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Do rotations with cover crops increase yield and soil organic carbon?—A modeling study in southwest Germany

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ABSTRACT

Conservation agriculture practices of crop rotation with permanent soil cover have been widely promoted for improving long-term agroecosystem resilience in the face of changing climate. However, there has been no comprehensive evaluation of site-specific agroecosystem services of soil health and crop yield in response to improved crop rotations with and without cover crops (CCs) on field and spatial scales. We calibrated and applied a process-based agroecosystems model to determine the effects of improved crop rotation and cover cropping on soil organic N content and mineralization rate, soil organic carbon (SOC) change rate, soil CO_2 efflux, and crop yields. A 10-year cropping systems dataset from six sites in southwest Germany was used to calibrate and evaluate the DSSAT model and to provide the typical management practices of the conventional farming system in the region as the *business-as-usual* (BAU) scenario for model application. A 4-year crop rotation was then designed with and without the inclusion of commonly grown non-legume and legume CCs and applied in three cycles at the research sites and the surrounding region. Crop rotation without CCs treatments provided the no-CC scenario, therefore the effect of CC inclusion could be tested. Relative to BAU and no-CC, the inclusion of CCs in crop rotation on annual rate, resulted in 12% and 3% higher soil organic N and 6% and 8% higher SOC change rate, respectively. Additional advantage of cover cropping on soil organic N and C was more pronounced by legume CCs while non-legume CCs were more efficient in reducing N leaching. Combined positive rotational and cover cropping effects were observed on winter wheat and oilseed rape yields at the research sites. However, we observed spatial variability of these results on regional scale, suggesting management by environment interactions that should be considered for site-specific management recommendations. Crop rotation with CCs significantly increased water productivity of cereal crops, but did not produce higher yield of winter and spring barley or silage maize compared with BAU unless only legume CCs were used in certain areas that are vulnerable to N losses. Our findings highlight the C sequestration potential of improved crop rotations and cover cropping emphasizing the need for site-specific management for agronomically improved and environmentally sound cropping systems.

1. Introduction

Intensified farming systems might contribute to satisfy the increased demand for food security by increasing crop production. Yet, in order to maintain stable levels of production while protecting the environment, sustainable management practices are pivotal. Management of soil organic carbon (SOC) of croplands is one of the most imperative directions for enhancing crop productivity and long-term sustainability. Increasing soil C stocks by transferring C from the atmosphere to the soil through plants which is referred to as C sequestration in soils can ultimately support climate change mitigation (Wiesmeier et al., 2020). However, utilizing this potential is highly complex and depending on various factors. Ciais et al. (2010) reported a mean soil C loss of 0.17 Mg C ha^{-1} yr^{-1} in European cropping systems over the past decades contributing to soil CO_2 emission to the atmosphere. In this regard, understanding the role of crop management on SOC change, aiming for increased SOC stocks and crop yield potential is of increased interest. Therefore, quantifying SOC development in response to management by environment interaction is important to support long-term system sustainability and food security whilst mitigating climate change (Garsia

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et al., 2023).

Conservation agriculture has been widely promoted as a feasible solution to achieve the climate-smart agriculture main pillars of production, adaptation, and mitigation (Corbeels et al., 2016; He et al., 2023). Three main principles contribute to conservation agriculture: reduced soil surface disturbance, i.e., no-tillage or conservation tillage, diversified crop rotation, and soil cover with residues and/or cover crops (CCs). Improved crop rotations can support yield productivity through improved soil physical, chemical, and biological conditions (Katupitiya et al., 1997; Boyer et al., 2015), with less fertilizers input (Foltz et al., 1995; Attia et al., 2015). Diverse rotations may also indirectly impact the SOC by producing greater quantity and/or better quality of residue returned to the soil. In this respect, residue retention and organic amendments were reported to significantly alter SOC dynamics and soil CO_2 efflux rate and subsequently crop yield in a wide range of environments (Allmaras et al., 2004; Wilhelm et al., 2004; Srivastava et al., 2016; Attia et al., 2021). In spite of this, controversies exist around the mechanisms of C accumulation and loss in the soil to debate the role of microbial derived C, which is relatively young C, for accumulating additional organic C in soils with high initial C content (Derrien et al., 2023). He et al. (2022) argued that the soil physical properties such as clay content, i.e., soils' stabilization capacity and aggregate stability may underpin the long-term microbially derived C accumulation. Further, interaction with other environmental factors such as the amount of rainfall could result in different turnover rates into the SOC pool, thus the desired outcome may not always be achieved.

