

Optimising irrigation scheduling for winter wheat-soybean relay intercropping in temperate Europe

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ABSTRACT

Crop diversification can buffer climate extremes and support biodiversity and has been reported to meet both production and sustainability needs. In Germany, winter wheat is the primary crop, often grown in relatively simple rotations with other cereals, rapeseed, and maize. Intercropping practices such as winter wheat-soybean relay intercropping (RC) with high spatial-temporal differentiation have the potential to enhance sustainability. However, the establishment of soybeans into a winter cereal remains a challenge due to high competition for water indicating the need for supplementary irrigation for successful RC in dry regions. This study presents an irrigation scheduling framework for winter wheat-soybean RC in temperate regions. We calibrated and validated the process-based agroecosystem model MONICA using three-year field data from 2020 to 2023. The model accurately reproduced aboveground biomass ($R^2 = 0.88$, $n = 66$) and grain yield for both crops in RC ($R^2 = 0.70$, $n = 16$), with root mean square errors of 2091 kg ha⁻¹ (biomass) and 372 kg ha⁻¹ (grain yield). The validated model was used to test the effect of irrigation timing, dosage, and strategy on RC yield performance across two soil types (594 simulations in total). A sensitivity test of 20 mm irrigation increments across phenological stages showed that soybean grain yield was most responsive to irrigation at the first pod stage, resulting in intercropped soybean yield increases up to 47% (+249 kg ha⁻¹) compared to rain-fed. Yield gains from irrigation increment of 20 mm peaked at moderate application rates of 80 mm in sandy and 120 mm in loamy soils, then declined. Contrasting soil texture simulations indicated that loamy soils required higher irrigation volumes but achieved greater land-use efficiency. Land equivalent ratio (LER) reached 1.21 with cumulative seasonal total irrigation of 140 mm, while sandy soils benefited from low-volume, high-frequency irrigation (LER = 1.11 with 140 mm), eliminating 64% of drought-induced yield loss versus 48% in loamy soils. These results highlight the importance of tailored irrigation strategies based on soil texture and crop phenology, providing a practical foundation for supplementary irrigation in cereal-legume RC systems and supporting crop diversification in temperate climates.

1. Introduction

Crop diversity in Central Europe largely relies on simple crop rotations involving cereal and oilseeds (Blickensdörfer et al., 2022; Palka et al., 2026; Stein and Steinmann, 2018). Winter wheat covers 48% of Germany's cropland and is commonly cultivated in short rotations, leaving limited opportunities for diversification (Blickensdörfer et al., 2022). Intercropping, defined as the cultivation of two or more crops in the same field (Vandermeer, 2009), has been proposed as a potential

strategy for enhancing crop diversification in Germany.

Among various intercropping configurations, relay intercropping (RC) is one of the systems new to Germany, offering high spatial-temporal differentiation and maximised crop-crop interactions which could contribute to yield production with higher resource use efficiency and ecosystem services (Huss et al., 2022; Tilman, 2020). RC involves sowing a relay crop into a developing first crop in a narrow row configuration (Tanveer et al., 2017), representing a crop diversification strategy that achieves sustainable intensification by increasing yield per

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unit area through enhanced temporal and spatial species diversity. The yield advantages of RC are attributed to complementary and selection effects (Chen et al., 2025). Complementary effects arise from abiotic facilitation, biotic feedbacks, and niche differentiation, while selection effects are driven by the disproportionate contribution of highly productive component crops (Loreau and Hector, 2001). A representative example of RC is the winter wheat-soybean system (Chan et al., 1980; Mead and Willey, 1980), which combines a cereal (wheat) with a nitrogen-fixing legume (soybean). The coexistence of winter wheat and soybean increases system resilience and reduces vulnerability to species-specific pests, diseases, and weeds (Parker et al., 2015; Singh et al., 2023). Moreover, contrasting canopy structures, root architectures, and phenologies between the two crops promote niche differentiation, enabling more efficient resource acquisition and utilization (Postma and Lynch, 2012). Notably, winter wheat typically yields almost twice as much as soybean (Yu et al., 2025), it often dominates the system and drives a positive selection effect (Loreau and Hector, 2001). An additional advantage of RC lies in the differentiated growing periods of component crops, which increases the harvest frequency of existing cropland without expanding the cultivated area (Ray and Foley, 2013). Despite its potential, evidence of RC adoption by European farmers remains scarce (Lamichhane et al., 2023a). Major barriers include crop management complexity and higher management costs compared to sole cropping (Lamichhane et al., 2023a).

The productivity and sustainability benefits of RC are not absolute (Brooker et al., 2015). Evidence has shown that RC is complex to implement in practice without irrigation, especially when the roots of the primary crop are fully developed and the establishment of the subsequent crop coincides with the drier part of the growing season (Lamichhane et al., 2023b; Xu et al., 2008). Both winter wheat and soybean experience yield losses under water stress, with severity strongly depending on the crop's phenological stage (Vadez et al., 2024). In winter wheat, drought stress during key development stages, such as germination, anthesis, and grain filling, negatively impacts the physiological processes and reduces yield (Ali, 2019; Liu et al., 2022). Drought during grain-filling alone has been reported to cause yield reductions of up to 57 % across five wheat varieties (Balla et al., 2011). Soybean exhibits similar vulnerabilities to water stress during flowering and the subsequent reproductive phases, leading to yield losses of approximately 40 % (Manavalan et al., 2009; Meckel et al., 1984; Specht et al., 1999). In RC systems, the critical periods of water demand for each crop may or may not overlap in ways that support complementary water use. When water requirements of both component crops peak simultaneously, the primary crop can outcompete the weaker crop for water, suppressing its growth and yield (Te et al., 2023). Consequently, the potential benefits of improved water use efficiency in RC may be limited if the relay crop underperforms (Brooker et al., 2015). Identifying the optimal phenological stages for irrigation in the context of RC is therefore essential for maximizing overall productivity and ensuring the viability of RC in water-limited environments.

Irrigation is not commonly practiced in cereal and legume production in Germany. However, drought has recently emerged, significantly impairing crop yield across Germany (Schmitt et al., 2022). Winter wheat alone has experienced annual losses amounting to €23 million due to drought (Schmitt et al., 2022), and production may continue to be impaired as climate extremes intensify. Previous research emphasized the importance of available soil water for the relay crop during summer in RC (Vrignon-Brenas et al., 2016). Supplemental irrigation during the reproductive stages has been reported to promote soybean growth and development under temperate humid conditions, regardless of irrigation treatment (Montoya et al., 2017). Field trials conducted on farmers' fields in Brazil revealed that RC success, especially combined with no-tillage cultivation, requires careful management to minimize interspecific competition (Baldé et al., 2020). Given the challenges posed by a changing climate, heterogeneous soil conditions, and the specific dynamics of RC, irrigation timing must be fine-tuned to meet the water

demands of the relay crop while allowing the primary crop to mature. However, a significant knowledge gap persists, with many farmers relying on visual estimation of crop conditions to schedule irrigation (USDA-NASS, 2018), which undermines irrigation efficiency. RC systems remain a niche practice with limited adoption, constraining both research investment and practical experience. Farmers lack evidence-based guidance on optimal irrigation timing and volumes specifically for temperate RC systems. Field experiments addressing irrigation strategies in RC remain scarce, creating a research-practice gap where limited scientific knowledge constrains adoption, while low adoption reduces incentives for further research into irrigation optimization for these complex cropping systems.

