EVALUATION OF VARIABLE RATE IRRIGATION WITH CENTER PIVOTS IN BRANDENBURG (GERMANY)

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Abstract

In Germany, irrigation is an option to safeguard crop yields but requires an efficient strategy. Field tests were combined with simulations to test the water saving potentials and yield effects of variable-rate site-specific (VRI) and deficit irrigation (DEF) in comparison to uniform full irrigation (UI) and non-irrigated references (NON). These strategies were applied at two fields with center pivot irrigation, which were heterogeneous in terms of soil conditions and plant growth. Delineation of management zones for VRI was based on the depth-dependent and lateral spatial variation in plant available water holding capacity (AWC).

The calculated crop water requirements differed between site-specific and uniform irrigation. Likewise, crop yields were not significantly different between these two strategies. Besides the rather small AWC range, these findings can be attributed to the minor importance of soil water storage for irrigation water needs.

Deficit irrigation saved up to 20% of water compared to uniform irrigation. Water savings and irrigation water productivity were larger for winter wheat and silage maize than for potatoes and forage peas. Without any irrigation, yields were considerably lower, particularly for peas and potatoes. This confirms the importance of irrigation for crop yield in our study region.

Precision irrigation in Germany revealed to be not economically sensible under the current conditions. But, uniform irrigation with reduced water amounts has been proven to be efficient, especially in case of growing winter wheat. Irrigation of potatoes and silage corn produced the best results with full water applications.

Abbreviations

AWC = available water content

ER_a = apparent electrical resistivity

ET = evapotranspiration

FC = field capacity

GDR = German Democratic Republic

IMZ = irrigation management zone

PET = potential evapotranspiration of the specific crop

PWP = permanent wilting point

VRI = variable-rate site-specific irrigation of heterogeneous fields

WRB = World Reference Base for Soil Resources

Keywords

irrigation strategy, irrigation scheduling, site-specific irrigation, deficit irrigation, yield, economy.

1. Introduction

Global warming is expected to result in more widespread, longer-lasting and more frequent soil moisture deficits in central Europe (Samaniego et al. 2018, Trnka et al. 2019, Webber et al. 2018). Our study region, the state of Brandenburg in eastern Germany, faces rising temperatures and hence rising evaporative demands, which has already decreased water availability particularly in the growing season (MLUL 2018). Water balance simulations revealed the negative influence of these climatic conditions on crop water supply and yield (Mirschel et al. 2006). The expansion of irrigation (up from today's 1.8% or 24,400 ha of cultivated land) may mitigate this impact of climate change, but would increase the pressure on already stressed ground and surface waters (MLUL 2018, Natkhin et al. 2012). The footprint of increased irrigation on potentially shrinking water resources could be reduced by improving irrigation efficiency.

One strategy to achieve this is the variable-rate site-specific irrigation of heterogeneous fields (VRI from here on), which avoids over-irrigation of subareas with low irrigation water demand (Goumopoulos et al. 2014, Hedley and Yule 2009, Monaghan et al. 2013). Site-specific management requires the division of a field into management zones that are spatial classifications of soil and/or plant properties (e.g. Delin and Berglund 2005; Fleming et al. 2000). In the framework of VRI, the objective is often to build homogeneous classes of plant available soil water holding capacity (e.g. Delin and Berglund 2005; Timlin et al. 2001). For the delineation of irrigation management zones, multiple statistical techniques were successfully applied, such as clustering (Boluwade et al. 2016, Haghverdi et al. 2015), kriging (Daccache et al. 2015, Fortes et al. 2015), linear programming (Haghverdi et al. 2015), and inverse modeling (Florin et al. 2011). Before an irrigation event, management zone maps are transformed into application maps that are usually updated with real-time information from sensors or models (O'Shaughnessy et al. 2019; Thorp et al. 2015).

Main drawbacks of VRI systems are their high costs and the extra effort for the farmer to operate them (Monaghan et al. 2013, O'Shaughnessy et al. 2019). To date, VRI techniques are used by only few farmers in Germany, which is predominantly due to doubts about their benefits. Limited implementation of site-specific sprinkler irrigation by producers was also reported for the U.S. (Evans and King 2012). It is recommended that farmers carefully consider the costs and potential advantages and disadvantages of this technology (O'Shaughnessy et al. 2019).

Globally, water savings with VRI typically range from 0 to 26% in comparison with uniform application rates (Evans and King 2012). While the mechanical performance of VRI systems is advanced, it is still considered a challenge to demonstrate water savings, improved water use efficiencies and yields (O'Shaughnessy et al. 2019). This difficulty derives from the uniqueness of each field regarding the tradeoff between advantages and disadvantages of these systems (Pokhrel et al. 2018): for one, the type and amount of variability is field-specific, but the return on investment also depends on factors like crop prices (Marek et al. 2001). The divergent reports on water savings with VRI are therefore not surprising. While several researchers did not find consistent advantages of VRI (Bhatti et al. 2020, Sharma and Irmak 2020, Stone et al. 2019, Thorp 2019), others were able to demonstrate positive effects (Hedley 2009, Sui and Yan 2017). It is also important for VRI performance that all relevant sources of variability in irrigation requirements are captured in the scheduling tool. While most reports focused on soil variability (Evans and King 2012), Bhatti et al. (2020) suggested that spatial estimates of crop evapotranspiration can improve the accuracy of computed spatial irrigation requirements. However, the practical implementation of plant-based VRI control faces a number of obstacles, including the high cost of data collection and analysis.

Another strategy to improve irrigation efficiency is deficit irrigation, in particular where water availability for irrigation is clearly limited (Fereres and Soriano 2007, Rudnick et al. 2019). If deficit irrigation takes into account the crop response to water stress during crop development (Kirda and Kanber 1999), it reduces water consumption while minimizing adverse economic effects. Hence, the main objective of deficit irrigation is to increase the irrigation water productivity (ratio of yield to irrigation water use, see Fernández et al. 2020), e.g., by eliminating irrigation that has little impact on yield (Kirda 2002). Long-term field experiments in the state of Lower Saxony, Germany, have shown that deficit irrigation of potatoes, silage maize, sugar beet and winter wheat provided at least 90% of maximum yield, if only about 60% of the seasonal water requirement is used (Fricke 2020, Riedel 2021). This reduction in irrigation water consumption is achieved by a delayed start of irrigation (triggered at 25-40% of available water holding capacity compared to 40-55% for full irrigation). The economic benefits of deficit irrigation, however, differ with the type of crop. Therefore, the choice between full and deficit irrigation requires considerable care.

In contrast to VRI, deficit irrigation is already applied in Germany, mainly in situations when high seasonal water demands meet limited water extraction permits. In some parts of western Germany, for instance, water authorities restrict the amount of irrigation water to 80 to 100 mm per year (Schittenhelm and Kottmann 2018). There is no unique deficit irrigation strategy; instead, several variants and mixtures of alternatives are possible. In our study region, farmers facing water shortages tend to accept longer gaps between irrigation cycles or apply a limited water amount. Controlled deficit irrigation with the help of a dedicated scheduling tool is not yet common practice.

The successful application of a scheduling tool, however, requires an appropriate irrigation strategy in the first place, one that also ensures an optimal return on investment under prevailing agronomic and economic constraints. Therefore, our main objective was to evaluate the water saving potential and economy of two such strategies, i.e., site-specific and deficit irrigation, as compared to uniform full irrigation. For this purpose, an irrigation setup was developed, which compares these strategies under Brandenburg's agricultural conditions: large fields, center pivot irrigation, and a typical crop rotation. The novelty of our study lies in this joint examination of three important irrigation strategies at the same fields. Moreover, the whole process, from management zone delineation and irrigation scheduling to the effect on crop yield was considered combining geostatistical methods, commercial irrigation software and crop modelling across a multiple year crop rotation. Lastly, our work was based on farmers' fields with conventional irrigation equipment and is therefore closely linked with agricultural practice.

2. Material and methods

2.1 Study area

The region of our study is located in the highly structured moraine landscapes of Brandenburg in Germany. The soil landscapes are predominated by ground and terminal moraines as well as large outwash plains, which alternate with strongly groundwater-dependent glacial valleys and meadows along riverside lowlands. Most soils are sandy (share of sand fraction in fine earth typically between 48 to 100%, but often more than 85%) except for some floodplain areas. Soil variation within a field is often due to the deposition and subsequent relocation of heterogeneous glacial and fluvial-glacial sediments. Climatically, the region is characterized by a humid continental climate (Dfb of Köppen climate classification) with a mean annual air temperature of 9.6°C and an annual precipitation of 584 mm.

This study took place at two farms in Brandenburg. At each farm, the farmers proposed one field where management history indicated considerable heterogeneity in crop growth conditions.

One field of 41 ha is located in north-western Brandenburg close to the village of Dahlhausen (53.08° N, 12.33° E, called "Dahlhausen" hereafter; Fig. 1). According to the WRB soil classification, it is covered by Arenosols in large parts, which cover melt water sands. In some locations, the subsoil shows gleyic properties (oximorphic colors). Since the field is drained, they indicate a former groundwater influence. A preliminary soil sampling campaign confirmed the dominance of a sandy soil texture with local and smooth increases in the fine earth fraction (silt and clay) towards a depth of 1 m. Peculiarities such as impermeable or gravel layers were not recorded. Soil heterogeneity in this field therefore relates to differences in the proportion of silt and clay in the fine earth fraction. Subsequent to the preliminary campaign, two soil pits at contrasting locations within the field were dug up to determine the soil texture, soil organic carbon content, water retention parameters and bulk density in four horizons (n = 3/horizon, analyzed as a composite sample for soil texture and soil organic carbon content). At one profile (Fig. 1, profile 1), the soil is a pure sand throughout the entire depth range down to

1.20 m (Tab. A.4). At the other profile (Fig. 1, profile 2), the percentage of sand was between 73 and 78%, while silt and clay held 16 to 21% and 3 to 11%, respectively (Tab. A.4).

The Dahlhausen field is used for conventional plant production with a crop rotation including silage maize, winter wheat and potatoes. A center pivot irrigation machine irrigates 31 ha of the field in a half circle (Fig. 1). The system was equipped with a VRI system for two out of six spans, which enables 53 nozzles (Nelson R3000 with 2,1 bar pressure reducers) to be controlled individually (Fig. 1; area under VRI = 13 ha). Different application rates are applied by pulsing the nozzles within time periods from 30 to 180s. Uniformity variations in the existing sprinkler chart are compensated by automatic adjustments. The wetting radius of a nozzle is approximately 11 m. After the pivot was installed, the uniformity of application along the pivot lateral was evaluated (e.g. O'Shaughnessy et al. 2013) which revealed a satisfactory performance of the VRI system: the root mean square error was 2.1 mm, which was obtained by recording the difference between the prescribed irrigation amount of 24 mm and the actually applied amount.

The other field covers an area of 31 ha and is located in southern Brandenburg close to the village of Schoellnitz (51.65° N, 13.99° E, called "Schoellnitz" hereafter; Fig.1). The crop rotation at Schoellnitz includes mainly silage maize after a catch crop and winter wheat. Most of the field (28 ha) is irrigated with a center pivot. As at Dahlhausen, the irrigation machine was equipped with individual nozzle control at the length of two span, which amounts to an area under VRI of 10 ha. The nozzles' wetting radii are also below 15 m.

The soil at the Schoellnitz field originated from melt water sands too, which locally cover glacial loams. As at Dahlhausen, the soil was classified as an Arenosol. During the preliminary soil sampling campaign, occasionally dense (less permeable) layers at 0.7 m soil depth on average occurred, which originated from the glacial loams. At some locations, these dense layers occurred already within the upper 0.5 m of the mineral soil, which hints at stagnic soil properties. The topsoils were consistently sandy. One of the two sampled soil profiles at this field was again characterized by pure sands in all horizons (profile 1, Fig. 1), whereas in the other profile, silt and clay, respectively, contributed up to 21 and 23% to the fine earth fractions (Tab. A.4). As expected, the highest clay content occurred in this profile's dense layer, which was located between about 0.45 and 1.0 m depth. As a consequence, the soil saturated hydraulic conductivity dropped from nearly 3000 mm/d in the horizon above to only about 300 mm/d in the dense layer (measured with soil cores, n = 5/horizon). Soil heterogeneity at Schoellnitz is therefore mainly characterized by the scattered occurrence of a dense and less permeable horizon in otherwise sandy profiles. Soil water retention parameters such as field capacity and wilting point are provided in Tab. 2 for management zones of both sites (see chapter 2.3 for methodology of management zone delineation).

At both fields, two meteorological stations were installed at the profile locations to measure rainfall, wind speed, temperature and humidity. The rainfall data were automatically transferred into our irrigation steering model; applied irrigation amounts had to be deleted manually, because the rain gauge was placed below the pivot. Soil moisture probes (type 10HS, locally calibrated in our lab) were installed in each soil profile pit at four depths of 0.2 m, 0.4 or 0.5 m, 0.8 m and 1.2 m. The 0.2 m probe was relocated to 0.5 m depth before the use of the cultivator and reinstalled at 0.2 m thereafter.

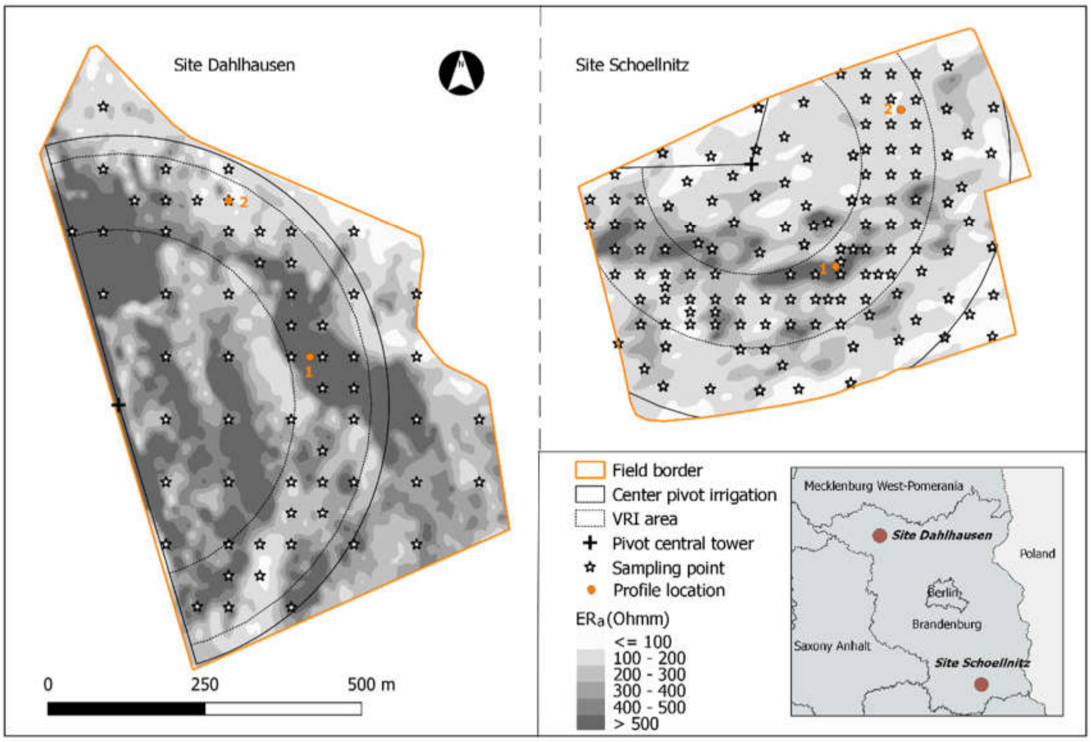

Fig. 1 Apparent electrical resistivity, ER_a, as well as sampling and profile locations at the field sites Dahlhausen and Schoellnitz. We show the ER_a data from 0-0.75 m depth for site Dahlhausen and from 0-1 m depth for site Schoellnitz, because these depth ranges are relevant for management zone delineation. The inlet shows the locations of the sites in the federal state of Brandenburg, Germany

2.2 Irrigation scheduling

To determine the irrigation timing and amount, we used a decision support system for irrigation scheduling called IRRIGAMA steering (IRRIGAMA: irrigation management). The system consists of two parts: the first part is a one-dimensional multiple layer soil hydrological model that simulates soil moisture changes driven by precipitation, evapotranspiration and percolation (Fig. A.1). The second part is an irrigation steering module. IRRIGAMA steering is a recently reprogrammed version of the BEREST model, which was developed in former East Germany. BEREST was extensively calibrated under East Germany's humid climatic and soil conditions using lysimeter experiments, which started in the 1970s and ran until 2001 (Roth et al. 2005). In the year 1981, the model was used to steer irrigation on 270,000 ha of cropland in the former GDR, which equated to 64% of the country's irrigated fields (Wenkel and Mirschel 1982). Today, its successor IRRIGAMA steering is used by agricultural consulting services in Germany.