Another important conservation agriculture pillar is the use of cover crops (CCs), also known as catch or service crops, usually planted after the harvest of the main crop in summer/fall for the provision of ecosystem services. CCs do not directly benefit the farmers in short-run, as they are usually not harvested. Instead, CCs provide numerous ecosystem services among which increasing SOC and organic N contents (Seitz et al., 2022; Peng et al., 2023), soil aggregate stability (Blanco-Canqui et al., 2015; Chahal and Van Eerd, 2020), and the subsequent cash crop yield (Chahal and Van Eerd, 2023) are the main benefits. An additional crucial advantage of CCs compared with other SOC management options such as induced land use change is that crop production is not compromised, i.e., trade-offs between SOC sequestration and crop production are small. However, several factors determine the impact of CCs inclusion on soil C sequestration such as the quantity of produced biomass, CCs' species and N fixing potential, the available cultivation window, and percent of biomass incorporation into the soil. A meta-analysis by Chahal and Van Eerd (2023) showed that subsequent crop yield in a temperate climate was increased by 14% with legume CCs compared with 7% with non-legume broadleaves CCs. The analysis also showed 15% higher yield due to CCs residue incorporation into the soil compared with leaving the CCs residue on the soil surface, suggesting interaction effects with other management practices. Inclusion of CCs in crop rotation may increase the biomass production of CCs in response to enhanced soil properties and longer cultivation window by crop rotation compared with monoculture. Another meta-analysis by Garba et al. (2022) showed a reduced cash crop yield by 11% in temperate dryland climate but an increased cash crop yield by 4% and 15% in continental and tropical climates in response to cover crops, respectively. In another temperate environment, winter wheat yield was decreased by 10% following CC compared with following fallow (Nielsen et al., 2016). Cash crop yield reduction following CC is usually observed in dry conditions due to the water use by the CC and subsequent precipitation after CC being insufficient to replenish the soil profile and fulfill the water requirements of the main crop (Nielsen et al., 2016; He et al., 2023). Nonetheless, yield reduction for some crops, i.e., silage maize and dry bean, was also reported in humid conditions/temperate climate by CC which was attributed to less N availability and other factors not exclusively attributed to CCs (Marcillo and Miguez, 2017; Chahal and Van Eerd, 2023).

The lack of short-term benefits and variations in crop yield response to CC represent a major challenge to CC adoption by producers, and therefore, further research could shed light on the impact of CC inclusion in crop rotation under site-specific soil and climate conditions. The inclusion of CCs in cropping system as well as diverse crop rotations have been widely promoted as a conservation agriculture strategy to enhance soil health and crop yield (Attia et al., 2015; Bourgeois et al., 2022; Zhao et al., 2022; Peng et al., 2023). However, few studies have focused on simultaneously assessing both strategies across varying soil and climate conditions on crop yield of various crops and SOC development. Process-based agroecosystem models allow for testing large number of treatments across spatio-temporal scales in a timely and cost-effective manner. The Century-based soil module (Parton et al., 1988) has been widely applied to simulate soil C and N in various cropping systems (Li et al., 2015a; Li et al., 2015b). In the present research, we applied a process-based agroecosystem model, following calibration and evaluation, to determine the impact of different CCs species inclusion in crop rotation on crop yield and SOC development across spatial scale in southwest Germany. Specific objectives were to: (i) calibrate and evaluate the Decision Support System for Agrotechnology Transfer (DSSAT) model using a detailed cropping systems dataset from six sites in two regions of southwest Germany, (ii) determine the impact of including non-legume and legume CCs into 4-year crop rotations on crop yield and SOC development compared with no-CC and *business-as-usual* (BAU) scenarios, and (iii) explore the potential outcomes of various CCs inclusion scenarios on large spatial scale as a pre-step for developing a user-friendly web-based decision support tool for optimization of crop rotations.

2. Materials and methods

2.1. DSSAT model and CENTURY-based soil module

The process-based agroecosystem model DSSAT version 4.8 (Hoogenboom et al., 2019) dynamically simulates crop phenological development as well as the growth and senescence of leaves and stems, growth of roots and shoots, biomass accumulation, and yield as a function of soil properties, daily weather, and crop management. Mathematical equations are integrated to describe the basic flow and conversion processes of soil N and C, water and nutrient balances on a daily basis and predict the temporal changes in nutrient uptake, water use, and crop growth and yield. Biomass accumulation in the CERES module is computed as the product of photosynthetically active radiation and cultivar specific radiation use efficiency on a daily basis which is then partitioned between above and below ground depending on phenological phase, the supply and demand of N and C nutrients and available water with a priority for aboveground biomass. The CROPGRO module simulates leaf-level photosynthesis using a hedge-row light interception model and leaf-level photosynthesis parameters (Boote and Pickering, 1994; Alagarswamy et al., 2006). Daily soil water content is simulated soil layer-wise based on soil water balance approach as a function of precipitation and irrigation, evaporation and transpiration, and runoff and drainage from the profile (Ritchie et al., 2009).

