content is the most important quality criterion in starch potato food production. Generally, the starch enrichment in the potato tuber is genetically determined [81], however, it is also affected by various subordinate external factors, e.g., weather conditions and water supply [82], soil properties and fertilization [83], and pest infestation [84].

The results of this study confirmed the dependency on the water supply of the starch enrichment in tubers of the HAPP *cv.* "Waxy/Henriette". The results indicated that a 90% irrigation level is sufficient to meet the starch content enrichment ability, as no significant differences were found in final starch content between the 90% and the 100% irrigation levels for tuber size classes S_C2 and S_C3. Significant differences in starch content between the tuber size classes indicated another dependence of starch enrichment on tuber growth and a further enhancement during later tuber maturation stages.

Incidences of deep scab and growth cracks are important quality criteria in starch potato production due to their facilitation of dirt accumulation, leading to starch quality degradation [85]. Common scab is generally caused by the soil-borne phytopathogenic *Streptomyces* species and may be managed by irrigation [86]. Other studies emphasized the dependence of common scab infestation on other external factors, e.g., the crop rotation, soil chemistry, or fertilization [87]. These considerations are in line with our experimental results, as no direct relationship was found between common scab infestation and the irrigation level, and the infestation was generally low. We further expected increasing incidences of tuber greening with increasing irrigation levels, resulting from irrigation intensity potentially causing soil erosion [88]. However, in this study, no relationship occurred between the ratio of green tubers and the irrigation level.

With no significant differences in total yield and starch yield found between the 90% and the 100% irrigation level, the first hypothesis is partly confirmed. Exceptions are made for the total starch content, which was significantly higher at the 100% irrigation level, compared to the 90% irrigation level, and for internal and external tuber quality criteria, which were higher (not significant) at the 90% irrigation level.

4.5. Economic Indices and Responses

The TPV_{total} was calculated as the total outcome of an agricultural production based on costs and estimated responses. Although the TPV_{total} usually lacks in reflecting specific relationships between inputs and outputs [63], comparable values can be obtained by (a) using the current global crop price and (b) taking into account fixed and variable production costs [57]. However, intra-seasonal fluctuations of variable production costs may reduce the comparability of economic responses [89]. These fluctuations are mainly attributed to variable costs of energy for irrigation. However, the operating duration (and hence the energy costs) of the used irrigation system remains mainly identical with a variable irrigation level. Accordingly, significant changes in energy costs for gun sprinkler irrigation are only expected with adjustments in the irrigation schedule (e.g., more frequent irrigation). However, other economic indices (e.g., the BCR) may enable deeper insights into the input–output relationships. Both the IWP and the WP are two of the most important indices taking into account both agricultural production and water use efficiency [90].

Based on the economic responses of variable irrigation levels, we recommend a 90% irrigation level for the HAPP *cv.* "Waxy/Henriette" grown on a loamy sand, as no significant differences were found for the TPV_{total}, the $TPV_{reduced}$, the total BCR, and the total WP between the 90% and the 100% irrigation levels. Moreover, the total IWP was significantly higher at the 90% irrigation level, compared to the 100% irrigation level. However, tuber quality losses led to significantly higher economic losses at the 90% irrigation level, compared to the 100% irrigation level. These indices allow us to partly confirm the second hypothesis, apart from increased tuber quality at lower irrigation levels. Increased economic responses to a lower irrigation level (i.e., 90%) were primarily achieved through lower production costs (Table 5) and higher yields (Figure 2).

The observation that applying a 90% irrigation level to the entire study farm (Section 2.6) during the growing season 2021 would have led to possible water savings of 87,469 m^3 substantiated the correctness of the third hypothesis. However, we assumed that all starch potato varieties equally react to variable irrigation levels in terms of yield and tuber quality compared to the investigated HAPP *cv.* "Waxy/Henriette". Nonetheless, there might be differences between potato varieties of the "Waxy" group and starch potatoes. For example, [83] showed significant differences in the yield response of different starch potato varieties to drought stress, although yield did not differ significantly within the investigated varieties of the "Waxy" group. HAPP are commonly classified as genetic clones of starch potatoes to reduce the formation of amylose inside the tubers [34,91]. However, further research is required on the differences between starch potatoes and HAPP, mainly attributed to a different response of amylose and amylopectin to the water supply [92]. These responses may have severe impacts on the starch enrichment of specific varieties and hence on the irrigation management.