The soil hydrological model simulates soil water replenishment after rainfall or irrigation events, water uptake from multiple soil layers by plant transpiration, and soil evaporation (Fig. A.1, Glugla 1970, Koitzsch et al. 1980). The model requires information on soil water retention, such as field capacity (FC hereafter) and permanent wilting point (PWP hereafter), for at least two layers. The first layer is mandatory and fixed to 0-

0.3 m depth, whereas the remaining one or two layer(s) can be defined as appropriate. The model simulates soil moisture changes for five internal model layers from 0 to 1.5 m soil depth. Other input variables include precipitation and short-grass reference evapotranspiration (ET_o). For ET_o, the formula of Turc and Wendling (Equation 1) is used (Wendling et al. 1991), because it provided slightly more accurate estimates of lysimeter evapotranspiration during calibration of BEREST than the Penman-Monteith formula (Günther 1997, Roth et al. 2005).

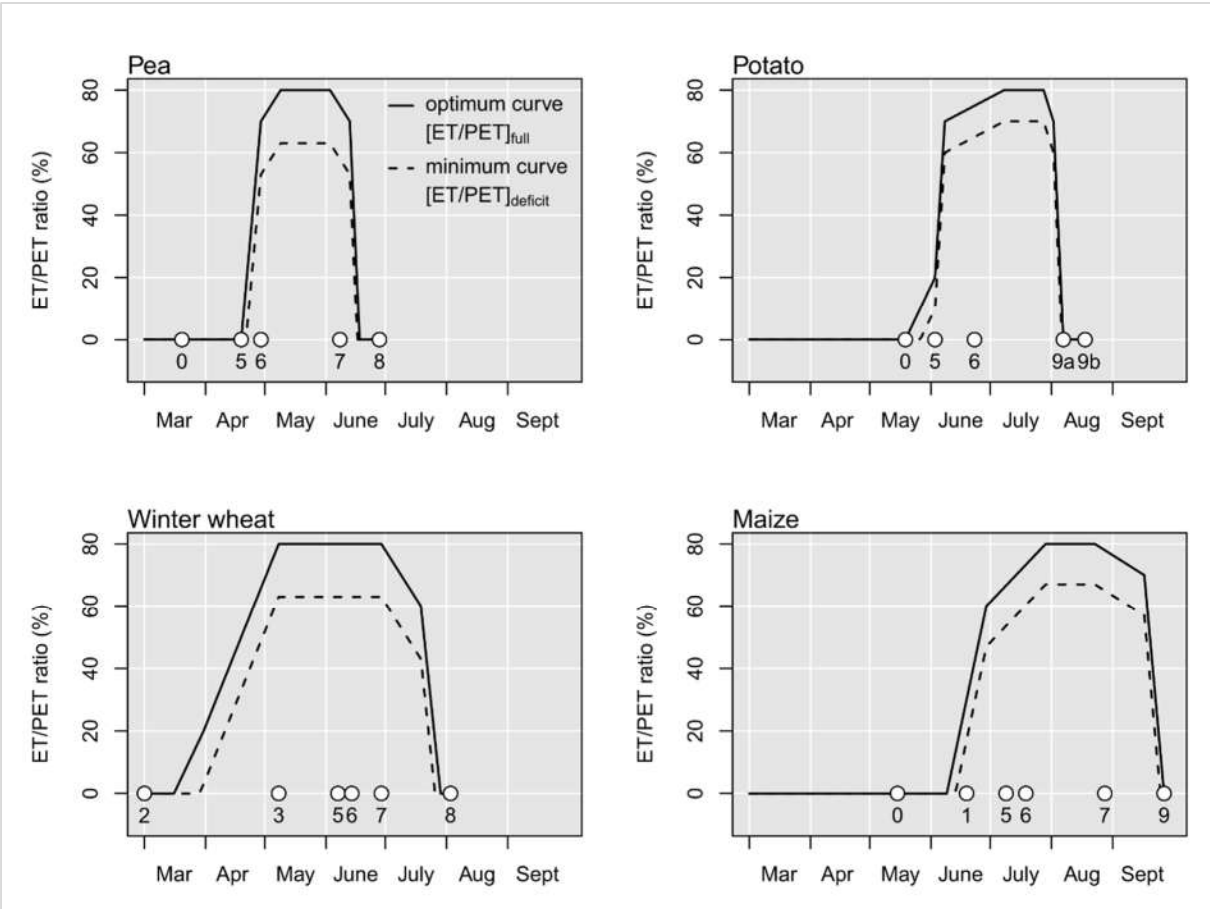

Fig. 2 Optimum and minimum steering curves for the simulated crops. The optimum steering curve is used to schedule full and the minimum curve to schedule deficit irrigation. The lengths of the irrigation seasons can be deduced from these curves (irrigation is required when they deviate from 0). The points on the bottom of the graphs refer to selected plant growth stages (Meier, 2018) and to the harvest date, respectively, for pea (0 = germination, 5 = inflorescence emergence, 6 = flowering, 7 = green ripe, 8 = harvest), potato (0 = emergence, 5 = inflorescence emergence, 6 = begin of flowering, 9a = leaves brownish, 9b = harvest), winter wheat (2 = begin of tillering, 3 = begin of stem elongation, 5 = begin of heading, 6 = flowering, 7 = milk ripe, 8 = harvest), and maize (0 = emergence, 1 = eight leaves unfolded, 5 = tassel emergence, 6 = flowering, 7 = milk ripe, 8 = harvest)

The reference evapotranspiration is dynamically corrected using crop-specific correction functions to estimate potential transpiration of the specific crop (abbreviated with PET hereafter; FAO56 synonym: ET_c). The correction functions are similar to FAO K_c crop factors and were derived empirically (Tab. A.2). They are internally stored in the IRRIGAMA steering database along with default values for rooting depths and canopy cover for more than 100 different crops including arable crops, vegetables, herbs and a number of fruit tree species. All internally stored values can be overwritten by the user.

The irrigation steering module calculates the optimum timing and amount of irrigation (Fig. A.1). The control parameter is the ratio between ET and PET, which is a widely used empirical stress factor (e.g. Peng et al. 2019). If the ratio equals 1, water availability is not limited. If the ratio drops below a certain threshold, however, transpiration is limited due to diminishing soil water availability. These thresholds (steering functions) were defined by crop-specific and growth-specific relationships between irrigation water supply and yield, which were derived from the lysimeter experiments for the investigated crops and implemented into the model database (Roth et al. 2005).

In addition to the ET/PET threshold values for full irrigation ($[ET/PET]_{full}$, Fig. A.1), minimum steering functions were derived in these lysimeter experiments ($[ET/PET]_{deficit}$). In line with general recommendations on deficit irrigation (Fereres and Soriano 2007), the minimum curves never fall below an ET/PET ratio of 60% (Fig. 2). We used them to steer our deficit irrigation strategy (chapter 2.4.).

2.3 Delineation of irrigation management zones

A geostatistical approach to divide the test fields into distinct management zones was applied based on soil data and ancillary information from proximal soil sensing. To get the ancillary data, a geo-electrical survey was performed in autumn 2017 with the Geophilus system (Lück and Rühlmann 2013). The system includes a multi-depth electrical resistivity sensor, a gamma ray sensor (for measuring soil-born γ activity) and a DGPS. Apparent electrical resistivity (ER_a hereafter) is explored in six depth levels from the soil surface up to a maximum depth of investigation of about 1.5 m. A focal parameter was ER_a because incorporation of the γ activity and altitude did not improve our results. The two fields were mapped with a track distance of about 15 m and a sampling distance within a track of about 3 m, which corresponds to approx. 300 data points per hectare.

For subsequent soil sampling, a gridded survey was performed, which is the usual choice because of its efficiency for sample collection and spatial prediction (Viscarra Rossel and McBratney 1998). Grid spacing was adopted to the correlation length of the target variables, which was roughly estimated from variograms of the ancillary data (Kerry et al. 2010), in our case the parameter ER_a. The ER_a data was also used as a covariate in subsequent statistical analysis. Our approach is summarized in Fig. A.2. The sources of soil heterogeneity differed between our two sides, which is why we chose different approaches for soil mapping and delineation of irrigation management zones (abbreviated with IMZ from here on). They are described in chapters 2.3.1. and 2.3.2. The statistical software R (R Core Team 2017) with the packages geoR (Ribeiro Jr et al. 2022) and raster (Hijmans 2020) was used for geostatistical analyses and interpolation.

2.3.1 Delineation of management zones at Dahlhausen

Since the preliminary campaign did not reveal any obvious peculiarities (chapter 2.1.), we decided to base the management zone delineation directly on our target soil properties FC and PWP.

The soil was sampled at three soil depths: 0.1, 0.35 and 0.6 m. These depths were selected to meet the requirements of our irrigation steering model (chapter 2.2.) as well as for practical reasons (deeper hand-dug profiles are unacceptable). To determine the grid distance of the soil sampling grid, variograms of the ER_a data were calculated for the depth intervals of 0 to 0.25 m, 0 to 0.5 m and 0 to 0.75 m. This analysis revealed ER_a autocorrelation distances of 200 to 400 m. We therefore chose an overall grid distance for our soil survey of 100 m and added some additional sampling locations at 50 m distance in the VRI area until the sample size equaled 60 (Fig. 1).

At the sampling locations, soil data were collected as follows: we manually dug a small soil profile down to about 0.8 m depth. At each sampling depth within a profile, then horizontal platforms were created to place three adjacent undisturbed soil cores (DIN EN ISO 11274:2014-07), which were extracted with a soil core sampler. The cores have an inner volume of 1e-4 m^3 (inner diameter = 57 mm, height = 40.5 mm). The sampled soil depth increments are 0.1-0.14 m, 0.35-0.39 m and 0.60-0.64 m. The cores were placed into padded boxes for a smooth transport to the lab of the Research Institute for Post-Mining Landscapes. In the lab, the cores were analyzed for their water content at FC (at pF 1.8) and PWP (at pF 4.2). Prior to further analysis, the mean FC and PWP were calculated, respectively, for the three replications at each depth.

The target variables were interpolated separately at the three sampled depths with external drift kriging. After exploratory data analysis and data transformation if necessary, the geostatistical model parameters were estimated with the REML-E-BLUP approach, which is described in detail by Lark et al. (2006). Several correlation functions (spherical, exponential, and pure-nugget) were tested and the performance of the fitted model was evaluated by leave-one-out cross-validation as proposed in Lark (2000). After identification of a suitable variogram, our target variables were predicted on a 1-m grid based on that model and the exhaustive ER_a data.

Next the predictive uncertainty was evaluated. This was possible because the kriging interpolation not only provided us with six soil maps (FC and PWP at three soil depths) but also with the prediction error at each prediction location. A procedure was developed to utilize this error for decision support on the number of classes or management zone.

Finally, the three-dimensional FC and PWP classes were overlaid. Very small classes, which covered < 0.5 ha of the field, were deleted and attributed the value of the neighboring class. In the same way we removed fragments, i.e. localized occurrences of a class which were smaller than 225 m^2 (the wetting radius of a single drizzle, see chapter 2.1.).

2.3.2 Delineation of management zones at Schoellnitz

In the year of the reconnaissance study, the Schoellnitz field was planted with sugar beet. It was obvious that previously described patterns of soil spatial variability (chapter 2.1.) strongly influenced the growth of the beet: at places without the dense layer, the sugar beet was notably smaller and suffered more from occasional drought stress. We therefore decided to base the management zones on the occurrence of the dense soil layer, which was derived from auger samplings as in the preliminary campaign.

As for Dahlhausen, the autocorrelation length of the ancillary data was used to determine the grid distance of the sampling grid. Because our target variable was recorded in the upper soil meter, the ER_a data of the 0 to 1 m depth increment was used for this purpose. The variogram model of this data had an effective range of about 160 m, which is why we set the minimum grid distance to 80 m (Fig. 1). To get a grip on small-scale fluctuation too, some extra points were added at 1 m distance to the main grid points. In addition, the grid resolution was doubled within the VRI area (Fig. 1). In total, the sample size amounted to 152 including the preliminary sampling.

For interpolation of our target variable, we applied indicator kriging after coding the data as "1" (presence of the dense layer in the upper soil meter) and "0" (absence). The k-means clustering algorithm was applied to next incorporate our ancillary variable, ER_a at the zero to one meter soil depth, into the spatial dataset. Prior to the cluster analysis, the datasets were standardized by subtracting the mean of the predictions from each predicted value and dividing the result by the standard error of the prediction. Because our target variable had only the two expressions "presence" and "absence", the number of classes was restricted to two.

Finally, a mean FC and PWP had to be assigned to each of the two created management zones at the three soil depths, which are parameterized in the steering model. This was obtained by extracting undisturbed soil cores at the three soil depths (0.15 m, 0.35 m, 0.6 m) from small soil profiles (ten within each zone) for lab analysis. Since unbiased estimates of the spatial means of FC and PWP were required, profile locations were selected within each zone randomly.

2.4 Evaluation of the water savings with site-specific and deficit irrigation

2.4.1 Irrigation strategies

IRRIGAMA steering was used to calculate irrigation water requirements both for field tests and a 12-year hypothetical crop rotation. Three possible approaches were tested for irrigation: (1) uniform irrigation (UI), which is oriented towards the average soil conditions of the field; (2) site-specific variable-rate irrigation (VRI) and (3) deficit irrigation (DEF). The strategies (1) and (2) received full irrigation, i.e., the optimum ET/PET ratio in IRRIGAMA steering is used to determine irrigation timing. For deficit irrigation we applied the minimum ratio function. All the strategies are summarized in Tab. 1.