Addressing the complex interplay among RC, irrigation timing, volume, and soil properties through field experiments is tedious and labour-intensive. Process-based crop models are increasingly used to assess water demand and improve irrigation efficiency (Umutoni and Samadi, 2024). They simulate the biophysical processes of crop growth and development by capturing interactions among plants, soil, management practices, and climate (Webber et al., 2020). A well-calibrated crop model can simulate soil water dynamics and crop water demand daily, allowing for precise irrigation scheduling (Seidel et al., 2016). Several models have been applied to simulate evapotranspiration and irrigation requirements in diverse cropping systems. For instance, STICS and AquaCrop were used to estimate water requirements of crops (Brisson et al., 2004; Zhang et al., 2023), SIMDualKc has supported water use assessment of wheat-maize and wheat-sunflower intercropping systems (Miao et al., 2016), while DSSAT was employed for analysing irrigation impacts under various climatic and management scenarios (Ding et al., 2021). However, comprehensive modelling guidelines for irrigating cereal-legume RC remain lacking. This is especially critical for RC, where the system's performance largely depends on the relay crop's establishment, which is often affected by the competitive pressure of the first crop.

This study aims to provide insight into irrigation management for wheat-soybean RC systems. Given the labour-intensive nature of field experiments involving irrigation timing and quantity across multiple environments, we employed an agroecosystem model to investigate the following research questions: 1) At which phenological stages of wheat and soybean in a RC system are irrigation interventions most critical for overall system productivity? 2) How do variations in irrigation volume at identified critical phenological stages influence the performance metrics of wheat-soybean RC systems? 3) To what extent do soil textural classes modulate the relationship between irrigation timing (relative to crop phenology), irrigation volume, and overall system productivity in wheat-soybean RC?

We hypothesise that: 1) Irrigation during the co-existing phase increases total RC yield more than that in the single-crop phase; 2) RC total yield increases with the irrigation volume, but the efficiency of water supply decreases with the input water supply; 3) Sandy soils require higher irrigation volumes than loamy soils to attain comparable RC productivity.

2. Materials and methods

2.1. Field experiments

The calibration and validation procedure were based on three years of field experiments (2020/2021, 2021/2022, and 2022/2023 growing seasons) for winter wheat-soybean RC. Experiments were conducted at the Experimental Field Station of the Leibniz Center for Agricultural Landscape Research (ZALF, 5252°N, 1413°E), Müncheberg, Germany, 50 km east of Berlin. Each year, the experiment was conducted in a different field within the experiment station. Soils in the region are sandy loams formed from glacial deposits. The average annual temperature was 9.0 °C with an average annual precipitation of 600 mm. On-station precipitation, evapotranspiration, and temperature data were

recorded. The study treatments included sole winter wheat (cv. Reform), sole soybean (cv. Merlin), and RC, each under irrigated and rainfed conditions. Supplementary irrigation was scheduled to avoid severe drought. Irrigated plots received 110–230 mm (over 8–10 events) during spring and summer in 2021, 2022, and 2023 (see [Supplementary Table 1](#) for the amounts per day).

The experiment followed a split-plot arrangement, each plot with a size of 24 m² (3 m × 8 m) with a 50 cm buffer strip between plots. Six replicated plots followed a randomised complete block design. Sole wheat was planted at a density of 416 seed m⁻² at a depth of 2 cm, with row distance of 12.5 cm. Sole soybean was planted in 70 plants m⁻² at a depth of 3 cm with row distance of 37.5 cm. For RC plots, soybean and winter wheat were arranged in an alternating row pattern. Each soybean row (with 37.5 cm row distance) was positioned between two adjacent rows of winter wheat (with 12.5 cm row spacing). Two doses of mineral N fertiliser were applied to sole wheat in March and April at the amounts of 60 kg and 40 kg. RC only received 60 kg of fertilizer in March to avoid negative effects on soybean nitrogen fixation. The experiment was conventionally managed, and manual weeding was conducted when necessary. Information regarding field management can be found in [Table 1](#) and a previous study (Yu et al., 2024). Soil characteristics of the experiment site are listed in [Table 2](#), and the complete dataset is available in a repository (Thompson et al., 2025c).

Crop phenology was visually estimated based on the BBCH scale (Meier, 2018). To rule out the border effect, aboveground biomass (AGB) was sampled from 0.5 m² of central rows in the plot, and then separated into leaves, stems, spikes, or pods. Leaf area index and light interception were measured by SunScan Canopy Analyser (Delta-T, UK). Soil moisture, referring to volumetric soil water content (m³ m⁻³), was measured in the 0–7 cm topsoil with a soil sensor (Delta-T Devices ML3 ThetaKit HH2 Moisture Meter and ML3 sensor in 2021–2022 and Acclima SDI-12 Sensor Reader RD1200 in 2023). Three measurements per plot were performed at each sampling date. Plant heights were measured non-destructively on three plants per plot. The measurements were conducted four times throughout the growing season. Final grain yield was measured using a combine harvester with a unique attachment customised for RC. The winter wheat and soybean were harvested separately by slightly bending the soybean rows with the attachment. The yield sampling area was 12 m² for each plot. The reported yields were converted to dry matter yield using the dry weight percentage derived from the biomass samples at the harvest date. To fulfil the model input, soil bulk densities and inorganic nitrogen content were measured from three soil layers in 0–30 cm, 30–60 cm, and 60–90 cm, separately

Table 1
Müncheberg site field management information in 2020/2021, 2021/2022 and 2022/2023.

Year	2020/2021	2021/2022	2022/2023
Sowing date, wheat	18 November 2020	14 October 2021	29 November 2022
Sowing date, soybean	6 May 2021	29 April 2022	16 May 2023
Sowing density, wheat	416 seed m ⁻² at a depth of 2 cm, row distance of 12.5 cm		
Sowing density, soybean	70 plants m ⁻² at a depth of 3 cm, row distance of 37.5 cm		
Harvest date, wheat	11 August 2021	21 July 2022	24 July 2023
Harvest date, soybean	27 October 2021	17 October 2022	11 October 2023
Amount of irrigation for water treatments ^a	120 mm / 50 mm	230 mm / 0 mm	105 mm / 70 mm
Precipitation sum	444.4 mm	386.2 mm	542.9 mm
N fertiliser	100 kg ha ⁻¹ for sole crops, 60 kg ha ⁻¹ for relay cropping		

^a Two irrigation levels were set for the water factor, irrigated and rain-fed, to prevent terminal drought for relay soybean. In 2020/2021 and 2022/2023, supplementary water was applied to rain-fed treatments to prevent terminal drought. Model inputs strictly follow the field experiment condition.

Table 2

Model-relevant characteristics of the sandy (Müncheberg) and loamy soil (Dedelow).

Soil	Depth (cm)	Bulk density (kg m ⁻³)	Sand content (%)	Clay content (%)	Silt content (%)	Organic carbon content (%)
Sandy	0–30	1302	72	5	23	0.54
	30–60	1548	89	2	9	0.15
	60–200	1388	83	4	13	0.05
Loamy	0–25	1660	60	12	28	0.47
	26–48	1760	61	12	27	0.10
	49–85	1900	61	12	27	0.02
	85–200	1910	61	13	26	0.03

sampled from three replicate soil cores.