4.6. Maximum and Lowest Profitable Irrigation Levels

Both the MPI and LPI are appropriate indices for assessing the yield, tuber quality and economic response to a variable irrigation level. The overall MPI of 104.1 mm (TWS = 359.2 mm) corresponded to an irrigation level of 87%, proving that a lower irrigation level than the common irrigation of the farmer is sufficient for securing yield, quality, and economic responses of the HAPP *cv.* "Waxy/Henriette", grown on a loamy sand. The varying MPI between different quality criteria (Figure 3) indicated a strong dependence of yield and dry matter on irrigation level, but starch enrichment is only partially affected by the amount of available water, which substantiated the findings of [84]. Hence, potato yield responds weakly to a large range of TWS, as soon as TWS nearly approaches the MPI, and depends on other external factors, e.g., pest infestation and the fertilization regime [93]. The LPI, however, does not focus on the most effective crop production, but may be helpful under expected climatic changes, increasing water scarcity, and for irrigation management in water scarce regions [94].

4.7. Experimental Limitations

This study primarily aimed to assess a novel methodology based on yield and tuber quality information at different irrigation levels and the economic response for the HAPP *cv.* "Waxy/Henriette". This methodology and the derived yearly experimental data are required for a practice-orientated implementation, as the underlying agricultural conditions differ between different growing seasons, e.g., in terms of meteorological variations, economic responses due to differing energy and irrigation costs as well as contractual gross returns, and soil conditions due to commonly applied crop rotations. Thus, single year experiments challenge spatial and temporal scaling and socio-technical implementation [95,96]. An increasing number of methodological studies showed the suitability of single-year field experiments in aiming to establish a practice-oriented contribution to agricultural practice [97,98]. Additionally, it is generally suggested to include additional data sources for minimizing the spatial and temporal uncertainty of the experimental results, e.g., remote sensing data for securing a spatial transferability [97,99] or yield and quality information from previous years [100]. Yield data from 2015 to 2020 for all cultivated HAPP varieties at the local farm in Mecklenburg–Western Pomerania, Germany, showed that the experimental results from 2021 are in line with the expected yield of HAPP under given agrometeorological conditions and irrigation levels (Table S2, $R^2 = 0.89$, $p = 0.0013$). However, an above-average TWS led to increased yields in 2021. The final starch content in 2021 was near to the average starch content of 2015 to 2020, however, it is not adequately described by linear regression (R^2 = 0.35, p = 0.155), indicating the dependency of starch accumulation on several external and genetic factors. Starch yield in 2021 was near to the maximum value of previous years, mainly due to the high total yields (R^2 = 0.94, p = 0.0002). Moreover, the yield data from 2015 to 2020 revealed that irrigation is mainly used for compensating for short-term drought. In 2017, for example, which was an above-average year according to precipitation (308.0 mm during the growing season), irrigation was shortened to 75.3 mm. The above-average water supply (TWS = 383.3 mm) led to the overall maximum yield of 566.2 dt ha^{-1}. On the other hand, in 2018, which was an exceptionally dry year with an overall precipitation of 122.2 mm from April to September, irrigation was near the maximum (134.8 mm). However, some drought stress might have led to yield reductions (470.4 dt ha^{-1}). In 2021, both precipitation (255.1 mm) and irrigation (119.2 mm) were above-average (194.8 mm and 96.3 mm, respectively), explaining the near maximum total yield (559.1 dt ha^{-1}). In comparison with long-term precipitation and air temperature during the growing season (Section 2.1), all of the previous growing seasons (2015–2020) were below the long-term average precipitation sum of 337.9 mm, with deficits ranging between 29.9 mm in 2017 and 215.7 mm in 2018. Moreover, mean air temperature during the growing season was above average (14.4 °C) in all years between 2015 and 2020, with higher air temperatures ranging between 0.9 °C in 2015 and 3.5 °C in 2019. The deficit in precipitation compared to the long-term average in 2021 was 82.8 mm, and the air temperature was 2.6 °C higher.