Tab. 1 Tested irrigation strategies

Abbreviation	Description	Soil parameterization[a]	Steering function[b]
UI	Uniform irrigation, full water supply	Field	Optimum
VRI	Site-specific variable-rate irrigation, full water supply	Management zones	Optimum
DEF	Uniform deficit irrigation, limited water supply	Field	Minimum

Note. [a]Spatial scale for soil parameterization in IRRIGAMA steering, [b]Choice of steering function (see chaper 2.2 and Fig. 2); optimum relates to a targeted ET/PET ratio of maximum 80% ($[ET/PET]_{full}$) and minimum is a targeted ET/PET ratio of maximum 60-70% ($[ET/PET]_{deficit}$

2.4.2 Field tests of irrigation strategies

All three irrigation strategies were tested at the Dahlhausen site in the years 2018, 2019 and 2020, when the farmer cultivated silage maize, winter wheat and potato. The conventional state of the art management included field preparation with a cultivator, herbicide applications for weed control as well as mineral and organic fertilization (Tab. A.2). Site-specific management was restricted to site-specific irrigation within the ring-shaped VRI area (Fig. 3). Variable-rate irrigation with center pivots does not favor a fully independent irrigation of each management zone. This is because each irrigation cycle requires a certain period of time (days). A more practical approach to VRI is to start the machine if one zone requires irrigation and to apply either less or no water to the remaining zones. Hence, we started irrigation when IRRIGAMA steering recommended it for at least one of the four zones. Irrigation amounts differed between 0 and 100% among zones.

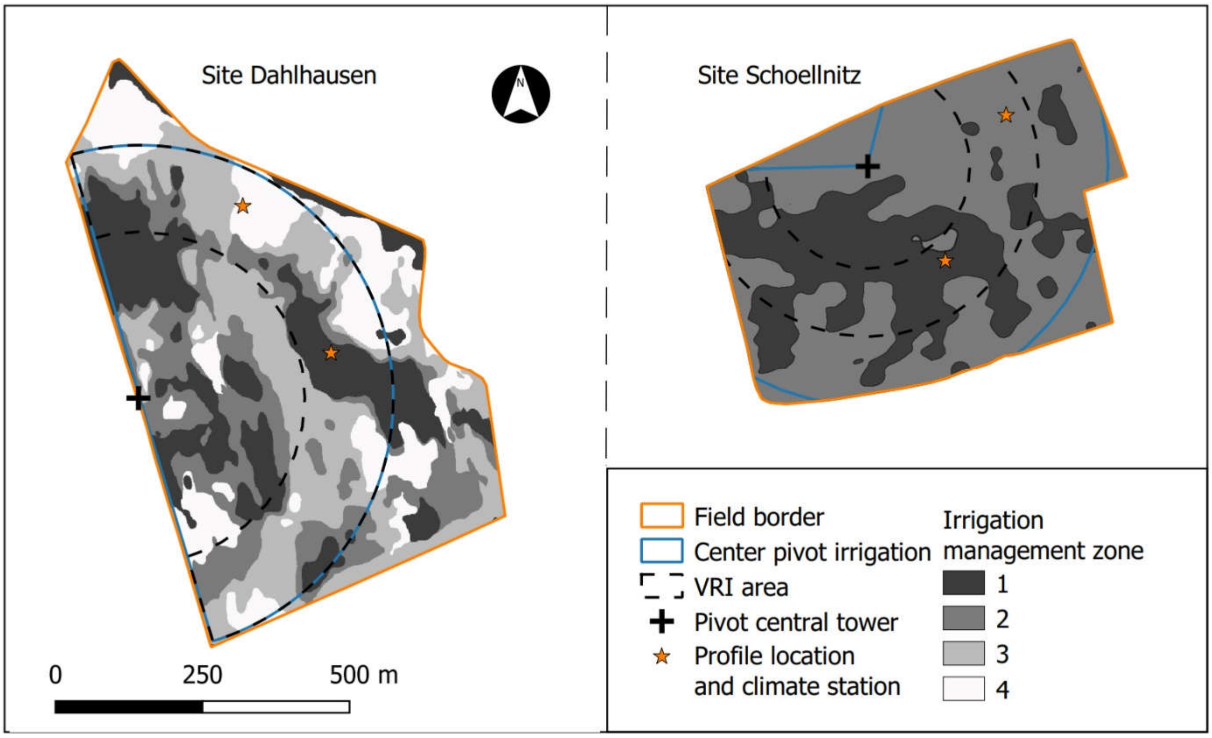

Fig. 3 Irrigation management zones at both test sites

2.4.3 Irrigation requirements for a hypothetical crop rotation

Because our field tests were restricted to three years and to the Dahlhausen site, respectively, we additionally simulated irrigation water requirements with IRRIGAMA steering for a twelve-year hypothetical crop rotation at both study sites. The years 2007 to 2018 were selected for the simulations. As for operational use of IRRIGAMA steering, the required daily data on rainfall and ET_o were taken from records of the German Meteorological Service. The hypothetical rotation consisted of forage peas (years 2007, 2011, 2015), potatoes of a medium early variety (years 2008, 2012, 2016), winter wheat (years 2009, 2013, 2017), and silage maize (years 2010, 2014, 2018). All four irrigation strategies were virtually applied in the same way as in the field tests (no independent irrigation of IMZ). For VRI we considered the entire irrigation area and not only to the area of two spans as in reality (Fig. 3).

Our simulations started on March 1st regardless of the crop because at the end of winter soil moisture can be assumed to be near or at field capacity; hence, it was set to 100% available water holding capacity (AWC). The virtually grown peas were sown on March 1st and winter wheat started tillering at this date. For potatoes and maize, the virtual cover was fallow before the hypothetical crop cultivation started later in spring. Peas have the shortest irrigation season of approximately two months, followed by potato and maize; in contrast, winter wheat may require irrigation from April until July (Fig. 2). The differences in ET/PET ratio between the optimum (full irrigation) and the minimum (deficit irrigation) steering curve are larger for peas and winter wheat than for maize and potato (Fig. 2). This is because the yield difference between full and deficit irrigation is smaller for winter wheat and forage peas than for green peas, maize, and potato (Fricke 2020, Roth et al. 2005). The maximum rooting depths within the growing season, which were adopted for our simulations, were the model defaults (Roth et al. 2005) of 0.7 m (pea and potato), 1 m (maize), and 1.2 m (winter wheat).

Since IRRIGAMA steering does not include a simulation tool, it could not be used for our simulations in a fully automated way. Moreover, it would have been too cumbersome to orient the irrigation amount toward the optimum ET/PET ratio (chapter 2.2.). For each simulated irrigation event, we therefore replenished the soil moisture in the effective root zone, i.e. the upper 0.6 m of our sandy soils, to 90% AWC for ease of calculation (less iterations necessary). In reality, replenishment would rather aim at 60 to 80% AWC in order to avoid over-irrigation. The effect of the AWC threshold on the simulation results can be considered negligible, as evidenced by a number of alternative simulation results with 80% AWC (not shown). The irrigation date was determined as in reality: irrigation is required if the forecasted ET/PET ratio falls below the target ratio. The start of an irrigation cycle was set to the day after that date as it reflects agricultural practice.

2.5 Estimation of irrigation effects on crop yield

2.5.1 Crop yields in field tests

At the Dahlhausen field site, 24 by 24 m plots were randomly located, which received the irrigation depending on the tested strategy (UI, VRI, DEF). The plots were relocated every year. In order to avoid boundary effects due to overlapping wetting radii, only the plots' centers were harvested at the time of harvest maturity immediately before the farmer's harvest. In order to minimize efforts and because IMZ 2, 3 and 4 are quite similar in terms of AWC (Tab. 2), IMZ 3 and 4 were considered as if they were the same (IMZ 3/4 hereafter). This was necessary also because IMZ 4 was too small to accommodate harvest plots for all irrigation strategies. The "poor" zone 1 had harvest plots for all tested strategies. IMZ 2 was not sampled for yield analysis.

In all years, non-irrigated references were established, which were as well randomly located within the VRI area. In 2018, the irrigation strategies UI and VRI were tested. In 2019, deficit irrigation was additionally applied. Due to the limited success of our VRI strategy, the field tests were restricted to UI and DEF in 2020.

In 2018, when the field was planted with silage maize, we harvested all plants within one row at a length of 3 m (n = 9 per strategy and IMZ). Winter wheat in 2019 was harvested within six 2 m² parcels per strategy and IMZ. Immediately after harvest, the fresh matter was determined. After shredding (maize) or threshing (wheat), a sample was analyzed for the water content in the lab. For winter wheat, grain was separated from straw before lab analysis (only grain yield is presented here).

Tab. 2 Soil water retention parameters at the field sites

Irrigation approach[e]	Site	IMZ[a]	FC (m³/m³)[b]			PWP (m³/m³)[b]			CV FC (%)[c]			CV PWP (%)[c]			Root-zone AWC (mm)[d]			
			0.1 m	0.35 m	0.6 m	0.1 m	0.35 m	0.6 m	0.1 m	0.35 m	0.6 m	0.1 m	0.35 m	0.6 m	*n*	Minimum	Median	Maximum
UI/DEF	Dahlhausen	–	20,2	17,9	17,6	8,0	6,8	5,5	15	18	34	20	30	57	60	43	70	108
VRI		1	17,2	15,7	13,4	6,4	5,2	3,3	7	16	20	13	18	34	15	43	59	77
VRI		2	19,7	18,1	16,2	7,6	6,3	4,6	4	8	6	5	5	17	13	55	72	86
VRI		3	21,4	18,5	17,9	8,7	7,2	5,0	6	8	5	5	5	15	21	50	77	108
VRI		4	21,8	19,3	18,4	8,9	7,4	6,7	7	6	5	9	8	10	11	62	75	84
UI/DEF	Schoellnitz	–	21,8	14,4	16,9	8,2	5,6	8,9	13	50	51	17	75	78	20	40	54	128
VRI		1	20,5	10,0	8,8	7,7	2,6	2,9	12	68	79	19	48	105	10	42	50	128
VRI		2	22,3	17,2	20,8	8,9	7,3	15,4	13	32	19	13	61	43	10	40	58	84

Note. [a]IMZ: irrigation management zone; [b]FC = field capacity; PWP: permanent wilting point; parameterization in IRRIGAMA steering for (1) UI: mean of the sample data and (2) VRI: mean of the interpolated data (Dahlhausen) and measured values (Schoellnitz) in each IMZ; [c] CV FC = coefficient of variation for the FC data in [b]; CV PWP = coefficient of variation for the PWP data in [b]; [d]plant available water holding capacity (AWC) based on the sample data; effective root zone = 0 to 0.6 m soil depth; the AWC is not an input for IRRIGAMA steering and only shown here for illustration; [e]UI: uniform full irrigation; VRI: variable-rate site-specific irrigation; DEF: uniform deficit irrigation

In 2020, the fresh matter of potato tubers was recorded within six parcels per strategy and zone at 3 m² each. For conversion into dry matter, the formula, which is implemented in the crop growth model HERMES (dry matter = 23% of fresh matter) was applied.

For statistical analysis, we first calculated the mean yield difference between UI and the other tested strategies including NON (no irrigation applied), separately for IMZ 1 and IMZ 3/4. Second the 95% confidence interval was computed for the difference between the means to draw conclusions about the yield effects as related to the irrigation strategies with uniform irrigation serving as reference:

$$(\bar{x}_1 - \bar{x}_2) \pm t_{n_1+n_2-2} \times \sqrt{\frac{(n_1-1)\times s_1^2+(n_2-1)\times s_2^2}{n_1+n_2-2}} \quad (1)$$

where $\bar{x}_1 - \bar{x}_2$ is the difference in sample means between treatment UI and the other treatments; *t* is the critical value from the *t*-distribution with $n_1 + n_2 - 2$ degrees of freedom; n_1 is the sample size for yield determination, treatment UI; n_2 is the sample size for yield determination, treatments NON/VRI/DEF and s_1 and s_2 are the corresponding standard deviations.

2.5.2 Modeling of crop yields for irrigation simulations

In order to derive crop-specific and site-specific effects of the tested irrigation strategies on yield for the 12 year hypothetical crop rotation (chapter 2.4.), the dynamic crop growth model HERMES (Kersebaum 1995, 2007) was applied. It simulated crop yield based on the fields' soil characteristics, nutrient supply and rain as well as irrigation water supply. HERMES was run with the soil data for the soil profiles (Tab. A.4) and the water retention parameters for the IMZ at the study sites. Each IMZ virtually received the irrigation amounts for the three tested strategies (Tab. 6) in addition to the natural rainfalls for each field and year, respectively. The input data for fertilization (composition, timing, etc.) were adapted to local farmers' practices (Tab. A.2).

The HERMES model has been tested at many locations of the world in comparison with large crop model ensembles (e.g. Asseng et al. 2013, Bassu et al. 2014, Falconnier et al. 2020). It operates at a daily time step and uses 0.1 m increments down to 2 m. It showed a good response to variable soil conditions in heterogeneous fields (Wallor et al. 2018) and has been applied to derive variable rate nitrogen fertilization for Precision Agriculture using spatial soil information (Kersebaum et al. 2005). It considers the most yield relevant soil processes, such as soil water dynamics using a tipping bucket approach, soil nitrogen dynamics (N mineralization, denitrification, N transport and leaching), and crop growth including phenological development. Different options for calculating daily grass reference evapotranspiration (ET_o) are integrated in the model, including FAO56 (Allen et al. 1998, Priestley & Taylor 1972), and Turc-Wendling (Wendling et al. 1991). Crop coefficients to estimate crop-specific reference evapotranspiration ET_c are linked to key development stages and are interpolated linearly based on the fulfillment of required degree days for each stage (Tab. A.3). The crop model simulates biomass production based on intercepted radiation and temperature using a gross photosynthesis minus respiration approach based on the SUCROS model (Keulen et al. 1982). Dry matter production is partitioned depending on crop development stage, which is calculated from a thermal sum or degree days (°C days), modified for each stage by day length and vernalization if applicable for a specific crop. Root dry matter is exponentially distributed over depth according to Page and Gerwitz (1974), with the rooting depth increasing with the abovementioned modified thermal sum until a crop-specific and soil-specific maximum is reached. Yield is estimated at harvest from the weight of the storage organ or the total above ground biomass for silage maize. The crop model follows a generic approach, which enables the simulation of various crops along crop rotations by using crop specific parameter sets.

For the purpose of this study, the HERMES model was calibrated based on the three-year field trial at the Dahlhausen site, which provided measured yields for the different treatment plots. For peas, default parameters were used which were applied successfully on other sites in Denmark and France (Kollas et al. 2015) and gave reasonable yields compared to statistical data of Brandenburg as well. The R^2 and mean absolute error (MAE) of simulated dry matter yields across all crops and treatments for Dahlhausen (Tab. 7) were 0.876 (slope 0.997, intercept 1.15 t ha^{-1}) and 1.69 t ha^{-1}, respectively.

2.6 Economic simulation

A simulation was conducted to calculate the profits of the irrigation strategies. The Irrigation profit is here defined as the additional net return from irrigation:

$$Irrigation\ profit = Nic - Nrc - Ci \tag{2}$$

were *Nic* is the net return of the irrigated crop, *Nrc* is net return of the rainfed reference and *Ci* are the costs of the irrigation. The net return is the sale revenue of a harvest, without considering any costs. A positive irrigation profit indicates the success of irrigation measures. All other costs for the crop management, like seedbed preparation, pest and weed control or harvesting are not considered in this approach.