2.2. The MONICA model

MONICA (Nendel et al., 2011) is a process-based crop simulation model for nitrogen and carbon dynamics in agroecosystems. The model is driven by daily weather, soil characteristics, species/cultivar-specific inputs, and agronomic management practices (Battisti et al., 2017, 2018; Nendel et al., 2014). MONICA simulates photosynthesis and respiration, and stomatal conductance feedback (Yu et al., 2001). Photosynthesis in MONICA separates clear-sky and cloudy conditions to estimate biomass accumulation, using light extinction coefficient for calculating the light interception as Goudriaan suggested for SUCROS (Goudriaan and Van Laar, 1978). The model considers the negative impacts of heat stress, water and nitrogen deficiency, and aeration deficits on crop growth processes and yield formation. These processes have been calibrated based on impact assessments published in previous studies for wheat and soybean (Asseng et al., 2019; Nendel et al., 2023). The original MONICA was developed for sole cropping systems, but Yu et al. (2024) recently developed and tested a new module to capture the winter wheat-soybean RC system using Tsubo and Walker's horizontal homogeneous canopy concept (Tsubo and Walker, 2002). The shared canopy concept assumes horizontal homogeneity while accounting for vertical light competition between species. This approach has been extensively tested and provided satisfactory results in APSIM, CROPSYST, and FASSET for a wide range of intercropping combinations, such as wheat-faba bean, sorghum-cowpea, and pea-barley. The shared canopy concept has been tested and provided satisfactory results in APSIM, CROPSYST, and FASSET for a wide range of intercropping combinations, such as wheat-faba bean, sorghum-cowpea, and pea-barley (Berghuijs et al., 2021; Berntsen et al., 2004; Chimonyo et al., 2016; Gaudio et al., 2019; Stöckle et al., 2003). The module separates the canopy into two layers based on the difference in plant height between the component crops. The leaf area index (LAI) of each layer depends on the plant height ratio between the two crops, and light interception is calculated based on the daily share of LAI in each layer accordingly (Yu et al., 2024). MONICA plant height simulation follows the logistic curve to the parameterized maximum plant height. To mimic the relay crop in RC, an empirical model of the plant height suppression factor related to the first crop temperature sum was employed in the intercropping version of MONICA (version 3.6.32.toth_ser_TUA, <https://github.com/zalf-rpm/monica>). This accounts for the plant height plasticity of the relay crop from suppression of the first crop. Although this assumption simplifies within-row heterogeneity, validation against field measurements confirms it captures the key light competition dynamics affecting system productivity. The model accurately reproduces observed light interception patterns, showing increased radiation capture in intercropping systems compared to sole crops ([Supplementary figure 1](#)). With radiation use efficiencies of 1.69, 1.50, and 1.93 g DM MJ⁻¹ for sole wheat, sole soybean, and intercropping, respectively. This

improved light capture simulation is critical for accurate yield prediction, as radiation use efficiency drives biomass accumulation in both sole and intercropped systems.

The new version of MONICA is equipped with a pedotransfer function for better predicting the soil water retention and hydraulic conductivity curve of various European soils (Tóth et al., 2015). The soil-plant water process of MONICA begins with a pre-infiltration phase that involves precipitation and irrigation. Daily precipitation is taken as a climate input. Irrigation is considered a setup within the management module that can be activated with the amount and time determined. MONICA treats irrigation as a net flow with no losses regardless of the application method. This water is the amount of water available at the soil surface for infiltration. The infiltration effectiveness follows the simple capacity model, which determines the fraction of available water that infiltrates into the soil at a given time step. The simple capacity model defines the maximum infiltration capacity as the difference between the soil saturation water content and actual water content, therefore, partially depending on the given soil conditions.

When the rainfall plus irrigation exceeds the soil infiltration capacity, the Horton and saturation flow are applied as a form of surface runoff. For evaporation, MONICA first calculates the evaporative demand based on the energy balance following the Penman-Monteith and Priestley-Taylor approaches. After the evaporative demand is estimated, MONICA follows the Beer-Lambert approach, which uses the LAI and extinction coefficient to calculate an evaporation coefficient to estimate the soil surface evaporation. The demand for transpiration in MONICA is still estimated by the Penman-Monteith and Priestley-Taylor methods. The potential crop transpiration is estimated by multiplying transpiration demand by a crop-specific coefficient. Crop transpiration is then adjusted to the transpiration surface through the Beer-Lambert type integrated approach using LAI. Then the actual transpiration can be reduced due to soil saturation, low soil moisture, and high temperature-induced stomata closure (Tenreiro et al., 2020). The daily root water uptake is calculated as a function of soil water content, the vertical rooting depth, the pressure head, actual transpiration, and the fraction of total root density in each soil layer. Drainage is simulated with a tipping bucket approach, which refers to the condition where water content exceeds the field capacity of the soil layer, and excess water flows vertically downwards to the next layer.

The water sharing is modelled by copying the soil profile of the primary crop (winter wheat) to the relay crop (soybean). It assumes that in RC, due to the advanced growth stage and developed root structure, the winter wheat possesses high competitiveness over soybean. Water is taken up primarily by the primary crop during the co-existing phase. With this assumption, soybeans will have low to no yield in very dry conditions, which was confirmed by the field experiment and similar studies in RC (Lamichhane et al., 2023a; Schell et al., 2025; Thompson et al., 2025b). The model calculates the water uptake and status through the soil-plant process of the primary crop daily. Then, the soil profile with the remaining soil water is transferred to the relay crop modelling section for calculating the relay crop's soil-plant process. Once both the primary and relay crops have utilized the soil profile, any excess water is returned to the primary crop's soil profile for use in the next day's calculations. Indirectly, the consequence of light competition, e.g., the change in LAI, also contributes to evapotranspiration and water uptake. A comparison of implementing this prior uptake assumption versus not is provided in the [supplementary materials \(Supplementary Fig. 2\)](#).

2.3. Calibration and validation

Measurements from the 2020/2021 season were used for model calibration. The calibration procedure began with determining the accumulated thermal time ranges to set simulated and observed phenological development stages. Specific leaf area was estimated from field-measured LAI and leaf dry weight. Subsequently, model parameters such as root penetration rate and stage-specific crop coefficients

(Kc) were automatically optimised to minimize the root mean square error (RMSE) between observed and simulated values for LAI, soil moisture (0–7 cm), biomass, and yield. A detailed list of calibrated parameters and their values is provided in the [supplementary material \(Supplementary Table 2\)](#).

In addition to the parameters described above, MONICA includes default parameter sets for winter wheat and soybean based on prior studies with German cultivars (Battisti et al., 2017; Nendel et al., 2023; Specka et al., 2015). Therefore, this study focused on calibrating only the minimum necessary parameters. The validated procedure has been conducted against independent data from the 2021/2022 and 2022/2023 seasons. The model was evaluated under rain-fed and irrigated conditions, capturing a wide range of crop responses to water availability. Model performance was assessed using root mean square error (RMSE), mean bias error (MBE), and the coefficient of determination (R^2) between simulated and observed values. In total, there are 98 points for aboveground biomass, 69 for soil moisture, and 24 for yield comparison. One data point was derived from 6 replicated plots and 3 repeated measurements each.

$$RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^N (Y_i - \widehat{Y}_i)^2} \quad (1)$$

$$MBE = \frac{1}{N} \sum_{i=1}^N (\widehat{Y}_i - Y_i) \quad (2)$$

$$R\text{-square} = \frac{\sum_i (\widehat{Y}_i - \bar{Y})^2}{\sum_i (Y_i - \bar{Y})^2} \quad (3)$$

2.4. Irrigation scenarios

Irrigation scenarios were evaluated in two steps. In the first step, six levels of water application, ranging from 20 mm to 120 mm in 20 mm increments, were tested. Each level was applied once during individual phenological stages to identify the most sensitive and responsive growth stages for each crop. This step also aimed to determine the irrigation amount that best met crop water requirements. Based on these results, seven key phenological stages were selected for further analysis in the second step: four for winter wheat (from stem elongation to maturity) and three for soybean (from the juvenile stage to first pod formation; Fig. 1). In the second step, irrigation water was applied cumulatively in 20 mm increments at each selected phenological stage (Table 3). Alongside these treatments, simulations under rain-fed conditions and simulations without water stress were also included to serve as baselines. Irrigation levels and timing were determined based on insights from prior research. For instance, soybean field trials have applied 20 mm of water when severe drought symptoms appeared, making it a standard for assessing yield sensitivity to stage-specific irrigation (Iijima et al., 2007). Other experiments conducted in temperate regions reported that approximately 120 mm of irrigation was sufficient to maintain high soybean yields in moderately dry years, while up to 165 mm was required during particularly dry conditions in Múncheberg, Germany (Gajić et al., 2018; Karges et al., 2022).