Furthermore, irrigation during the field experiment was unsteady, mainly related to the gun sprinkler irrigation system. A spatially uniform water distribution is usually not guaranteed by gun sprinkler irrigation systems [101]. To ensure at least an accurate estimate of water supply, we used the actual irrigation levels at each harvest parcel based on recorded 7-min GPS data, resulting in the highest possible accuracy of yield–quality–irrigation relationships under the given spatial and temporal gun sprinkler variance and its efficiency.

According to Darko et al. (2017) [102], for instance, the efficiency of gun sprinkler irrigation systems are mainly affected by changes in wind speed and its direction, spray evaporation losses, slopes in the field and resulting surface runoff, the evaporation of water droplets before infiltration, but also technical issues, as the type of irrigation nozzles, the age of the system, or the height of the gun sprinkler above the canopy. Thus, most irrigation system application efficiencies are displayed as a range, reflecting the variation in factors that can affect the system application efficiencies. For design, comparative, forecasting or irrigation scheduling, and analysis purposes, a single application efficiency value must usually be selected for each irrigation method. However, equating the crop water demand (i.e., the evaporative losses) with the irrigation demand of a crop is limited in agricultural practice, as unknown water losses due to the irrigation efficiency are commonly not regarded.

During the field experiment, the common irrigation level of the farmer (100%) was scheduled iteratively each irrigation day using ZEPHYR. However, ZEPHYR estimates the actual soil water deficit in comparison to optimum PAW ranges for potato production between 40% PAW and 80% PAW during early growth stages and between 40% PAW and 90% PAW during later growth stages [41]. Hence, the crop water demand provided by ZEPHYR does not equal the actual irrigation demand that usually integrates the irrigation efficiency. The results of this study, as well as in situ measurements of soil moisture dynamics, indicated that the local farmer underestimates the irrigation efficiency of a gun sprinkler system. A lower irrigation level than the common irrigation level of the farmer was sufficient to meet the irrigation demands of the crop (i.e., the water demand of the crop and the losses of irrigation water). However, the soil moisture dynamics indicated that the commonly applied optimum PAW ranges for potato irrigation are not sufficient for HAPP production.

5. Conclusions

This study aimed to investigate the optimum irrigation level for HAPP in terms of yield and tuber quality. The experimental results showed that HAPP have slightly shifted irrigation demands compared to the irrigation level recommended by commonly used tools for irrigation management.

The experimental results of this study contribute to the recent research of sustainable water use and demand-driven irrigation management. Irrigation decision support systems may be improved by the use of differentiated, variety-specific optimum PAW ranges. The presented approach for estimating economic responses of variable irrigation levels helps to implement a practice-oriented irrigation management.

The results of this study may hence serve as a first step towards a demand-driven starch potato irrigation management and as potential measures for future irrigation adaptation strategies in response to climate change and variance.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/agronomy12112685/s1, Table S1: Irrigation levels and total water supply (irrigation + precipitation, TWS) applied in the field experiment. The irrigation levels were defined in relation to the common irrigation practice of the local farmer (100%). The irrigation levels were planned as 80%, 90%, and 120%, respectively, but were affected by technical gun sprinkler properties, resulting in high spatial and temporal variances. Standard deviations calculated from 7-min GPS based speed and location gun sprinkler data are shown plot wise for each irrigation level and event. The actual irrigation levels were assessed using the ratio of each irrigation level compared to the common irrigation level of the farmer (100%) by dividing the actual irrigation level by the actual 100% irrigation level; Table S2: Harvest results on the local farm in Mecklenburg–Western Pomerania of all cultivated HAPP varieties from previous years (2015–2020) in comparison with experimental data from 2021 for the investigated HAPP *cv*. "Waxy/Henriette" and agrometeorological conditions and irrigation levels: I = irrigation (mm), P = precipitation (mm), TWS = total water supply (mm), T = air temperature (°C), Y = total yield (dt ha^{-1}), SC = starch content (g kg^{-1}), SY = starch yield (dt ha^{-1}). Agrometeorological parameters are shown for the growing season from 1 April until 30 September each year. The total water supply is calculated as the sum of irrigation and precipitation. Starch yield is calculated as the product of total yield and the starch content.

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