The costs for irrigation can be subdivided into investment costs for the irrigation technology and variable costs, which emerge while running the irrigation. They depend on the quantity of the water applied. The overall costs are the sum of both:

$$Costs\ of\ Irrigation = Investment\ Costs + Variable\ Costs. \quad (3)$$

Two scenarios with different market prices have been considered in the simulation (Tab. 3). The objective of this static approach was, to calculate the economic effects of irrigation for two representative levels of market prices per crop (low and high). The price data are from Deutscher Landwirtschaftsverlag GmbH (2021) and Bundesanstalt für Agrarwirtschaft und Bergbauernfragen (2021). They generally represent the typical range within the present decade in Germany.

Tab. 3 Assumptions for the different assessment-scenarios

Scenario	Crop	Market price for FM (EUR Mg^{-1})
A	Forage pea	185
	Potato	70
	Silage maize	60
	Winter wheat	140
B	Forage pea	210
	Potato	100
	Silage maize	80
	Winter wheat	200

An irrigation system consists of several parts besides the center pivot itself in order to transport water to the place of distribution. In this study, some equipment parts were used for the irrigation of several fields in addition to our study site. Among them were the well, the water pump, the frequency controller for the pump, the diesel power generator and the electricity line. The evaluation of the cost share of the components, which are used for the irrigation at the study site and on adjacent fields, was conducted as follows:

$$Cost\ Share = \frac{\sum Cw, Cp, Cfc, Cdg}{total\ irrigated\ Area} \times irrigated\ area\ of\ the\ study\ site \quad (4)$$

where *Cw* are the acquisition costs for the well, *Cp* are the acquisition costs for the pump, *Cfc* are the acquisition costs for the frequency controller of the pump and *Cdg* describe the acquisition costs for the diesel generator. Consequently, the investment costs for the irrigation at the study sites were calculated by:

$$Investment\ Costs = CS + Ccs + Cvri \quad (5)$$

where *CS* is the cost share of components which are used for the irrigation at the study site and on adjacent fields (equation 6), *Ccs* are the costs for components which are exclusively used for the irrigation at the study site and *Cvri* are the costs for the variable-rate irrigation control equipment.

The periods of amortization of the investment of the several components vary in regard to the German expenses for amortization rates (Bundesministerium der Finanzen 1996, 2000). The rates of interest take into account the investment costs and the length of the period of amortization.

An investment funding of 20% was considered in all scenarios to calculate the fixed irrigation costs, as this funding rate is current practice for center pivot irrigation in the German federal state of Brandenburg (Ministerium für Ländliche Entwicklung, Umwelt und Landwirtschaft 2019).

The electricity for the operation of the center pivot in Dahlhausen is produced by a mobile diesel power generator, located nearby the central tower. The generator supplies the center pivot on the study site and another center pivot and temporarily up to three hose reel systems on adjacent fields with electric energy. The well is close to the central tower of the pivot at the study site. In total, about 60 ha are irrigated with different systems but receive water and electric energy from one supply point. The Tab. A.5 lists investment costs for components which are used for the irrigation at the study site and at adjacent fields.

The center pivot at the study site consists of seven spans and an overhang. In reality the outer two spans and the overhang were modified for testing purposes with magnetic valves at each sprinkler nozzle. In this economic assessment the costs for the VRI-equipment have been calculated for the modification of all spans on a new, conventional non-VRI pivot. Tab. A.6 and Tab. A.7 list the investment costs for this modified system. The water pipeline from the well to the pivot is used exclusively on the study site. The costs for the water pipeline are relatively low, because the pivot is located close to the well (approx. 50 m). The costs for the site mapping and determination of irrigation management zones have also been considered.

In total, the investment costs at the site Dahlhausen amount to 214.27 EUR ha^{-1} $Year^{-1}$. The center pivot in Schoellnitz is connected to the electric grid. It covers an irrigated area of approx. 26.7 ha on the test field. For the calculation of the fixed costs at this site, we considered that the well, the water pump, the frequency controller for the pump and the electric line from the grid connection point to the pump are also utilized for irrigation of an adjacent field with another center pivot system. All together about 62 ha have to be irrigated. Thus, only the share of the costs for the machine at the demonstration field was included to the assessment. Tab. A.8 lists the full investment costs for components, which are used for the irrigation at the study site Schoellnitz and at the adjacent field. Investment costs for additional components, which are used for the irrigation at the study site Schoellnitz exclusively, are shown in Tab. A.9.
The pivot contains of six spans and an overhang. Two spans (span 4 and 5) were modified to enable full VRI-control for testing purposes in reality. Same as in Dahlhausen, magnetic valves and a specified control unit were installed. However, the economic assessment was conducted for a modified new machine, which has full VRI-control at all spans (see costs in Tab. A.10). The investment costs in Schoellnitz add up to 239.84 EUR ha^{-1} $Year^{-1}$ in total.

In this study, a water price of 0.01 EUR/m³ was considered, based on the water act of the federal state of Brandenburg (§40, Brandenburgisches Wassergesetz). The costs for water extraction from groundwater amounts to 0.115 EUR/m³ in Brandenburg, but it is assumed that 93% of the irrigation water flows back to the groundwater (ibid.).

In addition to the pure costs for the water, several other parameters influence the economy of irrigation (see Tab. A.11). As to the first, they depend on the irrigation amount which is applied or the energy, which is consumed during irrigation events. The costs for diesel fuel and electricity used in the simulation comply with current values that farmers do have to pay under real conditions. Also maintenance and inspection costs as well as irrigation consultancy are assigned as variable costs in this case.

3. Results and Discussion

3.1 Characteristics of the irrigation management zones

At Dahlhausen, both FC and PWP exhibit most variability at 0.6 m soil depth (Tab. 2), which is likely a result of landscape history and recent land use. Besides the effect of topsoil levelling by secondary soil cover on the unevenly deposited parent material, freezing and thawing cycles caused mixing of adjacent substrates in upper soil layers. This topsoil homogenization still progresses as a consequence of farming activities such as ploughing and organic fertilization. A certain decoupling of topsoil and subsoil horizons is also reflected by rather moderate correlations of FC and PWP among the investigated soil depths (Tab. 4).

Tab. 4 Correlation matrix (Pearson correlation coefficient) for field capacity (FC), permanent wilting point (PWP) and apparent electrical resistivity (ER_a) 1 (0-0.25 m depth), ER_a 2 (0-0.5 m depth), and ER_a 3 (0-0.75 m depth) at site Dahlhausen. Numbers in bold highlight the relationships which are used in the external drift kriging. If necessary, soil data were transformed prior to the calculation of correlation coefficients between soil and geoelectrical data

	FC 10	FC 35	FC 60	PWP 10	PWP 35	PWP 60	ER_a 1	ER_a 2	ER_a 3
FC 10	1,00								
FC 35	0,49	1,00							
FC 60	0,53	0,60	1,00						
PWP 10	0,58	0,40	0,39	1,00					
PWP 35	0,50	0,72	0,51	0,64	1,00				
PWP 60	0,30	0,52	0,65	0,38	0,39	1,00			
ER_a 1	**-0,71**	-0,53	-0,42	**-0,76**	-0,54	-0,38	1,00		
ER_a 2	-0,70	**-0,55**	-0,46	-0,74	**-0,56**	-0,40	0,98	1,00	
ER_a 3	-0,69	-0,61	**-0,49**	-0,68	-0,56	**-0,50**	0,93	0,98	1,00

Correlations between the soil and the ancillary ER_a data are strongest in the topsoil (site Dahlhausen, Tab. 4), which is not surprising because the Geophilus resistivity sensor always captures the whole soil profile from the surface to the target depth. As a consequence, the explanatory power of the geo-electrical signal decreases towards subsoil horizons and the predictive uncertainty for FC and PWP at 0.6 m depth is the largest of all layers (Tab. 5). The accuracy of the employed variograms was satisfactory as indicated by the results of the cross validation (Tab. 5): the median and mean of θ, respectively, were close to their expected values of 0.45 and 1.0. The largest prediction error was found for FC at 0.6 m soil depth, which is due to the pure nugget variogram (Tab. 5) and the only moderate correlation between FC and ER_a (Tab. 4). Regarding PWP at this depth, the correlation to ER_a was again moderate, but the fitted spherical covariance function provided a better prediction performance (Tab. 5).

In order to build management zones from the three-dimensional FC and PWP classes, we overlaid them at the 0.1 and 0.6 m soil depth; the 35 cm depth was not included because the spatial pattern was comparable to the 0.1 m depth. After removing too small and fragmented classes (chapter 2.3.1.), eight compound classes remained. For each of them, the FC and PWP mean was calculated based on the interpolated data as input to IRRIGAMA steering. Finally, some preliminary simulations with IRRIGAMA steering revealed only marginal differences in irrigation requirements among some of the classes. Therefore, the number of compound classes was reduced further by reassigning grid cells to neighboring classes. This left four classes – the final IMZ – which are distributed irregularly, though of course similarly to ER_a (cf. Fig. 1 and Fig. 3). The average AWC in these four zones varies between 59 and 77 mm in the effective root zone (Tab. 2). The largest spread in water storage capacity for the sample data occurs in IMZ 3. All in all, the differences in water storage capacity of the IMZs 2, 3, and 4 are rather small. In contrast, IMZ 1 was characterized by a lower AWC (Tab. 2).

Tab. 5 Results of the geostatistical data analysis, site Dahlhausen

				Variogram parameters[a]				Cross-validation[b]		Prediction error[c]		
Variable[d]	Depth	Lambda[e]	nr.	Ratio	Model	Range	Effective	Med θ	Mean θ	Mean	Max	nr.
	(m)		out[f]	nug/sill		(m)	range (m)			w.ci_100 (%vol)	w.ci_100 (%vol)	classes[g]
FC	0,1	-0,7	–	0,00	sph	61,8	62	0,45	1,00	8,2	12,1	3
	0,35	1,8	–	0,00	sph	111,0	111	0,51	0,97	9,6	12,2	2
	0,6	1,2	3	1,00	nug	0,0	0	0,41	0,98	18,0	22,3	2
PWP	0,1	1	–	1,00	nug	0,0	0	0,41	0,98	4,2	4,4	3
	0,35	1	–	0,61	exp	3,1	9	0,35	1,00	6,6	7,1	2
	0,6	0,2	–	0,50	sph	130,7	131	0,40	0,99	10,2	14,3	2

Note. [a]Ratio nug/sill = nugget to sill ratio; Model: fitted variogram model (sph = spherical model, exp = exponential model, nug = pure nugget model); [b]Med θ: median of θ-statistic, Mean θ: mean of θ-statistic (Lark, 2000); [c]Mean w.ci_100, Max w.ci_100 = mean and maximum, respectively, of the confidence interval widths for the predictions; [d]FC: field capacity, PWP: permanent wilting point; [e]value of the Box-Cox exponent; [f]number of spatial outliers, identified with the standard error of cross-validation; [g]number of classes for management zone delineation, calculated with Eq. D.2

At Schoellnitz, we first interpolated the presence/absence of impeding layer occurrence by indicator kriging (chapter 2.3.2.). Among the tested variogram models, the spherical model provided the best fit with a nugget-to-sill ratio of 0.35 and a range of 16 m. It is likely that the main part of the nugget variance results from small-scale variation of impeding layer occurrence (cf. chapter 2.1.). For the subsequent cluster analysis, the number of clusters was constrained to two (chapter 2.3.2.). These clusters form the IMZ at the Schoellnitz site (Fig. 3). Although the occurrence of the dense layer markedly influenced plant growth at Schoellnitz (chapter 2.1), it has surprisingly little effect on AWC (Tab. 2). This is because the larger FC in the subsoil of IMZ 2 involves a larger PWP too. As a consequence, the difference in the median root zone AWC between the two IMZ at Schoellnitz is only 8 mm (Tab. 2).

Because we could not sample the soil below 0.6 m depth, we parameterized the 0.6 to 1.5 m soil layer in IRRIGAMA steering with the data from 0.6 m (Tab. 2). The resulting uncertainty is unknown; however, a limited influence on calculated water requirements is expected. This is because fine roots are concentrated in the upper half meter of our sandy soils (Tab. A.4). Because three soil layers were parameterized, our approach accounts for the depth gradient of soil variation (Haghverdi et al. 2015).

Most studies on site-specific irrigation have considered available water holding capacity as the most important soil parameter for irrigation management zone delineation (Evans and King 2012). Therefore, this approach was adopted as well in this study because it reflects the current state of technology in the few German irrigation farms that have already invested in VRI. Large AWC differences are likely to result in large benefits of soil-based VRI. In our case, the AWC differences among our management zones are limited to about 10 mm in the main root zone, which in sandy soils can be equated with the first 0.6 m of soil (Ad-hoc-Arbeitsgruppe Boden

2006). Although the data range was much larger than that (Tab. 2), the technically required minimum zone size implied that extreme data points were absorbed into an average.

Given the limited AWC differences among the IMZ, the question arises if plant growth at our test fields is at all heterogeneous at the management zone scale. We therefore considered a yield map of winter wheat, which was acquired from the harvester's yield monitor at the Dahlhausen field in the year before our study started (Fig. 4): The yield pattern obviously matches our management zones very well as in the low AWC zone 1, the smallest yield was consistently found (inlet of Fig. 4). The coefficient of variation (CV) for yield was 25% in the irrigated area, a figure which is comparable with the range of published CVs for winter wheat yield for the whole of eastern Germany (Karpinski et al. 2015, Karpinski 2014). Areas with a CV > 16% are considered highly heterogeneous (Karpinski 2014). At our Schoellnitz test field, a CV of 27% for silage maize yield in the year 2017 also indicates heterogeneous conditions for plant growth.