To assess the impact of soil texture on the irrigation regimes, we compared two specific sites, both suitable for soybean and winter wheat cultivation as sole crops. Besides the site in Múncheberg with sandy soil, a site in Dedelow, Germany (53°22' N, 13°48' E) was selected with a loamy soil. Both were used to execute the previously described irrigation scenarios (Ehrhardt et al., 2023). The soil profile at Dedelow was selected due to its detailed characterization and consistency with the measurement protocol, as the Múncheberg site (Omari et al., 2025). Although located approximately 120 km from the Múncheberg site, the Dedelow soil contains more than twice the silt content of the

Irrigation for relay-row intercropping

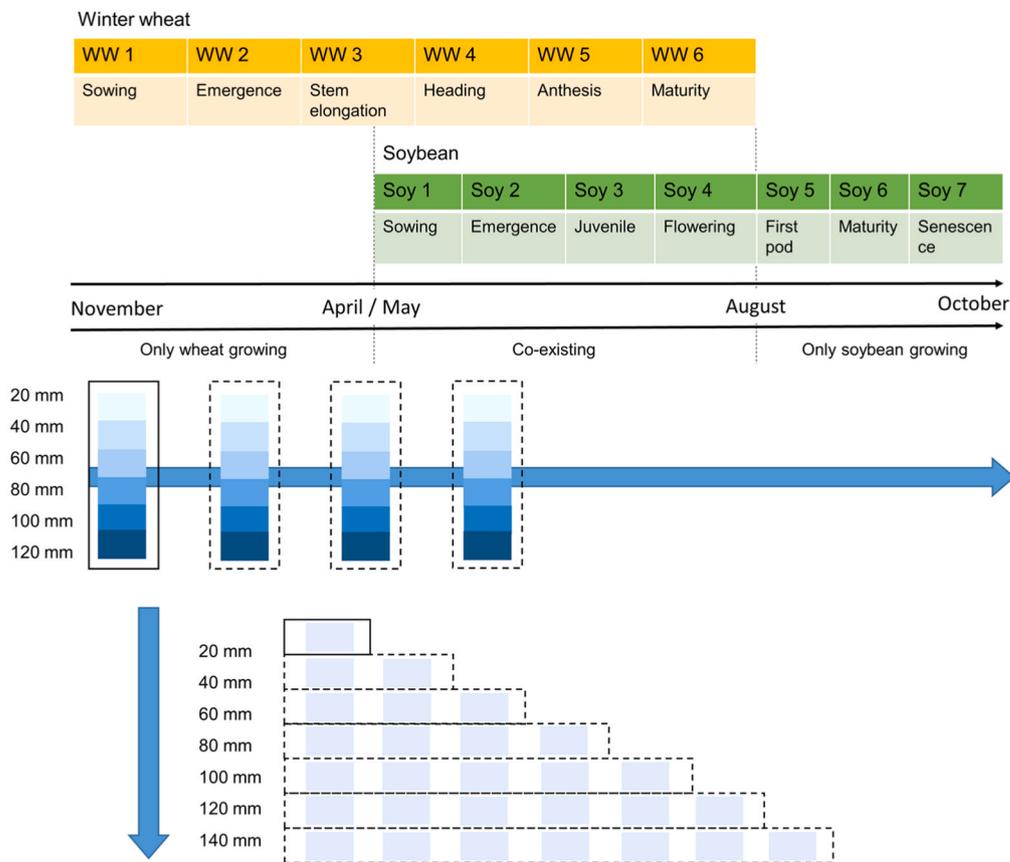
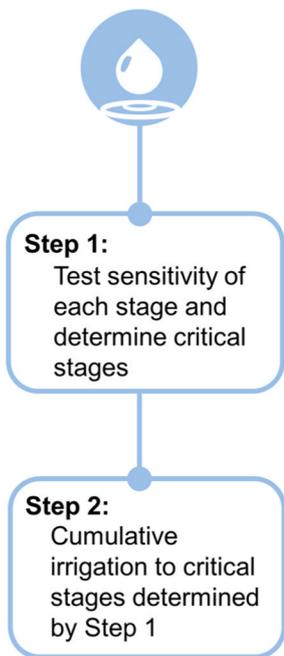


Fig. 1. Schematic map for irrigating winter wheat-soybean relay intercropping. The map illustrates the winter wheat and soybean development stages in the MONICA model and the two-step evaluation for irrigation scenarios. Step 1 is applying different amounts of irrigation to single stages at single times to elucidate the stage sensitivity. After identifying critical stages, irrigation doses of 20 mm each time were cumulatively applied to those stages in Step 2.

Table 3
Land equivalent ratios (LER) and eliminated water stress (EWS) of cumulative seasonal irrigation scenarios in sandy and loamy soil.

Phenological stage		Cumulative irrigation					LER ± SE		EWS ± SE (%)		
WW 3 ^a	WW 4	WW 5	WW 6	Soy 3	Soy 4	Soy 5	(mm)	Sandy soil	Loamy soil	Sandy soil	Loamy soil
							0	0.85 ± 0.02	1.11 ± 0.03	0	0
							20	0.98 ± 0.02	1.06 ± 0.03	31.7 ± 2.3	15.3 ± 1.9
	20						40	1.03 ± 0.03	1.05 ± 0.02	39.9 ± 3.0	17.8 ± 1.8
	20	20					60	1.05 ± 0.04	1.14 ± 0.04	47.6 ± 3.7	29.1 ± 3.1
	20	20	20				80	1.09 ± 0.05	1.19 ± 0.05	52.5 ± 4.3	33.5 ± 3.8
	20	20	20	20			100	1.08 ± 0.05	1.17 ± 0.06	56.9 ± 4.6	40.5 ± 4.6
	20	20	20	20	20		120	1.08 ± 0.04	1.18 ± 0.05	57.0 ± 4.1	42.3 ± 4.1
	20	20	20	20	20	20	140	1.11 ± 0.06	1.21 ± 0.07	64.2 ± 5.0	47.9 ± 5.2
							Full potential	1.60 ± 0.20	1.69 ± 0.28	100	100

^a WW: winter wheat, Soy: soybean. The winter wheat development stages are WW3: stem elongation and double ridge; WW4: heading; WW5: anthesis; and WW6: maturity. The soybean development stages are Soy3: juvenile phase; Soy4: flowering; Soy5: first pod.

Müncheberg soil, rendering it more favourable for plant growth. Key soil characteristics used for model input are presented in Table 2. To isolate the effects of soil texture, simulations for Dedelow were run using the climate data from the Müncheberg site. This ensured that differences in crop performance could be attributed solely to soil properties. In total, 594 simulations were conducted across both locations. For clarity, the soils are referred to throughout this study as “sandy” for Müncheberg and “loamy” for Dedelow. Three indicators were employed to quantify the effects of irrigation. Eliminated water stress (Eq. 4), a metric developed to quantify the relative mitigation of drought-induced yield loss achieved through irrigation, expressed as:

$$Eliminated\ water\ stress(\%) = 1 - \frac{Y_{T,P} - Y_{T,I}}{Y_{T,P} - Y_{T,R}} \times 100\% \tag{4}$$

where $Y_{T,P}$ represents the potential total RC yield under drought-free condition, $Y_{T,I}$ for the actual total yield under given irrigation, the numerator represents the remaining yield gap between potential yield, and $Y_{T,R}$ for the total yield exposed to the natural drought stress.

A second metric, termed incremental irrigation efficiency, was also calculated. This indicator quantifies the efficiency of each incremental irrigation application by dividing the relative yield improvement by the corresponding increase in irrigation volume (Eq. 5). n refers to the amount of increase in irrigation volume, which is 20 mm in this case.

$$Incremental\ irrigation\ efficiency(\% \quad mm^{-1}) = \frac{(Y_{T,i+1} - Y_{T,i})/Y_{T,R}}{n} \times 100\% \tag{5}$$

Lastly, the land equivalent ratio (LER) was used to assess land use

efficiency in RC. It is calculated as the sum of intercropping yields scaled by sole cropping yields. To better compare the land use efficiency across irrigation scenarios, the respective sole winter wheat and soybean yield are always the yield without drought response presented as $Y_{sw,p}$ and $Y_{ss,p}$ (Eq. 6). Y_{iw} represents the intercropped winter wheat yield, and Y_{is} represents the intercropped soybean yield.

$$LER = \frac{Y_{iw}}{Y_{sw,p}} + \frac{Y_{is}}{Y_{ss,p}} \quad (6)$$

3. Results

3.1. Simulation and observation

The aboveground biomass and yield simulated by MONICA showed strong agreement with field observations in both the calibration and validation (Fig. 2). For aboveground biomass, the calibration and validation phases also demonstrated a good fit with R^2 of 0.78 and 0.88, respectively. The model slightly overestimated aboveground biomass ($MBE_c = 206 \text{ kg ha}^{-1}$ for calibration, $MBE_v = 423 \text{ kg ha}^{-1}$ for validation), with RMSE values of 2091 kg ha^{-1} and 1771 kg ha^{-1} , respectively (Fig. 2). The main sources of deviation were associated with sole cropping and the 2021/2022 season. In the calibration phase, the model achieved a high coefficient of determination ($R^2 = 0.96$) for wheat and soybean yields under both sole cropping and RC systems, with only marginal overestimation ($MBE_c = 297 \text{ kg ha}^{-1}$) and high accuracy ($RMSE_c = 372 \text{ kg ha}^{-1}$). In the validation phase (2021/2022, 2022/2023 seasons), model performance declined moderately, with R^2 decreasing to 0.70 and the overestimation shifting to an underestimation of -192 kg ha^{-1} . For soil moisture, the model explained 62 % of the variability in the calibration phase and 56 % in the validation phase. Although soil moisture was moderately overestimated, the overall fit remained acceptable with small absolute errors ($RMSE = 0.04 \text{ m}^3 \text{ m}^{-3}$), suggesting reasonable model performance in capturing soil water dynamics (Fig. 2).

3.2. Development stages and timing of irrigation for sole cropping and relay cropping

With a fixed 20 mm irrigation applied at different development stages of winter wheat and soybean, the variability in relative yield

change was larger for soybean than for winter wheat (Fig. 3). In sole winter wheat, the 20 mm irrigation had minimal impact, with yield changes ranging from -6% to $+9.0 \%$. A yield increase was only observed when irrigation was applied at heading, immediately preceding anthesis. Irrigation at sowing and emergence slightly reduced yields compared to the rainfed condition, though the decreases were marginal (Fig. 3). In contrast, sole soybean yield responded positively to 20 mm irrigation at nearly all stages, with relative yield increases ranging from 1.63 % to 22.19 %, except during senescence. The greatest response was observed when irrigation was applied at the first pod stage. In RC, irrigation mainly benefited soybean, which showed the highest average relative yield change of 46.86 % (Fig. 3). However, this substantial percentage increase was based on a very low mean intercropped soybean yield of only 531 kg ha^{-1} , translating to an absolute increase of 249 kg ha^{-1} . This was reflected in total yield response as well. Despite significant variation in soybean response, the total RC yield change ranged only from 0.07 % to 6.35 %, with winter wheat remaining the primary contributor (Fig. 3).

3.3. Effects of irrigation volume, timing, and soil characteristics

Irrigation substantially increased the total yield in both sandy and loamy soils, while the magnitude of the response differed between soil types (Fig. 4). In general, higher irrigation amounts (up to 120 mm) resulted in greater yield increases. However, the relative yield response was strongly influenced by the phenological stages during which irrigation was applied. Irrigating only during the winter wheat growing period did not lead to significant gains in total yield. Notably, in the loamy soil, applying 120 mm of irrigation at winter wheat sowing and emergence resulted in a 10 % (-380 kg ha^{-1}) decrease in total yield (Fig. 4). Greater yield gains were observed when irrigation was applied during the co-existing phase of both crops, compared to irrigation applied during the sole wheat or sole soybean phases. For instance, irrigation at wheat emergence, which caused the largest negative yield response in loamy soil, led to an 11 % ($+417 \text{ kg ha}^{-1}$) yield gain in sandy soil when 40 mm was applied (Fig. 4). This contrast between sites was not observed during the soybean-only growing period, where irrigation generally led to greater yield improvements in the loamy soil, where irrigation at the soybean first pod stage increased total yield up to 53.6 %. While soil texture did not drastically change the most beneficial

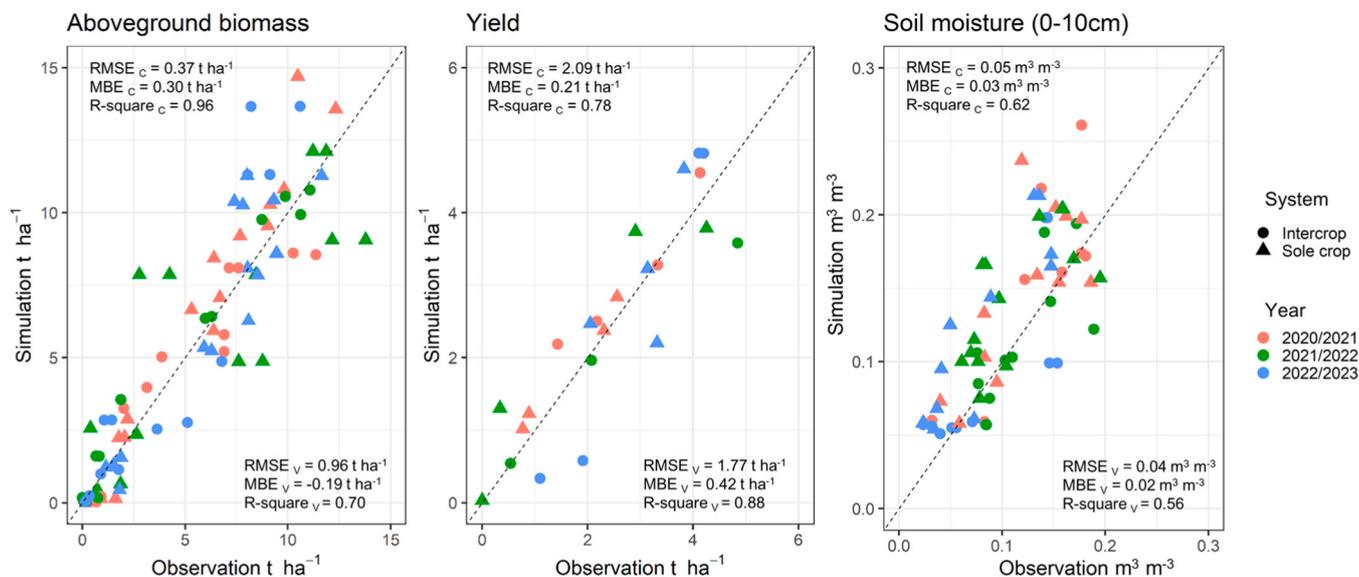


Fig. 2. Simulated year-wise sole and intercropping aboveground biomass, yield, and soil moisture (0–10 cm) against observations. Points of round dots represent the intercroppings, and triangles represent the sole crops. Colours represent three seasons of field experiments. RMSE, MBE, and R-square with C as subscript were derived from the calibration season (2020/2021), and V represents validation seasons (2021/2022 and 2022/2023).