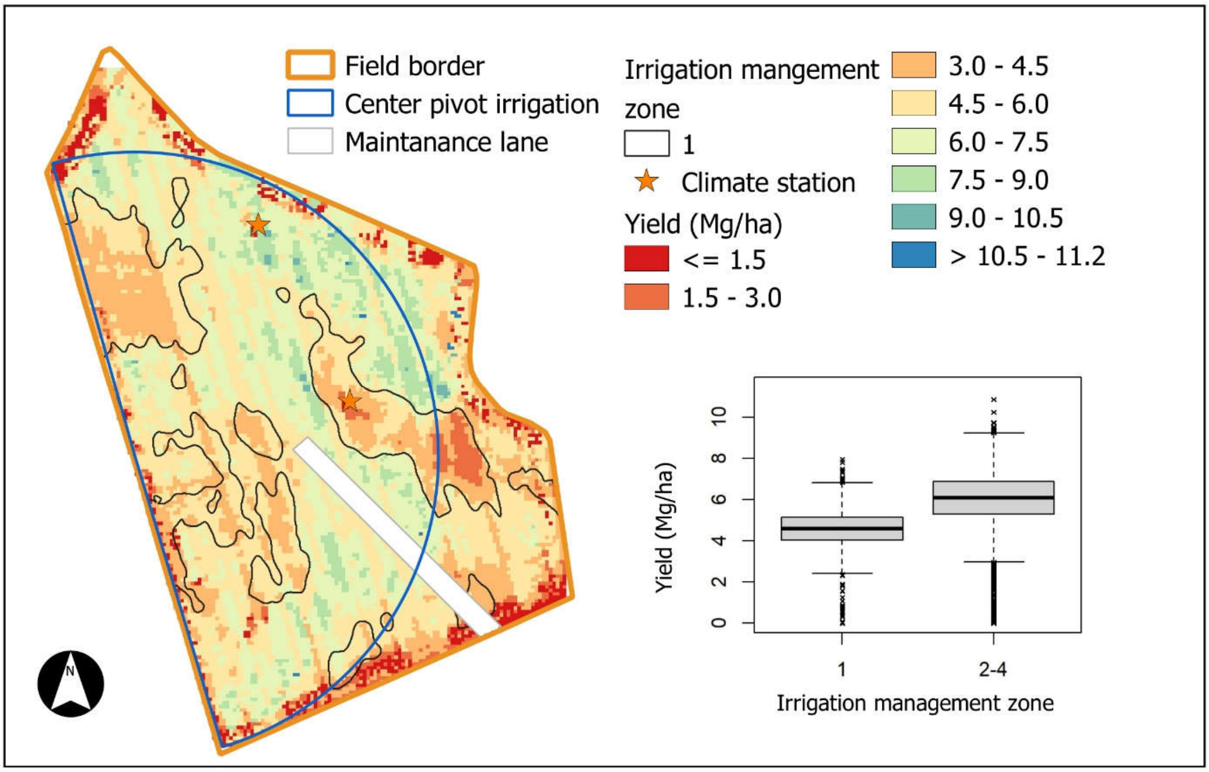

Fig. 4 Winter wheat yield at field Dahlhausen, recorded with a combine harvester, year 2017. Please note that irrigation treatments started in 2018 whereas in 2017, uniform full irrigation was provided. The inlet compares the yield data in irrigation management zone 1 compared to the pooled yield data in the remaining zones

3.2 Water savings and yield effects of the investigated irrigation strategies

3.2.1 Overall conditions during the investigation period

In the year 2018, the federal state of Brandenburg as well as large parts of Germany and Europe suffered from a severe agricultural drought. It was also the simulation year with the smallest ET/PET ratio during the maize irrigation season (Tab. 6). At the Schoellnitz site, the situation was even more unfavorable than at Dahlhausen with 364 versus 278 mm of required seasonal irrigation. As a consequence, the irrigation requirement of 364 mm was the largest of all years and crops, respectively (Tab. 6). The differences in seasonal irrigation amounts between the two sites are due to the soil and meteorological differences (Tab. 6). However, the differences in irrigation requirements between years (crop and site fixed) are larger than the differences between the sites (crop and year fixed). That is to say, the weather conditions in the irrigation season exert a stronger influence on plant water supply than the soil differences between the two investigated fields.

Tab. 6 Meteorological conditions and irrigation requirements for the years of the field tests (site Dahlhausen only, years 2018-2020) and the simulations (both sites, years 2007-2018)

Year	Crop	ET/PET ratio[a]		Irrigation requirements (mm)[b]	
		Dahlhausen	Schoellnitz	Dahlhausen	Schoellnitz
2007	Forage pea	73	65	82	69
2008	Potato	42	50	254	222
2009	Winter wheat	68	71	170	187
2010	Silage maize	68	76	188	143
2011	Forage pea	50	46	136	175
2012	Potato	66	72	129	109
2013	Winter wheat	69	77	188	171
2014	Silage maize	71	64	131	170
2015	Forage pea	49	46	124	139
2016	Potato	61	63	183	184
2017	Winter wheat	82	70	172	280
2018	Silage maize	46	35	278	364
2019	Winter wheat	50	–	151	–
2020	Potato	34	–	145	–

Note. [a]average ET/PET ratio during the irrigation season, calculated with IRRIGAMA steering (soil parameters: field average; irrigation strategy: NON (no irrigation)); length of the irrigation season is crop-specific (cf. Fig. 3); [b]simulated irrigation requirements for strategy UI (uniform full irrigation)

3.2.2 Effect of uniform irrigation on crop yield

Due to the considerable need for irrigation in our study area, the rainfed treatments at our test field showed considerably lower yield compared to reference strategy UI (Fig. 5). This was particularly true for IMZ 1 for silage maize and winter wheat (Fig. 5). Consider for instance silage maize in 2018, where rainfed parcels produced only 44% of yield compared to fully irrigated parcels in IMZ 1, but still nearly 80% for IMZ 3 and 4 in spite of extreme water stress conditions in this season (Fig. 5). Our data do not enable us to explain this result; among possible hypotheses are site-specific differences in root systems or interactions between water and nutrient supply. In any case, it appears that soil conditions and irrigation performance are not independent of each other, as irrigation on soils with low AWC increases yield more than irrigation on soils with better water storage. This assumption is supported by Haghverdi et al. (2019) who also found that – in their case – cotton lint responded differently to supplemental irrigation depending on the soil type. As in our study, the yield increase due to irrigation was more pronounced for coarse-textured than for fine-textured soils.

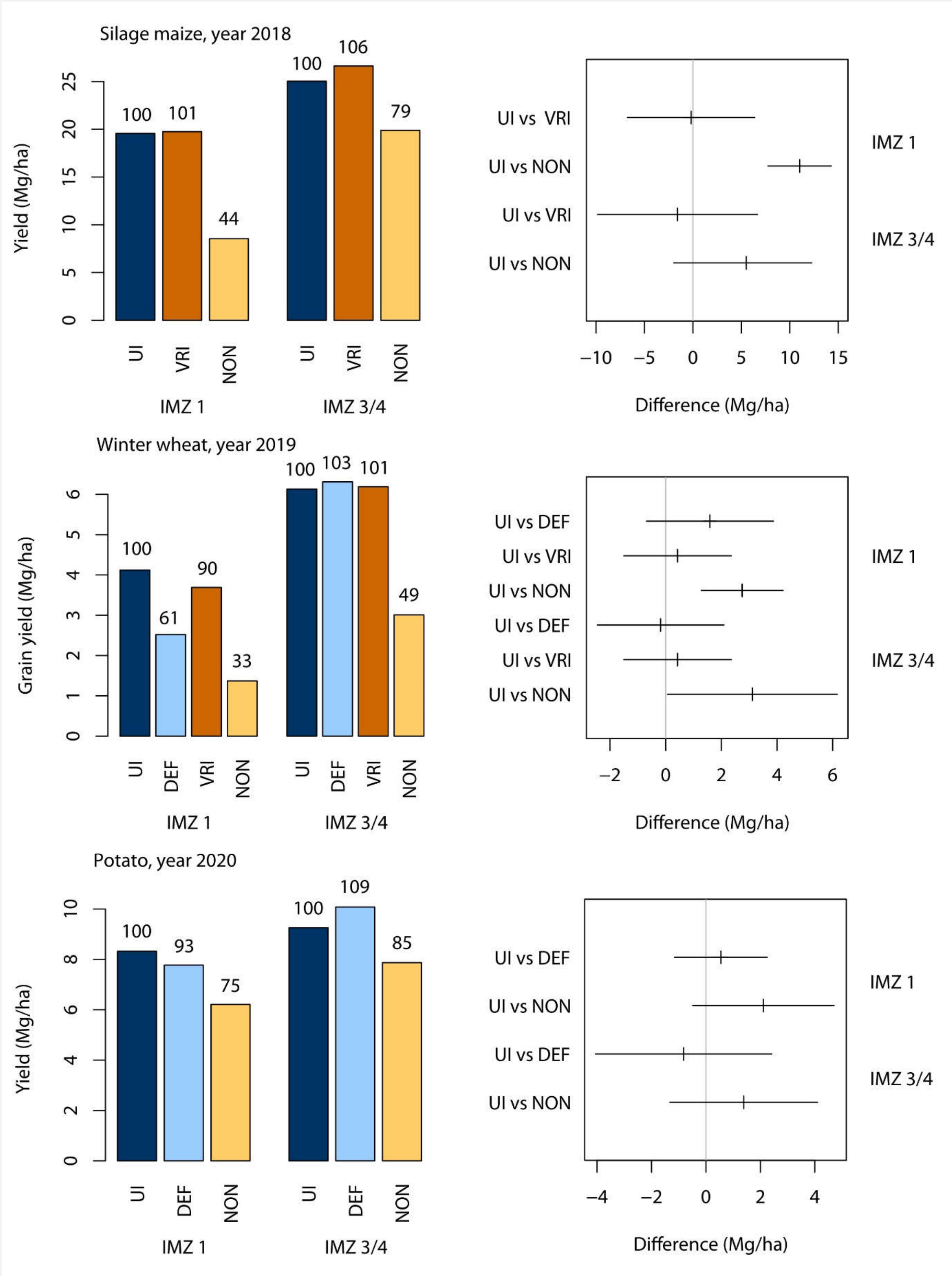

Fig. 5 Mean yield or mean grain yield in the irrigation management zones (IMZ), respectively, for the field tests, field Dahlhausen (left charts). The numbers above the bars indicate the relative yield with strategy UI (uniform full irrigation) serving as reference for the strategies VRI (variable-rate site specific irrigation), DEF (deficit irrigation) and NON (no irrigation). The mean difference between irrigation strategies (right charts, vertical lines) is plotted together with its 95 % confidence interval (horizontal lines). Samples sizes for each strategy are

9 (silage maize, year 2018) and 6 (other crops and years); for potato, year 2020, IMZ 1, strategy NON, sample size is only 3. If the confidence intervals include 0, the difference between the two strategies under comparison is considered non-significant

The simulated yields (HERMES model) for each of the four crops in the hypothetical crop rotation differed only marginally between the two fields (Tab. 7). In contrast, mean yields differed by 0.1 Mg ha^{-1} (winter wheat) up to 2.5 Mg ha^{-1} (potato) between IMZ 1 and IMZ 2 (Schöllnitz) and IMZ 4 (Dahlhausen), respectively, under uniform full irrigation. Likewise, the yield effect of irrigated (strategy UI) compared to rainfed (strategy NON) agriculture was again larger for IMZ 1, particularly for potato and winter wheat. Considering the mean yield effects for our four crops, peas benefited most from irrigation as indicated by only 20 to 30% of yield under NON compared to UI treatment (Tab. 7). The lowest irrigation influence on yield was simulated for silage maize.

Tab. 7 Simulated grain (winter wheat) and dry-matter (all other crops) yields

Site	Crop	Mean yield (Mg ha^{-1})[a]			Relative yield (%)[b]										
		UI[c]			NON[d]			DEF[e]			VRI[f]			VRI_DEF[g]	
		IMZ[h] 1	IMZ 2/4[i]	Mean[k]	IMZ 1	IMZ 2/4[i]	Mean[k]	IMZ 1	IMZ 2/4[i]	Mean[k]	IMZ 1	IMZ 2/4[i]	mean[k]	IMZ 2/4[i]	Mean[k]
Dahlhausen	Forage pea	2,1	2,5	2,3	26	26	27	71	75	71	108	100	103	84	100
Dahlhausen	Potato	10,7	13,1	11,4	39	47	41	91	93	91	100	101	101	92	99
Dahlhausen	Silage maize	22,3	23,5	22,7	65	66	65	96	96	96	101	100	100	98	100
Dahlhausen	Winter wheat	6,3	6,4	6,3	52	64	55	99	100	100	100	100	100	100	100
Schoellnitz	Forage pea	2,3	2,6	2,4	19	20	22	71	73	72	99	99	99	93	96
Schoellnitz	Potato	10,7	13,1	11,6	50	56	53	98	96	97	99	100	100	99	99
Schoellnitz	Silage maize	21,9	22,8	22,2	66	67	67	98	98	98	100	99	100	98	99
Schoellnitz	Winter wheat	6,9	7,0	6,9	49	60	56	98	100	99	100	100	100	100	100

Note. [a]Mean yield of the three simulation years per crop and field, respectively; [b]Difference of an irrigation strategy to strategy UI; [c]UI = uniform full irrigation; [d]NON = no irrigation; [e]DEF = uniform deficit irrigation; [f]VRI = variable-rate site-specific irrigation; [g]VRI_DEF = site-specific deficit irrigation; [h]IMZ: irrigation management zone; [i]IMZ 2 at field Schoellnitz and IMZ 4 at field Dahlhausen, resp.; results for IMZ 2 and 3 at Dahlhausen are not shown; [k]Area-weighted mean for the irrigated part of the field; weights are given by the relative IMZ areas

3.2.3 Water savings and yield effects of site-specific irrigation

At our test field Dahlhausen, site-specific irrigation was applied to silage maize in 2018, winter wheat in 2019, and potato in 2020. Water use of VRI was nearly identical to that of uniform irrigation (Tab. 8). Only in 2018, VRI required 7 mm less water than UI. Given the high seasonal irrigation water requirement of 287 mm (UI) in this year, this saving is irrelevant. Considering the 12-year hypothetical crop rotation, the calculated irrigation amounts for UI and VRI were very similar (Tab. 8).

This seemingly contradictory result was due to more irrigation events, larger irrigation amounts in better AWC zones, or both. Because UI was often required a bit later than VRI of IMZ 1 (which normally resulted in irrigation of the other zones too), it happened that UI did not require the last irrigation cycle. The replenishment to 90% AWC was the reason that IMZ with larger AWC received more irrigation water per cycle, which could also result in higher seasonal water use if the number of irrigation events was the same or larger for VRI than for UI. Overall, the differences between UI and VRI are due to calculation artifacts rather than actual differences in water demand between these two strategies. Even if an independent irrigation of the zones was affordable, there would be little change in this result: At Dahlhausen, independent VRI simulations again revealed no savings compared to UI and at Schoellnitz, the average savings increased slightly to 6 mm (results not shown).

Tab. 8 Applied irrigations in field tests

Year	Crop	Seasonal irrigation amount (mm)								
		Ui[a]	VRI[b]					DEF with VRI[c]		VRI_DEF[d]
			mean[e]	IMZ 1	IMZ 2	IMZ 3	IMZ 4	IMZ 1	IMZ 3/4	mean
2018	Silage maize	287	280	285	279	279	277	–	–	–
2019	Winter wheat	151	151	151	151	150	151	121	125	132
2020	Potato	145	145	145	145	145	145	130	135	138

Note. [a]UI: *uniform* full irrigation; [b]VRI: variable-rate site-specific irrigation; [c]deficit irrigation (DEF) was applied to IMZ 1 and IMZ 3 and 4 using the site-specific soil information; [d]weighted mean (see [e]) for irrigation amount of UI for IMZ 1 and of DEF for IMZ 2 to 4, respectively; [e]area-weighted mean; weights correspond to the areas of the management zones

Uniform and site-specific irrigation produced similar and not significantly different yields of silage corn and winter wheat in our test field (Fig. 5). The simulated yield differences of VRI relative to the reference strategy UI were marginal too; in many cases, yields under VRI were exactly the same as under UI (Tab. 7). These findings are not surprising given that the seasonal irrigation amounts hardly differed between uniform and site-specific irrigation.

Other studies also found small to negligible benefits of VRI (e.g. Bhatti et al. 2020, Sharma and Irmak 2020, Stone et al. 2019, Thorp 2019), which were e.g. attributed to comparatively small AWC differences among zones (Daccache et al. 2015). In contrast, VRI saved between 9 and 19% of water compared to UI for some investigated fields in New Zealand, which showed a more than two-fold difference in AWC between zones, with additional heterogeneity in stone content or groundwater influence (Hedley et al. 2009).

Tab. 9 Calculated irrigation requirements for the hypothetical crop rotation for uniform full (UI), uniform deficit (DEF) and variable-rate site-specific irrigation (VRI)

Site	Crop	Seasonal irrigation amount (mm)[a]							Number of irrigation events[a]					
		UI	DEF	VRI					UI	DEF	VRI			
				mean[b]	IMZ[c] 1	IMZ 2	IMZ 3	IMZ 4			IMZ 1	IMZ 2	IMZ 3	IMZ 4
Dahlhausen	Forage pea	114	81	110	112	108	110	111	4	2	5	4	4	4
	Potato	189	169	195	187	195	199	200	7	5	8	8	8	7
	Silage maize	199	166	199	207	193	197	200	6	4	7	6	6	6
	Winter wheat	177	133	199	209	197	195	196	6	3	8	7	7	7
Schoellnitz	Forage pea	128	104	134	139	131	–	–	4	3	5	5	–	–
	Potato	172	142	172	176	170	–	–	7	5	7	7	–	–
	Silage maize	226	188	228	228	228	–	–	7	5	8	7	–	–
	Winter wheat	213	160	212	214	211	–	–	7	4	8	7	–	–
Both sites	All crops	177	143	181	184	179	175	177	6	4	7	6	6	6

Note. [a]Mean for the three simulation years per crop; [b]Area-weighted mean; weights correspond to the areas of the management zones; [c]IMZ: irrigation management zone

In addition to the limited AWC differences among zones, the inefficiency of VRI in terms of irrigation water savings can also be attributed to low in-season precipitation and large potential evapotranspiration. Although located in the humid climate zone, our study area often faces such dry conditions in spring and summer, which is reflected in the strongly negative climatic water balance during this time of the year (less than -150 mm for the months April to September, years 1981 to 2010; data freely available from the German Meteorological Service, https://cdc.dwd.de/portal/). As a consequence, soil moisture hardly approaches field capacity within the growing season (this is in line with the soil moisture data at our field sites) and AWC differences become meaningless for irrigation water needs. This observation of the limited influence of soil water holding capacity on site-specific irrigation requirements is in line with Evans and King (2012), who reported that VRI is most effective in humid climates with repeated in-season precipitation, whereas its benefits are generally limited in arid and semi-arid locations.

In general, site-specific plant water requirements do not only depend on soil moisture status (Adeyemi et al. 2017). In the AWC-based approach, however, variables other than soil moisture are generally considered constant throughout the field, which is a clear limitation (Evans et al. 2013). Instead of the exclusive consideration of soil variability, Adeyemi et al. (2017) suggested to consider the plant itself as an indicator of water availability. Evans et al. (2013) and Fontanet et al. (2020) follow in the same direction, calling for dynamic management zones which are defined by sensing variability within a field in real time. One option for this approach is to consider site-specific variation of transpiration in addition to soil water storage and availability. This is possible, for instance, by using crop (kc) coefficients.

Real-world solutions to map the space-time variability of crop coefficients or, more generally, plant development and transpiration, using unmanned aerial systems or satellite date have already been developed (e.g. (Barker et al. 2018, Bhatti et al. 2020, Fontanet et al. 2020, O'Shaughnessy et al. 2020, Pereira et al. 2020). Future work will show if this approach to site-specific irrigation is a worthwhile option in our study region.

3.2.4 Water savings and yield effects of deficit irrigation

Deficit irrigation was applied at the Dahlhausen field site in the years 2019 (winter wheat) and 2020 (potato). Compared to uniform irrigation, it required 30 mm and 15 mm less water, respectively. The larger saving for winter wheat is due to the larger difference between the optimum and minimum steering curve for this crop (Fig. 2). For both winter wheat and potatoes, yield under deficit irrigation was statistically undistinguishable from yield under uniform irrigation (Fig. 5).

In the hypothetical crop rotation, deficit irrigation also required less water than uniform irrigation for all simulated crops at both sites (Tab. 9). Average savings per crop are in the range of 20 mm to more than 50 mm or between 9 and 32% (20% on average) compared to UI. At both sites, percentage savings were largest for peas and winter wheat (peas: 32% at Dahlhausen / 22% at Schoellnitz; winter wheat: 25% at Dahlhausen / 27% at Schoellnitz; potatoes: 9% at Dahlhausen / 19% at Schoellnitz; maize: 16% at Dahlhausen / 17% at Schoellnitz). This is due to the somewhat larger difference between the optimum and minimum steering curve for these crops (Fig. 2).

The yield simulation revealed that deficit irrigation produced 90 or more percent relative yield compared to uniform irrigation in all but one case: Peas (virtually) suffered from an about 30% yield decrease (Tab. 7). The latter fits into the picture that this crop seems to thank irrigation most. It is important to note, however, that the HERMES model could not be calibrated with real yield data for forage peas (chapter 2.5.). Hence, the simulated yield difference between UI and DEF should be interpreted with caution.

For winter wheat, the difference in mean yield between strategies DEF and UI was only 1% (Schoellnitz) and even non existing (Dahlhausen). This is somewhat surprising as water savings with deficit irrigation were considerable for this crop (Tab. 9). Because no significant yield difference was observed for winter wheat between the strategies UI and DEF in our field trials too, HERMES model uncertainty is unlikely to be the only reason for this observation. A possible explanation is that wheat has already established its full root system and passed the main growing season when water scarcity usually becomes evident. Therefore, wheat can better buffer dry periods. Since wheat has its most sensitive phase around flowering and early grain filling, deficit irrigation has less effect during the rest of the growing season. Therefore, a targeted water application during this sensitive phase has the highest effect on crop yield (Ruiz-Ramos et al. 2018).

Deficit irrigation comes at a cost, however, because yield increase is positively related to the amount of irrigation water applied until a certain threshold is reached (Fereres and Soriano 2007, Roth and Kachel 1989). Many studies report an increase in water productivity under (moderate) deficit compared to full irrigation (e.g. Alghory and Yazar 2018, Eissa et al. 2018, Karasu et al. 2015, Martínez-Romero et al. 2019), which was also evident in our simulation results for winter wheat and silage maize: strategy DEF increased the water productivity by 2 to 5 kg mm^{-1}. For potato and pea, the effect was less pronounced or even inverse. This may infer that our deficit irrigation strategy might be less successful for these crops. Possible reasons are the smaller rooting depths and the shorter cultivation periods of these crops compared to winter wheat and silage maize.

3.3 Comparison of the economic efficiency of the different strategies

The net returns of the rainfed reference are displayed in Tab. 10. All values are based on the area-weighted mean of the yield of the rainfed crop in the different IMZ. The calculation considers both levels of the product price (scenario A and B). The values range from 59 EUR ha^{-1} (Schoellnitz, forage pea, 2011, scenario A) to 4,261 EUR ha^{-1} (Dahlhausen, silage maize, 2014, scenario B). The average annual net returns of the whole 12 years-rotation are 1,177 EUR ha^{-1} a^{-1} (Dahlhausen) and 1,301 EUR ha^{-1} a^{-1} (Schoellnitz) in scenario A respectively 1,609 EUR ha^{-1} a^{-1} (Dahlhausen) and 1,788 EUR ha^{-1} a^{-1} (Schoellnitz) in scenario B. Silage maize shows in every year at both sites the highest net return of all crops, followed by potato. The smallest values can be observed for pea, in every year and at both sites. Differences are also noticeable between the profits of each cultivation site of a specific crop. For instance, the net returns of pea, winter wheat and silage maize in Schoellnitz exceed the values in Dahlhausen, in two years, while of potato they are higher in all three years.

The overall average irrigation profits for both sites (Fig. 6) range from -221 EUR ha^{-1} (winter wheat, VRI, scenario A) to 2,178 EUR ha^{-1} (potato, UI, scenario B). No significant differences between the different strategies in each scenario of each crop were detected by the t-test due to the low number of cases (N = 6) and the high standard deviation of the data (see Tab. 11). The profits of the variable-rate irrigation strategy (VRI) for each crop and scenario are generally smaller than for UI and def. The profits for potato are always positive, whereas for pea they are negative in most cases, except for UI at a high price level (scenario B). Winter wheat only shows positive profits with UI and DEF at a high market price (scenario B) and also with DEF at a low market price (scenario A). The profits of silage maize are positive for all irrigation strategies in scenario B and also for UI and DEF in scenario A, where the result for VRI is around zero. The difference between UI and DEF is small. For silage maize and potato the uniform irrigation with optimal water amount is the most effective strategy.

Tab. 10 Net returns (EUR ha^{-1}) of the rainfed reference at both simulation sites

Crop	Year	Scenario A (low prices)		Scenario B (high prices)	
		Dahlhausen	Schoellnitz	Dahlhausen	Schoellnitz
Forage pea	2007	126	141	143	160
	2011	149	59	169	66
	2015	90	98	102	112
Potato	2008	685	1,307	978	1,868
	2012	1,755	2,265	2,507	3,236
	2016	1,670	1,973	2,386	2,818
Silage maize	2010	2,660	3,022	3,546	4,029
	2014	3,196	2,862	4,261	3,816
	2018	2,118	2,136	2,824	2,848
Winter wheat	2009	569	622	812	888
	2013	480	777	685	1,110
	2017	630	354	900	505

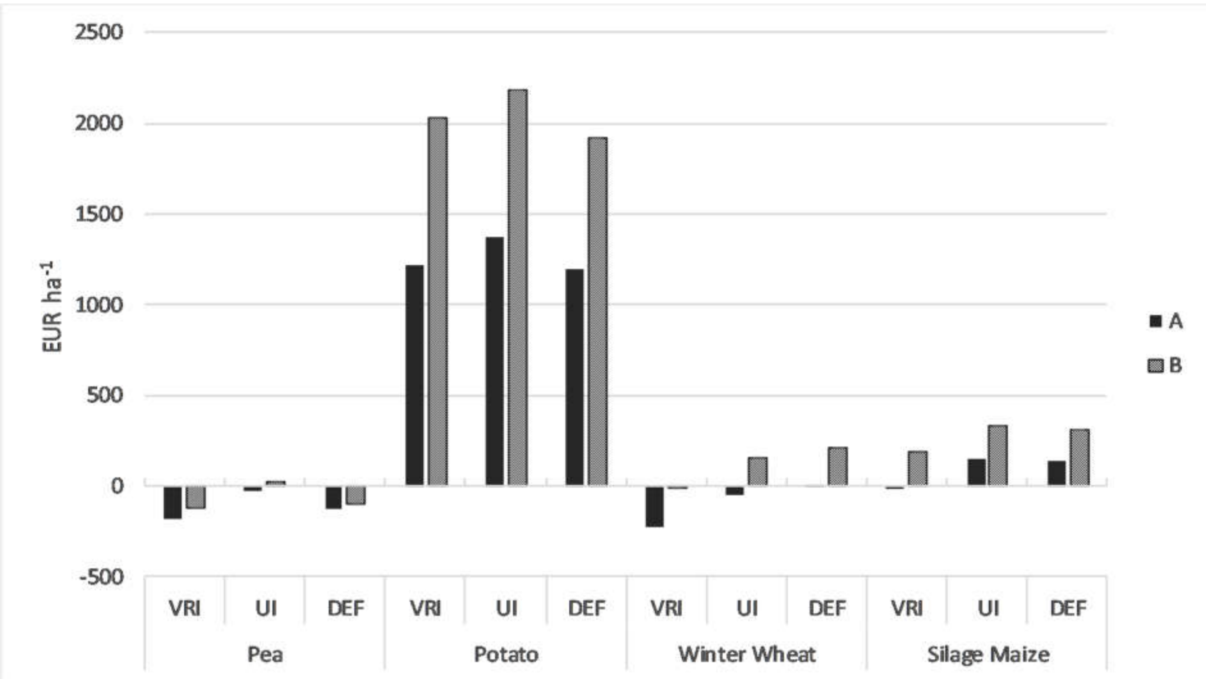

Fig. 6 Overall average irrigation profits for the different irrigation management strategies and scenarios at both sites (A = Scenario A, B = Scenario B)

Tab. 11 Standard deviations of the irrigation profits (EUR ha^{-1}) from the different crops, scenarios and irrigation control strategies

Scenario	A			B		
Strategy	VRI	UI	DEF	VRI	UI	DEF
Forage pea	102.07	130.68	76.37	121.89	154.72	94.71
Potato	672.78	666.43	596.79	997.85	984.01	881.93
Silage maize	179.52	206.37	208.39	261.27	292.15	290.57
Winter wheat	217.75	209.32	209.09	327.72	319.03	318.49

Tab. 12 presents in detail the mean irrigation profits for the different economic simulation scenarios for each site. The crop-specific values represent the average of three cultivation years. The overall average is from the whole 12-years rotation at each site.

The overall profits in Dahlhausen range from 261 EUR ha^{-1} (scenario A, VRI) to 747 EUR ha^{-1} per season (scenario B, UI). The uniform irrigation with optimal water supply (UI) has the highest profit of all irrigation strategies in both scenarios, whereas VRI leads to the lowest overall profits in case of pea, winter wheat and silage maize. Potato shows the lowest values after deficit irrigation (DEF). Taking a closer look at the profits of different crops in the rotation, the average values range from -171 EUR ha^{-1} (pea, scenario: A, VRI) to 2,466 EUR ha^{-1} (potato, scenario B, UI).

Tab 12. Average irrigation profits (EUR ha^{-1}) of the considered crop rotation in Dahlhausen and Schoellnitz (Senario A= low price), Scenario B = high price)

Site	Crop	Scenario	Irrigation profits (EUR ha^{-1})		
			VRI	UI	DEF
Dahlhausen	Forage pea	A	-171	-39	-127
		B	-119	11	-95
	Potato	A	1,423	1,568	1,276
		B	2,329	2,466	2,037
	Silage maize	A	40	184	154
		B	237	380	327
	Winter wheat	A	-248	-63	1
		B	-56	130	192
	Overall	A	261	413	326
		B	598	747	615
Schoellnitz	Forage pea	A	-180	-20	-133
		B	-124	36	-96
	Potato	A	1,008	1,173	1,123
		B	1,721	1,891	1,800
	Silage maize	A	-49	106	126
		B	133	289	299
	Winter wheat	A	-194	-44	20
		B	27	176	235
	Overall	A	146	304	284
		B	439	598	560

The overall average irrigation profits in Schoellnitz range from 146 EUR ha^{-1} (scenario A, VRI) to 598 EUR ha^{-1} (scenario B, UI). As in Dahlhausen, uniform irrigation with optimal water supply (UI) has the highest profits of all irrigation strategies in both scenarios The lowest overall irrigation profits appear in the VRI irrigation management in both scenarios. Potato in scenario B with uniform irrigation strategy (UI) with 1.891 (EUR ha^{-1}) has the highest profit of all crops, scenarios and irrigation management options, whereas -194 EUR ha^{-1} is the lowest average profit or rather highest loss for winter wheat in scenario A with variable-rate irrigation (VRI). The uniform deficit irrigation (DEF) is the most profitable irrigation strategy for silage maize. For potato, strategy UI offers the highest profits in Schoellnitz. The average profits of peas are mostly negative, regardless of the irrigation management and product price, except for scenario B, irrigation management UI.

Fig. 7 shows the irrigation profits of potato, silage maize and winter wheat in Dahlhausen depending on the irrigation strategy and site quality. The values are an average of both price scenarios. The aim is to derive the optimal irrigation strategies taking into account the site quality. VRI was not considered, because of its general economic failure. For the same reason, pea was also not considered. The site quality is expressed by the available soil water capacity (AWC), which increases from IMZ1 to IMZ4 (Tab. A.4). For potato, the site effect does not have an influence on the choice of the irrigation management option. In each irrigation management zone, UI has the highest profit. In principle, this also applies to silage maize. In Dahlhausen, UI was in any case more economic than DEF. In contrast, strategy DEF is superior to UI for winter wheat. Interestingly, the profit decreases with increasing site quality regardless of the irrigation strategy. In IMZ4, this leads to a loss for UI.