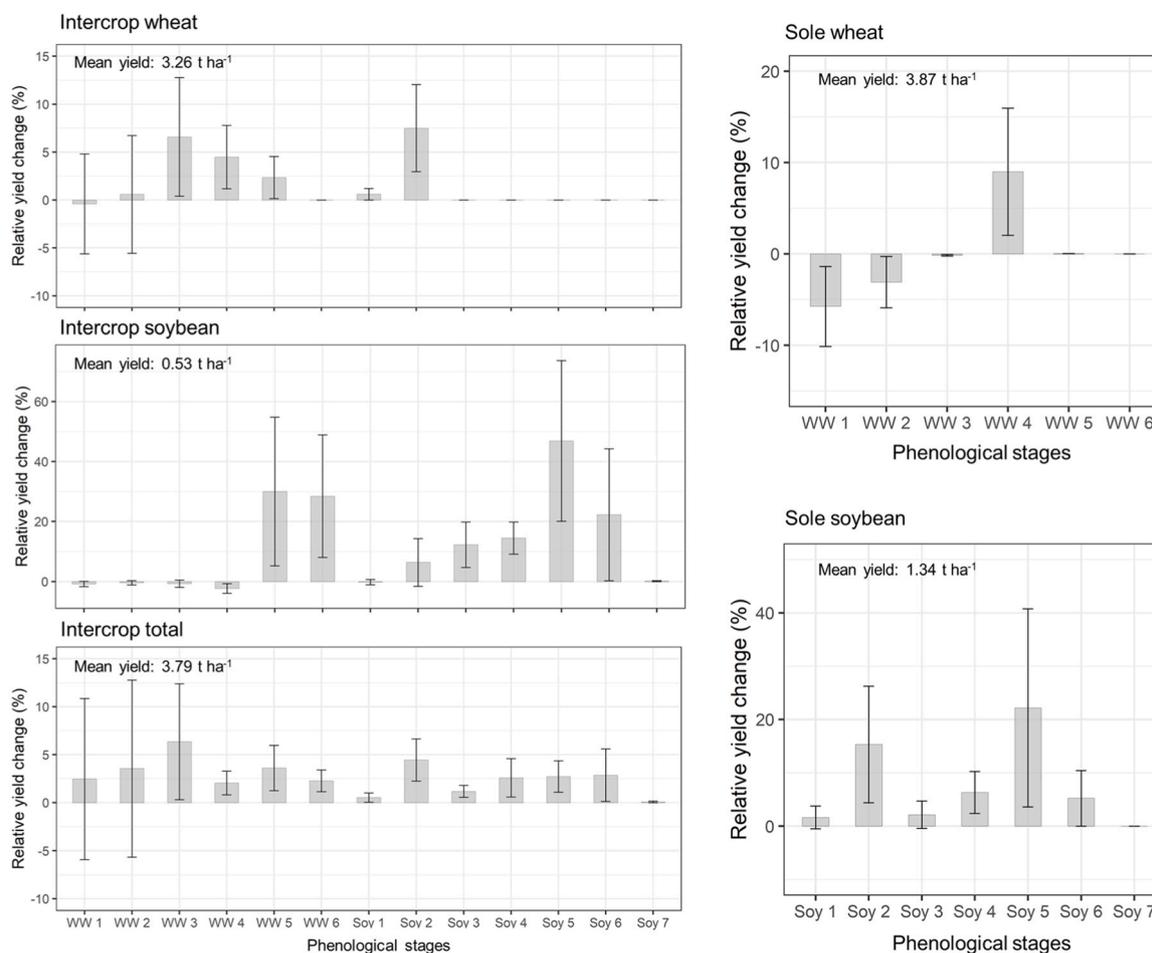


Fig. 3. The yield percentage change of sole winter wheat, sole soybean, and their intercropping when 20 mm of irrigation was applied to different phenological stages relative to the three years simulated rain-fed mean yield. WW: winter wheat, Soy: soybean. The winter wheat development stages are WW1: sowing; WW2: emergence; WW3: stem elongation and double ridge; WW4: heading; WW5: anthesis; and WW6: maturity. The soybean development stages are Soy1: sowing; Soy2: emergence; Soy3: juvenile phase; Soy4: flowering; Soy5: first pod; Soy6: maturity; and Soy7: senescence.

phenological stages for irrigation, it did affect the optimal irrigation for RC performance (Fig. 4). The highest incremental irrigation efficiency was typically observed during the co-existing phase and subsequently, during the soybean first pod stage. Across all phenological stages, the optimal irrigation volume was consistently higher in loamy soil than in sandy soil (Fig. 4). Incremental irrigation efficiency generally increased with irrigation volume up to a point of stagnation (around 80 mm in sandy soil and 120 mm in loamy soil) beyond which further gains were limited, although loamy soil showed potential for continued increases beyond this threshold.

Cumulative irrigation scenarios resulted in higher LER in loamy soil compared to sandy soil. Even under rain-fed conditions, the RC showed greater land use efficiency than the sole cropping, with LER values exceeding 1 (Table 3). However, in loamy soil, cumulative irrigation amounts of 20 mm and 40 mm led to a decline in LER compared to the rain-fed condition. In contrast, in sandy soil, cumulative irrigation up to 80 mm consistently increased the LER, though a slight decrease was observed when an additional 20 mm was applied during the soybean juvenile and flowering stages. Applying 140 mm of cumulative irrigation raised the LER from 0.85 to 1.11 in sandy soil, and from 1.11 to 1.21 in loamy soil (Table 3). The eliminated water stress (EWS) demonstrated that cumulative irrigation during the co-existing phase offset more drought-induced yield loss in sandy soil than in loamy soil. At higher irrigation levels, LER and EWS increased marginally. Although complete mitigation of drought effects was not achieved under any scenario, cumulative irrigation of 140 mm eliminated 64.2% of drought-induced

yield loss in sandy soil and 47.9% in loamy soil (Table 3).

4. Discussion

4.1. Necessity of irrigation

Even though many studies show that intercropping in general outperforms sole cropping, especially under water-deficit conditions (Liang et al., 2020; Renwick et al., 2020; Zhang et al., 2022), our results highlight the necessity of irrigating winter wheat-soybean RC in dry temperate regions, particularly in sandy soils (Fig. 2 and Fig. 4). For instance, intercropping wheat with pea has been shown to use the water more efficiently than sole cropping and is suitable for dryland conditions to achieve higher yield (Pankou et al., 2021), which is in contrast with our findings. This difference is primarily attributed to variations in sowing times inherent to the RC system (Fig. 1). Sole soybean has been shown to develop a weaker root system than pea under dry conditions (Benjamin and Nielsen, 2006). In our case, the relayed soybean faced drought stress in addition to strong competitive suppression from a more developed primary crop, whereas with a wheat-pea combination, the crops were sown simultaneously. Soybean growth was stunted early in the 2021 season (which had the lowest precipitation during all seasons), and this was accurately captured by our crop model (Fig. 2), in accordance with on-farm trials conducted under similar soil and climate conditions (Thompson et al., 2025a). Thus, not all intercropping combinations perform well under rainfed conditions, as water competition