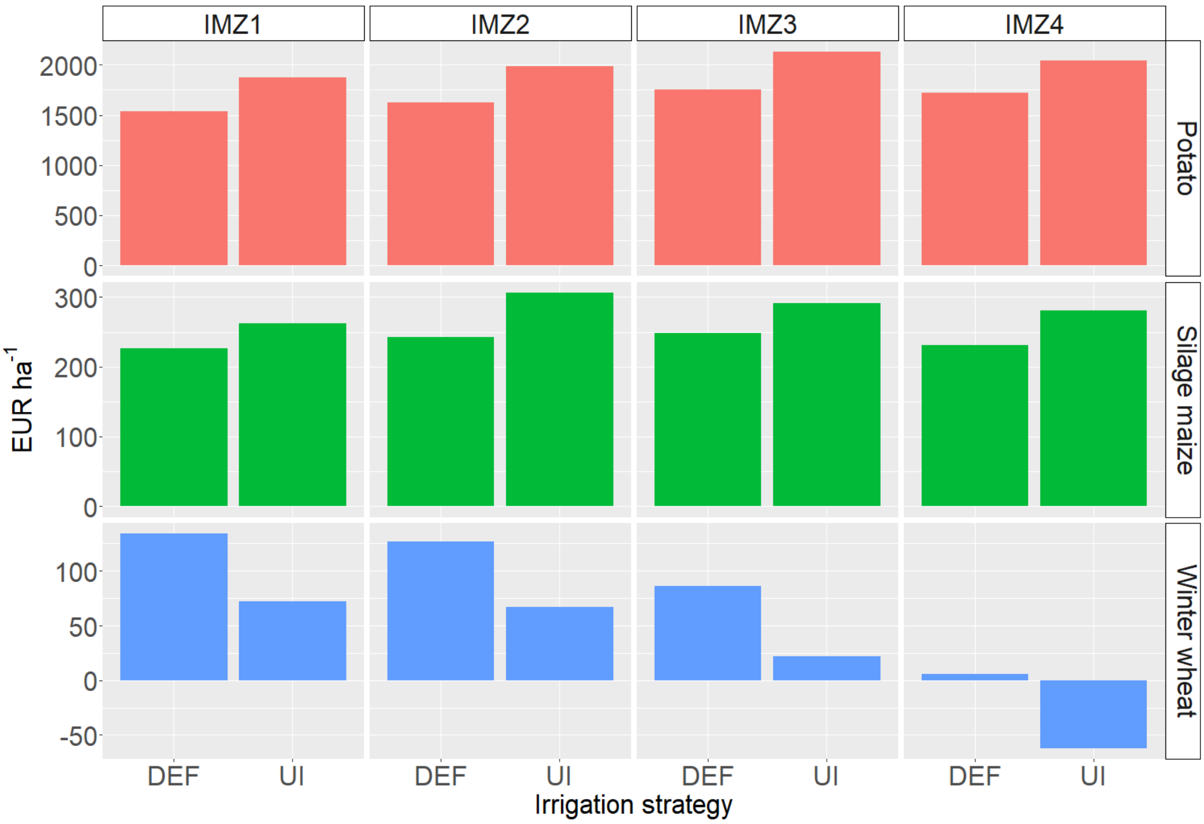

Fig. 7 Irrigation profits of three crops at different IMZ at the site Dahlhausen, comparison of DEF and UI

The results are suitable to highlight the differences in yield and economic performance of the investigated crop types with specific irrigation management strategies. Based on data from the yield modelling with HERMES, it seems not worthwhile to irrigate peas at the investigated sites. Only in 2011 a positive irrigation profit at both locations could be achieved with uniform optimal irrigation (UI, not shown). The yield was increased almost fivefold (Dahlhausen) or twelvefold (Schoellnitz) by irrigation in that year. This was not the case in the other two simulated years. This enormous increase led to the positive result, especially in Schoellnitz. In comparison with the literature, however, the model yields of pea appear relatively low, especially for the non-irrigated reference. In the state variety trials of Landesamt für Ländliche Entwicklung, Landwirtschaft und Flurneuordnung (2019), field peas were able to achieve a mean grain yield of 1.94 Mg ha^{-1} at a location in Brandenburg in 2018. Landwirtschaftskammer Niedersachsen (2019) found mean grain yields of 3.6 to 6.1 Mg ha^{-1} on sand and clay sites, years 2015 to 2019. Butz (2018) reported a yield of 3.26 Mg ha^{-1} for forage peas without irrigation in a cultivation trial in Baden-Württemberg. Irrigation has resulted in a yield increase of about 1.5 times. The irrigation rates were similar to those in our simulation, but the yield increase due to irrigation was significantly lower. However, the site characteristics of the examples listed are certainly only partially comparable to Dahlhausen and Schoellnitz. One reason for the comparatively low simulated pea yields at both trial sites could be the lack of calibration of the HERMES model with real yield data from Dahlhausen and Schoellnitz.

Irrigation led to a clear increase in yield of winter wheat in every case, on average by 83 % compared to the rainfed reference. Nevertheless, site-specific irrigation of the crop is not worthwhile. The retrofitting of the irrigation machine with additional costs for variable-rate irrigation equipment resulted in negative profits (VRI). In contrast, uniform irrigation (UI) is economically feasible, at least with a high wheat price and especially with reduced water quantity (DEF). The plant yield with this variant is in average almost as high as with optimal water quantity (UI) at both locations, but the irrigation costs are about 60 to 95 EUR ha^{-1} lower due to the significantly reduced water quantities. With a low market price, irrigation of winter wheat cannot be recommended in general.

Fricke (2013) was able to demonstrate a positive result with a producer price of 220 EUR Mg^{-1} for winter wheat in Hamerstorf, which is located in Lower Saxony, too. The overall yield level was higher than in Dahlhausen and Schoellnitz (5.1 Mg ha^{-1} without irrigation, 7.9 Mg ha^{-1}, with irrigation) but significantly lower than in Jelmstorf (9.2 Mg ha^{-1} and 11.3 Mg ha^{-1}, respectively), which is also a reason for the lack of profitability in Jelmstorf, where the relative yield increase and the additional revenue from irrigation were significantly lower than in Hamerstorf, Dahlhausen or Schoellnitz. DeWitte (2017) also proved a positive economic balance by irrigation for winter wheat grown in the Altmark region in Saxony-Anhalt. A distinction was made between reduced and optimal water quantity. The profits were 29 and 45 EUR ha^{-1} (deficit and optimum irrigation, respectively). However, there is no information on the producer price, which was taken into account for the calculation of profitability. Nevertheless, DeWitte (2017) also concluded that irrigation of cereal crop rotations only becomes economically viable at higher price levels starting at 200 EUR Mg^{-1}. This basically coincides with the results of this study.

Potato and silage maize proved to be particularly worthy of irrigation at the two study sites. Both crops responded with clearly positive irrigation profits, with the exception of VRI at a low product price for silage maize. The influence of the market price on the result is quite clear. The higher price in scenario B led to substantial additional mean revenues for both crops compared to scenario A. Irrigation is therefore always worthwhile in this case. For both crops, uniform irrigation with optimal water quantity (UI) turned out to be the best economic option. Homogeneous deficit irrigation (DEF) is also more effective than site-specific irrigation (VRI).

It was shown, that variable-rate irrigation with a fully equipped center pivot and the considered crops under the conditions of this study is not an economic option. Additional costs will be required to equip the sprinkler system. However, water savings could not be proven and plant yields are not higher, compared to a uniform irrigation with optimal application (UI). Sharma and Irmak (2020) also were able to prove this in principle in an experiment in Nebraska. However, in some cases, significantly lower water quantities were applied with the investigated system than with a compared uniform variant. A fundamental yield advantage of VRI was not shown, which, in addition to the higher investment costs, ultimately also led to poorer economic efficiency of site-specific irrigation.

It was also of interest to clarify which of the uniform control strategies is preferable depending on the quality of the location, in order to be able to derive recommendations from this. With potatoes, the highest irrigation profit could be achieved with uniform full irrigation (UI) regardless of site quality. Moreover, only minor differences between irrigation strategies existed between the individual IMZ.

The same applies for silage maize. For these two crops, irrigation control according to variant UI leads to the most beneficial economic result and the quality of the site does not seem to have any particular influence on the irrigation profits. This is due to the simulated dry matter yield of silage maize and potato in the individual IMZ, which show differences between the IMZ but no clear trend with regard to increasing or decreasing site quality, neither without irrigation nor in the two irrigation variants. Since irrigation in all cases leads to a comparable increase in yield in all IMZ, the profits do not differ considerably between the individual IMZ.

The high yield level of maize and potato leads to higher revenues with optimal irrigation compared to the savings in variable costs with deficit irrigation. The yield level is also lower with deficit irrigation, which is an additional reason. In winter wheat, on the other hand, uniform irrigation with reduced water quantity (DEF) is the effective variant on each IMZ, and this all the more the lower the site quality is. Thus, the profit on IMZ1, at 134 EUR ha^{-1}, was 128 EUR higher than on IMZ4. In IMZ4, the profit of the UI variant was even negative. The yield increases by irrigation hardly differed between the irrigation control variants on all IMZ. However, they were lower in the IMZ with higher quality (AWC) than in the IMZ with lower quality, which explains the comparatively higher irrigation profits on the poorer IMZ. Since there were hardly any differences in yield between optimal and deficit irrigation, the savings in variable costs with reduced irrigation led to higher profits in the DEF variant.

4. Conclusions

We investigated the water requirements and yield effects of variable-rate site-specific and deficit irrigation at two heterogeneous fields in the state of Brandenburg, Germany. At the same fields, uniform full irrigation and no irrigation treatments served as references. The study was based both on a 3-year field trial (silage maize, winter wheat, potato) and a 12-year hypothetical crop rotation (forage pea, potato, winter wheat, silage maize).

Depending in crop and year, respectively, uniform full irrigation required water amounts between less than 100 and more than 300 mm per season. It increased crop yield of all investigated crops as indicated by relative yields for the non-irrigated treatment between less than 30% and 75% compared to full irrigation. Soil conditions and irrigation success were interrelated. That is, the yield increase under irrigation appeared more pronounced for soils with low plant available water holding capacity, particularly under full irrigation.

Site-specific variable-rate irrigation and uniform full irrigation had very similar water requirements. This is because soil moisture differences within a field, which are accounted for in our management zones, only played a minor role for irrigation water demands. Spatial variation in crop water requirements is rather attributable to differences in plant transpiration. Future studies on site-specific irrigation in our region should therefore focus on variation of plant transpiration.

Regulated deficit irrigation resulted in water savings of about 20%. It is currently the most promising alternative to full irrigation in regions or periods of limited water availability. Of the four investigated crops, the benefits of deficit irrigation in terms of water savings and irrigation water productivity were larger for winter wheat and silage maize than for potatoes and forage peas.

In terms of economy site-specific irrigation of forage peas, winter wheat, potatoes and silage maize was not beneficial in comparison to uniform irrigation for the conditions of this study. This is because site-specific irrigation did neither result in water savings nor yield benefits, which could have balanced the costs for additional hardware as well as mapping and site-specific calculation of irrigation amounts. Deficit irrigation of winter wheat was economically superior to uniform full irrigation, mainly because of water savings and the associated reduction in variable irrigation costs. Winter wheat should also be irrigated primarily on sites with a low available water holding capacity because the additional yield by irrigation is higher than on sites with better soil conditions. Potatoes and silage maize should receive full irrigation, if possible, in order to exploit the full yield potential of these crops.

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Appendix

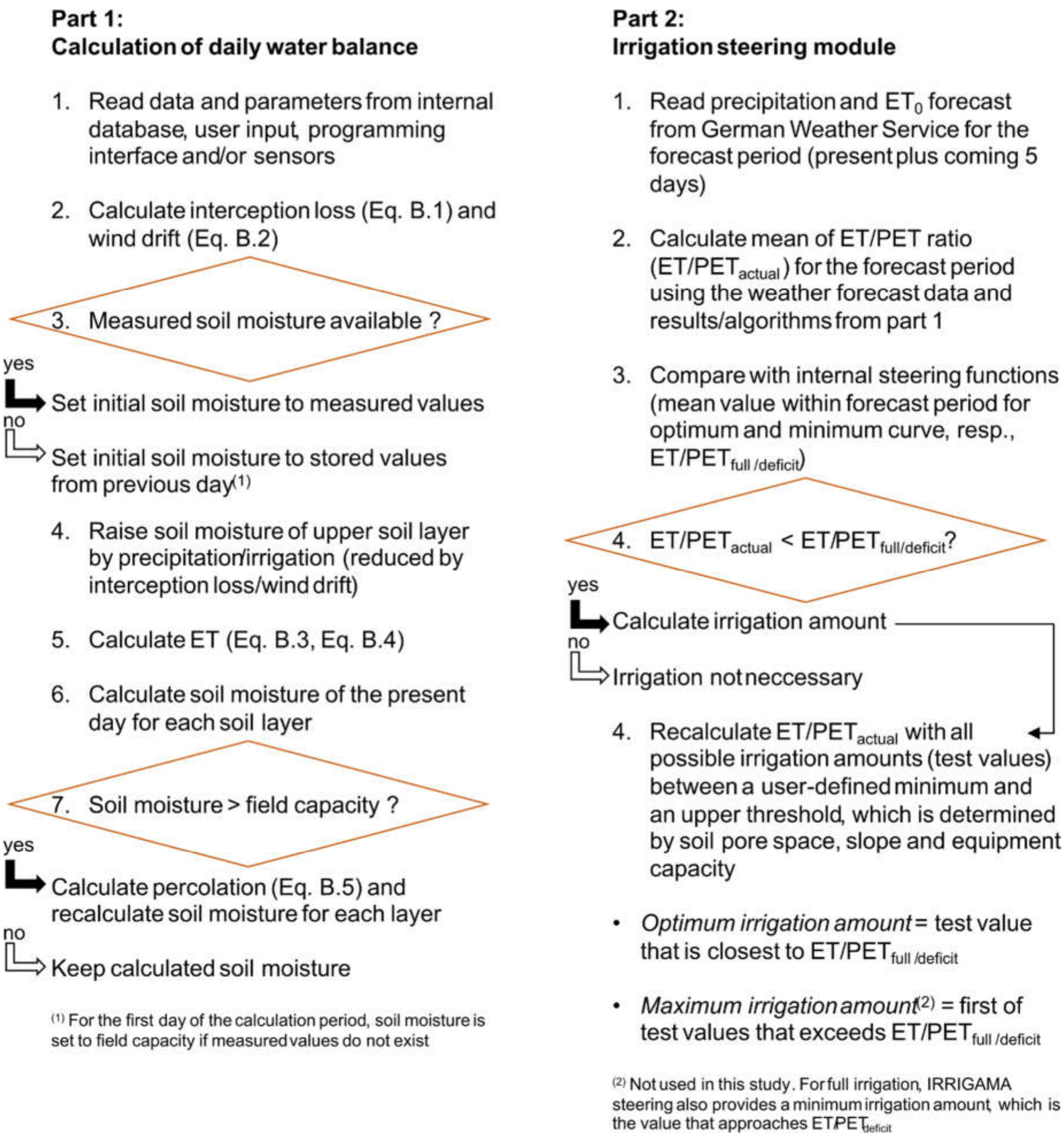

Fig. A.1 Flowchart for IRRIGAMA steering calculations

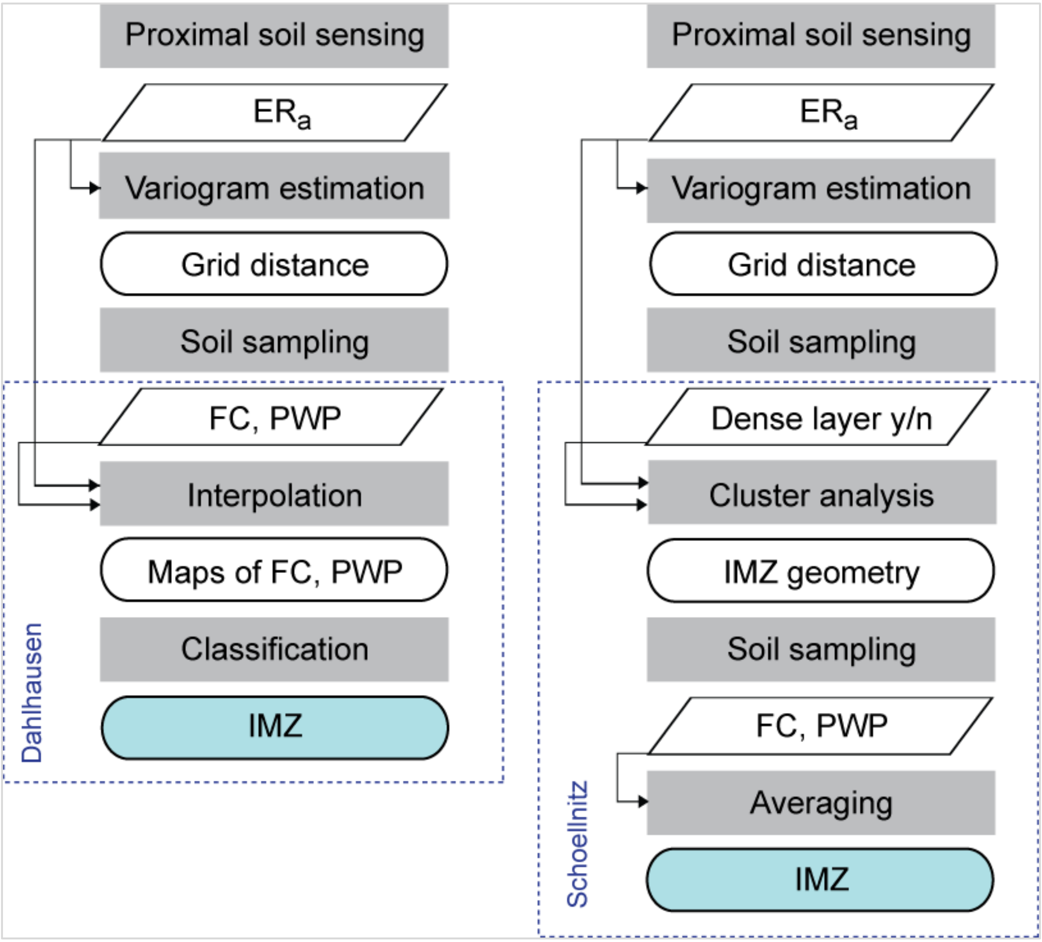

Fig. A.2 Overview of applied methods for management zone delineation. ER_a stands for apparent electrical resistivity, FC and PWP are field capacity and permanent wilting point, respectively, and IMZ refers to irrigation management zone. Grey boxes indicate actions, rhomboids indicate data resulting from actions, and rounded rectangles present results

Tab. A.1 Values of the correction function, $kc_{IRRIGAMA}$, to correct ET_o for the four investigated crops

Crop	Cd[a]	Growth stage[b]	$kc_{IRRIGAMA}$
Forage pea	40	germination	1,0
	50	inflorescence emergence	1,1
	95	n/a	1,1
	105	ripening	0,9
	120	fully ripe	0,1
Potato	35	emergence	1,0
	50	inflorescence emergence	1,0
	70	begin of flowering	1,4
	85	end of flowering	1,5
	115	leaves brownish	1,3
	120	n/a	1,0
Silage maize	15	emergence	1,0
	60	n/a (10 days before tassel emergence)	1,4
	140	n/a (20 days after milk ripe)	1,4
	170	n/a (20 days after full ripe)	0,1
Winter wheat	60	begin of tillering	1,0
	118	n/a	1,0
	128	begin of stem elongation	1,3
	190	n/a (10 days after milk ripe)	1,3
	200	n/a	1,0
	220	n/a (5 days after over-ripe)	0,1

Note. [a]Cumulative days from sowing (peas, silage maize) / planting (potatoes) and from season start (winter wheat), [b]According to the BBCH scale, Meier (2018); n/a: no defined growth stage, if appropriate, nearest growth stage is given in parantheses

Tab. A.2 Herbicide and fertilizer applications during the three-year field experiments

Year	Crop	Deployed Materials[a]	Application rate
2018	Silage maize	fresh chicken manure (23% DM, 13 kg/Mg N, 8 kg/Mg P_2O_5, 7 kg/Mg K_2O, 2 kg/Mg MgO, 21 kg/Mg CaO)	4.38 Mg ha^{-1}
		digestate (7.2% DM, 5.1 kg/Mg N, 2.1 kg/Mg P_2O_5, 5.4 kg/Mg K_2O, 0.8 kg/Mg MgO)	7.2 Mg ha^{-1}
		mineral fertilizer (37% K)	300 kg ha^{-1}
		mineral fertilizer (46% N)	250 kg ha^{-1}
		mineral fertilizer (18%, 46% P_2O_5)	106 kg ha^{-1}
		mineral fertilizer (N, P, Mg, S)	90 kg ha^{-1}
		herbicide (30.0 g/l Foramsulfuron, 9.77 g/l Thiencarbazone, 0.85 g/l Iodosulfuron)	0.0011 m³ ha^{-1}
		herbicide (333 g/l Terbuthylazin, 200 g/l Flufenacet)	0.001 m³ ha^{-1}
2019	Winter wheat	mineral fertilizer (37% K)	190 kg ha^{-1}
		mineral fertilizer (46% N)	215 kg ha^{-1}
		mineral fertilizer (27% N, 12.5 % CaO)	214 kg ha^{-1}
		liquid fertilizer (150 g/l B)	2e-04 m³ ha^{-1}
		liquid fertilizer (80 g/l Mn)	0.00175 m³ ha^{-1}
		liquid fertilizer (5% N, 20% P_2O_5, 5% K_2O)	0.00185 m³ ha^{-1}
		herbicide (6.8% Pyroxsulam)	0.15 kg ha^{-1}
		herbicide (482.3 g/kg Tribenuron)	0.025 kg ha^{-1}
2020	Potato	fresh chicken manure (23% DM, 13 kg/Mg N, 8 kg/Mg P_2O_5, 7 kg/Mg K_2O, 2 kg/Mg MgO, 21 kg/Mg CaO)	4.16 Mg ha^{-1}
		digestate (7.2% DM, 5.1 kg/Mg N, 2.1 kg/Mg P_2O_5, 5.4 kg/Mg K_2O, 0.8 kg/Mg MgO)	15.6 Mg ha^{-1}
		lime (41% CaO, 2.3% MgO)	20.3 Mg ha^{-1}
		mineral fertilizer (37% K)	380 kg ha^{-1}
		liquid fertilizer (5% N, 20% P_2O_5, 5% K_2O)	0.5 m³ ha^{-1}
		liquid fertilizer ($MgSO_4$)	0.005 m³ ha^{-1}
		herbicide (500 g/l Metobromuron)	0.003 m³ ha^{-1}
		herbicide (500 g/kg Aclonifen + 30 g/kg Clomazone)	2.4 kg ha^{-1}
		herbicide (700 g/kg Methrybuzin)	0.5 kg ha^{-1}

Note. [a]DM = dry matter, B = bor, Ca = calcium, K = potassium, Mg = magnesium, Mn = manganese, N = nitrogen, O = oxygen, P = phosphorus, S = sulphur

Tab. A.3 Crop development stages in the HERMES model

Crop	Development stage	Growing degree days (°C days)	Tbase (°C)	Vernalization (days)	Daylength (base[b]) (hours)
Winter wheat	Sowing to emergence	138[a]	0	-	-
	Emergence to double ridge	284	1	45	20 (0)
	Double ridge to heading	260	1	-	20 (7)
	Heading to flowering	180	1	-	20 (7)
	Flowering to maturity	570	7	-	-
Silage maize	Sowing to emergence	110[a]	6	-	-
	Emergence to stem elongation	300	6	-	-
	Stem elongation to tasseling	250	6	-	-
	Tasseling to flowering	150	6	-	-
	Flowering to maturity	1080	6	-	-
Potato	Planting to emergence	136[a]	3	-	-
	Emergence to basal side shoots	150	3	-	-
	Leaf growth to full coverage	300	3	-	-
	Tuber formation	280	3	-	-
	Inflorence emergence to flowering	350	3	-	-
	Flowering to harvest	800	3	-	-
Forage pea	Sowing to emergence	70[a]	5	-	-
	Emergence to stem elongation	180	5	-	16
	Stem elongation to inflorence emergence	180	1	-	16 (7)
	Inflorence emergence to flowering	100	1	-	16 (7)
	Flowering to pod ripening	510	4	-	-

Note. [a] Using soil temperature; [b] Base daylength determines slope of the function

Tab. A.4 Soil data for the sampled soil profiles

Site	Profile	IMZ[a]	Soil depth[b] (m)	Horizon[c] (m)	Roots[d]	Sand[e] (%)	Silt (%)	Clay (%)	SOC[f] (%)	BD[g] (g/cm³)	AWC[h] (mm)
Dahlhausen	1	1	0,2	0,4	yes	91	6	3	0,59	1,72	40
			0,5	0,625	no	92	5	3	–	1,75	21
			0,8	0,9	no	95	3	2	–	1,64	23
			1,2	1,2	no	97	2	1	–	1,80	26
	2	4	0,2	0,3	yes	78	17	5	0,7	1,79	51
			0,4	0,575	yes	76	21	3	–	1,77	41
			0,8	1,2	no	73	16	11	–	1,91	34
			1,2	1,2	no	77	17	6	–	1,87	53
Schoellnitz	1	1	0,15	0,25	yes	89	8	3	0,93	1,70	27
			0,4	0,4	yes	90	7	3	–	1,64	11
			0,8	0,85	no	92	6	2	–	1,66	42
			1,2	1,3	no	98	2	0	–	1,64	27
	2	2	0,15	0,25	yes	78	17	5	1,23	1,64	48
			0,4	0,45	yes	86	12	2	–	1,74	24
			0,8	0,95	yes	56	21	23	–	1,87	49
			1,2	1,4	no	73	17	10	–	1,89	22

Note. [a]IMZ: irrigation management zone; [b]Soil sampling depth and depth at which soil moisture sensors were installed (3/depth); [c]Lower limit of corresponding soil horizon; [d]Visible occurrence of fine roots; [e]Soil texture was determined according to DIN 19683-2; [f]SOC: Soil organic carbon content, only determined for upper soil layer according to DIN ISO 10694; [g]Bulk density of fine-earth fraction, determined according to DIN ISO 11272 :2001-01; [h]AWC: plant available water holding capacity, determined according to DIN ISO 11274

Tab. A.5 Fixed costs, part I: Investment costs for components which are used for the irrigation at the study site Dahlhausen and at adjacent fields (all together = 60 ha)

Component	Acquisition costs (EUR)	Period of amortization (years)	Rate of interest (%)	Annual interest and depreciation per ha irrigated area, inclusive 20% financial funding (EUR ha^{-1} $year^{-1}$)
Well, construction	30,000.00	20	2.5	24.83
Water pump	4,000.00	20	2.5	3.31
Frequency control for water pump	4,300.00	20	2.5	3.56
Diesel power generator	18,000.00	19	2.5	14.90

Tab. A.6 Fixed costs, Part II: Investment costs for additional components, which are used for the irrigation at the study site Dahlhausen exclusively (irrigated area = 29.1 ha)

Component	Acquisition costs (EUR)	Period of amortization (years)	Rate of interest (%)	Annual interest and depreciation per ha irrigated area, inclusive 20% financial funding (EUR ha^{-1} $year^{-1}$)
Water pipeline from well to center pivot	1,500.00	10	4.0	2.39
Center pivot (400 m), fixed parts (central tower, control technology, hydrant, etc.)	13,000.00	20	2.5	22.93
Center pivot (400 m), movable parts (span pipes, drive trains, sprinkler, wheels, end gun, etc.)	42,000.00	10	4.0	142.36

Tab. A.7 Investment costs for the VRI control equipment at the site Dahlhausen

Component	Acquisition Costs (EUR)	Period of Amortization (years)	Rate of Interest (%)	Annual interest and depreciation per ha irrigated area, inclusive 20% financial funding (EUR ha^{-1} $year^{-1}$)
Magnetic valves, electric signal lines, VRI controller	32,000.00	10	4.0	108.84
Site mapping and determination of irrigation management zones (IMZ)	15,000.00	20	4.0	38.06

Tab. A.8 Fixed costs, Part I: Investment costs for components which are used for the irrigation at the study site Schoellnitz and at an adjacent field

Component	Investment costs (EUR)	Period of amortization (years)	Rate of interest (%)	Annual interest and depreciation per ha irrigated area, inclusive 20% financial funding (EUR ha^{-1} $year^{-1}$)
Well, construction	30,000.00	20	2.5	24.83
Water pump	4,000.00	20	2.5	3.31
Frequency control for water pump	4,300.00	20	2.5	3.56
Electric power line	10,000.00	20	2,5	8,28

Tab. A.9 Fixed costs, Part II: Investment costs for additional components which are used for the irrigation at the study site Schoellnitz exclusively (irrigated area = 26.7 ha)

Component	Acquisition costs (EUR)	Period of amortization (years)	Rate of interest (%)	Annual interest and depreciation per ha irrigated area, inclusive 20% financial funding (EUR ha^{-1} $year^{-1}$)
Water pipeline from well to center pivot	1,500.00	10	4.0	36.49
Center pivot (400 m), fixed parts (central tower, control technology, hydrant, etc.)	13,000.00	20	2.5	24.99
Center pivot (400 m), movable parts (span pipes, drive trains, sprinkler, wheels, end gun, etc.)	42,000.00	10	4.0	155.15

Tab. A.10 Investment costs for the VRI control equipment at the site Schoellnitz

Component	Acquisition costs (EUR)	Period of amortization (years)	Rate of interest (%)	Annual interest and depreciation per ha irrigated area, inclusive 20% financial funding (EUR ha^{-1} $year^{-1}$)
Magnetic valves, electric signal lines, VRI controller	32,000.00	10	4.0	118,21
Site mapping and determination of irrigation management zones (IMZ)	15,000.00	20	4,0	41.34

Tab. A.11 Additional parameters of variable costs

Related site	Parameter	Factor
Dahlhausen	Diesel fuel costs (EUR $litre^{-1}$)	0.98
	Fuel consumption (liter Diesel m^{-3} water)	0.15
	Water pumping costs (EUR m-³)	0.14
Schoellnitz	Electricity costs (EUR kWh^{-1})	0.22
	Electricity consumption (kWh m^{-3} water)	0.60
	Water pumping costs (EUR m^{-3})	0.13
both	Irrigation consultancy (EUR ha^{-1})	17.18
	Maintenance and inspection (EUR ha^{-1})	17.18