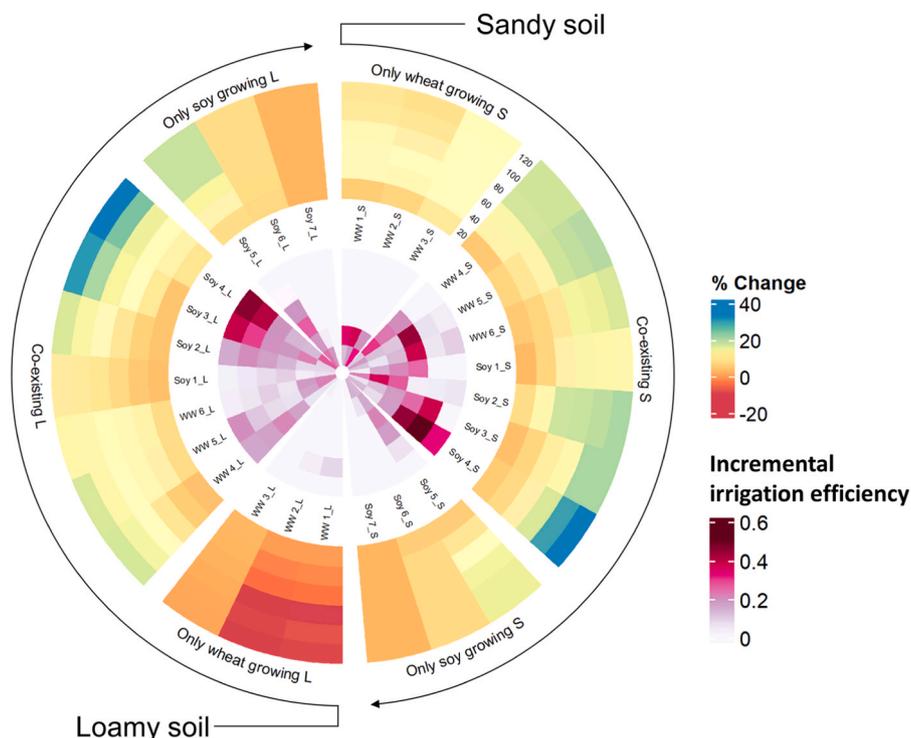


Fig. 4. The winter wheat relay intercropping total yield change (%) and incremental irrigation efficiency (IE) as affected by irrigation amount applied across development stages of component crops relative to the total intercropping yield of the rain-fed system. Each pixel represents the mean of 3-year simulations (2020–2024). The RC system was divided into three phases: only the wheat growing phase, the co-existing phase (winter wheat and soybean), and the soybean growing phase. The left side illustrates the simulation for the loamy (L) and the right side for the sandy (S) soil. Each stage at the two sites was opposed to the other.

can negate intercropping benefits, and irrigation management should be carefully planned to alleviate drought.

4.2. Critical phenological stages for irrigation

Field experiments in semi-arid areas have suggested that the optimum timing for irrigating winter wheat and spring maize RC is during the heading stage of wheat and the heading and anthesis stages of the relayed maize (Zhang et al., 2007). In our study, the optimal irrigation timing of the winter wheat-soybean RC was similar (Fig. 3). However, a new critical period emerged during the vegetative growth stage of soybean (Fig. 3 and Fig. 4). This is due to the primary crop having a significant advantage in resource acquisition, and consequently achieving a higher yield compared to the relay crop (Liu et al., 2015). Therefore, the early growth of the relay crop must be supported with supplemental water to secure an adequate yield.

Soybean emergence in the RC system partly overlapped with wheat heading to anthesis, leaving a depleted soil water profile for soybean. Interspecific competition at this stage, combined with unfavourable climate conditions, often threatens the establishment of soybean and may lead to crop failure (Lamichhane et al., 2023b). Several studies have reported yield reductions in soybeans due to water stress in both sole cropping and intercropping systems (Amanullah et al., 2021; Anda et al., 2020). Water stress during soybean grain filling reduces grain size and mass (Borrmann et al., 2009; Doss et al., 1974; Eck et al., 1987). Our findings corroborate a previous study on winter wheat-soybean RC, which emphasized that supplemental irrigation is essential for soybean survival and performance in RC systems established on soils with low moisture-holding capacity (Duncan and Schapaugh Jr, 1997).

In our study, irrigation applied during the co-existing phase mainly enhanced soybean yield rather than winter wheat, and consequently improved total system productivity (Fig. 4). These findings present both opportunities and challenges for breeders. With increasing attention on crop diversification, breeding for intercropping systems has gained

momentum (Brooker et al., 2015; Chen et al., 2021; Rubiales et al., 2023; Wolfe et al., 2021). In this context, breeding soybean genotypes with highly acquisitive root growth traits is recommended to alleviate drought stress during the vegetative phase. However, root anatomical traits exhibit high plasticity and moderate heritability, making it a challenging breeding target (Kadam et al., 2017; Schneider and Lynch, 2020). This recommendation is supported by previous evidence showing that vigorous root development of the relay crop in RC enhances above-ground biomass accumulation, particularly after the peak competition phase (Ma et al., 2020).

4.3. The role of soil in irrigation effectiveness

The phenological stages during which the crop can benefit from irrigation are not significantly altered by soil texture. However, the beneficial irrigation window is narrower in loamy soil than in sandy soil (Fig. 4). Large irrigation volumes are unsuitable for loamy soils for two reasons. First, the primary crop may be harmed by excessive water during early development stages, and fine-textured soils with lower potential water percolation rates are more likely to develop water-logging situations in which the roots suffer from oxygen deficiency (Fig. 4). Second, already ample irrigation may boost the primary crop's growth, intensifying its competitiveness and thereby suppressing the relay crop. This is undesirable for farmers who aim to enhance total protein production through RC. The situation is less likely to occur in sandy soil, which has lower water-holding capacity and reduced primary crop yield potential.

Irrigating during the co-existing phase supports both crops. It helps enhance winter wheat yield and assists soybean establishment during the critical vegetative phase. Drought stress during this phase negatively affects the nodulation, nitrogen fixation, and biomass accumulation in soybean (Lumactud et al., 2023). It begins with stomatal closure, reducing internal CO₂ concentration, which leads to oxidative stress, degradation of photosynthetic pigments, inactivation of photosystem II

and Rubisco, and ultimately, to inhibited photosynthesis (de Sousa et al., 2020; Markulj Kulundžić et al., 2022). This cascade triggers early senescence and shortens the time available for yield formation (Ergo et al., 2021), resulting in yield loss. A greenhouse experiment quantified this effect, showing a 28 % yield reduction when water stress occurred during the vegetative stage (Jumrani and Bhatia, 2018). In sandy soils, irrigation applied after the co-existing phase is often less effective. Due to early resource competition, soybean tends to accumulate low biomass, which limits the crop's recovery ability even in the absence of wheat.

In contrast, irrigation during the soybean first-pod stage significantly improved total yield in loamy soil, suggesting better recovery potential under higher water-holding capacity. Loamy soils maintain higher moisture in the rooting zone, enhancing crop biomass and yield potential compared to sandy soil (Lawes et al., 2009). This difference is particularly pronounced during the co-existing period when both crops' water demand needs to be satisfied. During periods of only one crop exists, both soil types maintained relatively higher moisture availability due to reduced competition, though the absolute water-holding capacity remained consistently higher in loamy soil. This difference in moisture retention capacity explains why irrigation strategies must be tailored to soil type, with sandy soils requiring more frequent applications to maintain adequate moisture during critical crop development stages. However, in such conditions, winter wheat may gain a stronger competitive advantage. Therefore, RC management across soil types should avoid disproportionately favouring the primary crop (through irrigation or fertilization) and instead prioritise resource access for the relay crop to optimize system-level productivity.

Crops on sandy soils benefit more from low-volume, high-frequency irrigation strategies (Fig. 4 and Table 3). In our sandy soil, cumulative irrigation of 140 mm improved LER by 30.5 %, compared to only 9 % in loamy soil. Previous studies on winter wheat have shown that soil texture affects transpiration responses to water deficits, indicating that irrigation strategies should be tailored to soil conditions (Wu et al., 2011). Our findings on incremental irrigation efficiency are consistent with the earlier research on flood-irrigated maize systems in arid regions, where fewer but larger irrigation events worked better on loamy soils, while crops on sandy soils performed better under frequent, smaller applications (Yi et al., 2022). This aligns with recent work on sole-soybean systems, which reported yield benefits from increased irrigation frequency in sandy conditions (Rajanna et al., 2022). Notably, in a sandy soil, a LER that exceeded 1 was achieved with just 40 mm of irrigation, substantially lower than the 120–165 mm typically recommended for sole crops (Gajić et al., 2018; Karges et al., 2022). These results highlight the importance of soil texture as a determinant of irrigation scheduling. Incorporating soil-specific strategies can improve management recommendations for RC across environmental gradients.

4.4. Model assumptions and soil water content

The minor overestimation of soil moisture observed here is consistent with early MONICA applications at several field sites (Nendel et al., 2011), but not a general observation in more recent studies (Figueiredo Moura da Silva et al., 2025; Kimball et al., 2023). Discrepancies between observed and simulated values can also be attributed to the uncertainties in soil moisture measurements and spatial variability in the field (Yi et al., 2022). Point sensors for moisture measurement reflect a narrow soil volume and depth, whereas models represent a thicker layer. As with all process-based crop models, MONICA abstracts reality using empirical assumptions. For real-time irrigation support, it is important to understand these assumptions and their consequences for simulation outcomes. Although simulated soil moisture was within an acceptable range, it suggests an underestimated evapotranspiration, particularly for RC. The level of agreement in soil moisture is consistent with known challenges in simulating crop-soil water dynamics, especially under high evaporative demand conditions. A recent publication by Webber (2025)

addressed the point that a broad model ensemble systematically underestimates drought stress. It demonstrates that the uncertainty arises from the physiological controls that govern evapotranspiration, thus an improvement in the simulation of atmospheric evapotranspiration demand is advocated in the modelling community. For MONICA, crop water deficit is triggered when actual crop transpiration falls below potential transpiration, representing an insufficient water supply to the crop. In this study, transpiration was likely underestimated, leading to lower irrigation requirements.

In addition, MONICA treats irrigation as a net flow with no losses, which overestimates irrigation efficiency regardless of the application method. This assumption may have differential impacts across soil textures, as sandy soils typically experience higher percolation and runoff losses than loamy soils under field conditions, meaning the model's "no losses" assumption creates a larger overestimation of irrigation efficiency for sandy soils compared to loamy soils. However, since all simulations use the same assumption, the relative comparisons between irrigation scenarios and soil textures remain valid for identifying optimal timing and volumes, though absolute water requirements may be underestimated, mainly for sandy soils. As a result, the model's suggested optimum irrigation volumes for RC are to be considered conservative, while the identification of critical irrigation timing remains reliable.

Moreover, the model assumes that in RC, water competition always favours the first crop. With water uptake priority prescribed according to the model configuration, this approach represents belowground competition implicitly based on established crop-specific water demand patterns and root architecture assumptions. The simulated water uptake patterns are consistent with known rooting behavior of both crops. While this is valid under water-limited conditions, it may not hold when water is abundant. In such cases, water acquisition becomes more dependent on root architecture and competition dynamics between crops, requiring further investigation. Direct root measurements were beyond the scope of this study. Future studies combining root profiling or isotopic tracing could improve the representation and validation of modelling crop-specific water uptake in RC.

Optimum irrigation strategies involve not only preventing drought but also avoiding over-irrigation, which can lead to waterlogging. When large irrigation volumes are applied at a single time, excess water accumulates in the soil profile, reducing oxygen availability. Crop responses to oxygen deficiency are time- and stage-dependent and can affect assimilate accumulation (Liu et al., 2023). MONICA accounts for waterlogging using a simple routine that reduces transpiration after a phase of anoxia. MONICA limits the transpiration, and thus the water supply to crops, which consequently affects photosynthesis.

4.5. Limitations and perspectives

Model uncertainties rise from multiple sources, including soil pedotransfer functions, cultivar parameterization, and measurement limitations. Soil pedotransfer functions used to estimate hydraulic parameters from texture data can introduce substantial uncertainties in water retention and conductivity estimates, particularly for intermediate soil textures. Additionally, cultivar-specific parameterization contributes uncertainty, as crop physiological parameters were based on generic variety characteristics rather than site-specific cultivar traits (genotype \times environment interactions), potentially affecting growth timing, water use efficiency, and stress responses. The MONICA intercropping version considers light and water competition but not nitrogen. The current experiment without N treatment lacks evidence to support the model for nitrogen use assumptions. Further, due to the temporal niche between winter wheat and relayed soybean, the nitrogen potentially fixed by soybean is less likely to transfer to wheat stands, considering the timing of N demand. Therefore, no competition for nitrogen was assumed in the present version.

Although our simulation approach effectively isolated soil texture

effects, transferability to other temperate sites may require consideration of local conditions. The irrigation timing principles identified here (mainly the critical importance of the co-existing phase and differential responses between sandy and loamy soils) are applicable across temperate relay cropping systems with similar crop combinations, as these are based on fundamental crop physiology and interspecific competition dynamics. However, the specific optimal irrigation volumes (80 mm for sandy, 120 mm for loamy soils) are climate-specific and may require adjustment for sites with different precipitation patterns, evapotranspiration demands, or soil hydraulic properties. Future research should apply the identified timing principles and soil-specific relationships while adjusting irrigation volumes through site-specific field validation.

Other than that, the lack of an ecological perspective has been repeatedly highlighted as a limitation in crop yield modelling, leaving pathogens, weeds, and pests out of scope. The limitation may be more critical in intercropping systems than sole cropping due to the interplay between management practices and biotic stressors, which can influence yield and ecosystem services. For instance, irrigation can increase the risk of disease outbreaks by raising relative humidity or soil moisture (Perez-Mercado et al., 2022). However, this is unlikely to happen in intercropping systems, which reduce the risk of weeds (Gu et al., 2021) pests and pathogens compared to sole crops, as they modify the microclimate, particularly moisture levels, and alter wind dynamics through a more heterogeneous canopy structure, which improves ventilation (Boudreau, 2013; Chadfield et al., 2022; Zhang et al., 2019). However, most of the current mechanistic models do not account for these interactions, limiting their ability to evaluate pest- and disease-related trade-offs and ecological benefits associated with intercropping.

5. Conclusion

Our work presents the first irrigation scheduling strategy for winter wheat-soybean RC in temperate regions. Based on field experiments and the calibration and validation of the agro-ecosystem model MONICA, we demonstrate that the model, despite using simplified assumptions for water sharing combined with a homogeneous horizontal canopy approach for light competition, accurately simulated RC biomass and yield. Supplementary irrigation significantly increased the total yield of the RC, with the gains primarily driven by enhanced soybean yield. Irrigating during the competition phase yielded more than irrigation applied solely during the winter wheat and soybean phases. Irrigation efficiency, measured by yield response per irrigation increment, followed a typical response curve, increasing with irrigation volume up to an optimum, and declining thereafter. Further simulations on contrasting soil types revealed that while the critical phenological stages benefiting from irrigation were consistent, the optimal irrigation amount was higher and the beneficial window narrower in loamy soil than in sandy soil. The latter benefited more from low-volume, high-frequency irrigation, achieving a LER of 1.11 with 140 mm of water and eliminating 64.2 % drought-induced yield loss. Despite the limitations of the crop model, particularly its simplified assumptions and focus solely on the abiotic stressors, this study represents an important step toward improving irrigation management and supporting the broader adoption of crop diversification practices in temperate climates.

CRediT authorship contribution statement

Moritz Reckling: Writing – review & editing, Supervision, Resources, Funding acquisition, Conceptualization. **Ehsan Eyshi Rezaei:** Writing – review & editing, Writing – original draft, Supervision, Investigation. **Jay Ram Lamichhane:** Writing – review & editing, Validation, Methodology. **Thompson Jennifer Briana:** Writing – review & editing, Data curation. **Claas Nendel:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Jing Yu:** Writing – original draft, Visualization, Methodology, Formal analysis, Data

curation, Conceptualization.

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Declaration of Competing Interest

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

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at [doi:10.1016/j.agwat.2025.110031](https://doi.org/10.1016/j.agwat.2025.110031).

Data availability

Data will be made available on request.

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