The CENTURY-based soil module simulates SOC considering three types of SOC pools and two fresh organic C or litter pools (Porter et al., 2010). Pools of SOC are: (i) easily decomposable SOC known as active, (ii) recalcitrant SOC such as lignin and cell walls known as slow, and (iii) stable SOC known as passive; whereas the two pools of fresh organic C are easily decomposable surface and soil metabolic litter and the recalcitrant structural litter (Gijsman et al., 2002). The module simulates the SOC development for different crop rotations in a continuous simulation allowing carry-over of soil, water, SON and SOC among seasons (Hoogenboom et al., 2019). Two pools of SOC are initialized for simulating soil C dynamics: (i) total SOC measured at various layers and (ii) stable SOC. Since stable SOC is not easily measurable, it can be determined by the management history of the site or a regression relationship based on soil texture (Porter et al., 2010); the latter was used to initialize the stable SOC. The regression model by Porter et al. (2010) predicts the proportion of silt and clay associated C. This prediction is very similar to the estimate given by the regression model from (Six et al., 2002). The proportion of stable SOC, on-average, ranged from 50% to 70% of total SOC. The active SOC and recalcitrant SOC are then estimated to be 5% and 95% of the remaining total SOC, respectively.

2.2. *Study area and model input data*

A high-quality dataset of ten cropping seasons from 2008 to 2018 at six sites in southwest Germany was utilized for model calibration and evaluation (Fig. 1). This resulted in a 60 site-year dataset, i.e., 2 regions × 3 sites × 10 cropping seasons (Table 1), with detailed soil and crop measurements as well as management records (Weber et al., 2022). The sites were equipped with eddy covariance stations measuring fluxes of carbon, water, and heat in half-hourly resolution.

2.2.1. *Study area*

Research sites were located in two regions, Kraichgau (48°55’42" N, 8°42’5" E, 319 m a.s.l) and Swabian Alb (48°31’40" N, 9°46’15" E, 690 m a.s.l). In each region, there were three research sites that will be referred to as S1 to S3 in Kraichgau and as S4 to S6 in Swabian Alb (Fig. 1). Both regions are located in the Baden-Württemberg state, southwest Germany. Kraichgau is characterized by fertile soils (Stagnic Luvisols) in a basin surrounded by low mountain ranges extending over about 1600 km^2 at an altitude range from 100 to 400 m a.s.l. (Weber et al., 2022). Swabian Alb is located southeast of the Kraichgau and structured in several geographic regions covering over 5700 km^2 from southwest to northeast direction with two main subdivisions, the *Mittlere Kuppenalb* and the *Mittlere Flächenalb*. The *Mittlere Kuppenalb* is a hilly area located in the western part of the region with higher elevation reaching 800–850 m a.s.l. whereas the *Mittlere Flächenalb* is located southeast with lower elevation of about 600–750 m a.s.l. (Fig. 1). The soils are calcareous Rendzina or shallow calcareous clay loam and classified as Calcic Luvisol at S4, Anthrosol at S5, and Rendzic Leptosol at S6 according to the World Reference Base for Soil Resources (IUSS Working Group WRB, 2006). Monthly minimum and maximum temperatures and precipitation averaged from 2006 to 2020 of the six sites are presented in Figure S1. Monthly mean temperature ranged from −1.6 °C to 25.3 °C with mean annual temperature of 9.9 C at Kraichgau sites. The mean annual precipitation was 812 mm at Kraichgau sites with May receiving the highest amount of precipitation of 88 mm on average (Fig. S1). At Swabian Alb sites, monthly mean temperature ranged from −4.2 °C to 23.0 °C with mean annual temperature of 8.0 °C. Summer months received higher amounts of precipitation ranging from 94 to 112 mm with mean annual precipitation of 857 mm (Fig. S1).

The research sites in both regions were established on farmers’ fields and conventional agricultural practices of each cropping system were applied and directly reported by the farmer. Dominant field crops grown in the region such as winter wheat (WW) (*Triticum aestivum* L.), winter oilseed rape (WR) (*Brassica napus* L.), and winter barley (WB) (*Hordeum vulgare* L.) are produced in most farms while cattle farmers also grow silage maize (SM) (*Zea mays* L.), clover and field grasses (Weber et al., 2022). Table 1 shows the cropping system grown at each site and the total cultivated area of each site where research plots were established.

Table 1
Field crops planted in six research sites from 2008 to 2018, three sites in Kraichgau and three sites in Swabian Alb shown in Fig. 1.

Year of harvest	Kraichgau			Swabian Alb		
	S1	S2	S3	S4	S5	S6
	14.9 ha	23.6 ha	15.8 ha	8.7 ha	16.7 ha	13.4 ha
2009	CC†	WW	SM	WW	WR	WW
2010	SM	WR	WW	WR	WW	CC-SM
2011	WW	WW	CC-SM	WW	CC-SM	WW
2012	WR	CC-SM	WW	CC-SB	SM	WB
2013	WW	WW	WR	WR	WB	CC-SM
2014	CC-SM	CC-SM	WW	WW	SP	WW
2015	WW	WW	CC-SM	WW	CC-SM	WB
2016	CC-GM	WR	WW	CC-SB	CC-SM	CC-SM
2017	WW	WW	WW	CC-SM	WB	WW
2018	WR	WW	CC-SM	WW	WR	WB

† CC: Cover crop; SM: silage maize; GM: grain maize; WR: winter oilseed rape; WW: winter wheat; SP: spelt; WB: winter barley; SB: spring barley

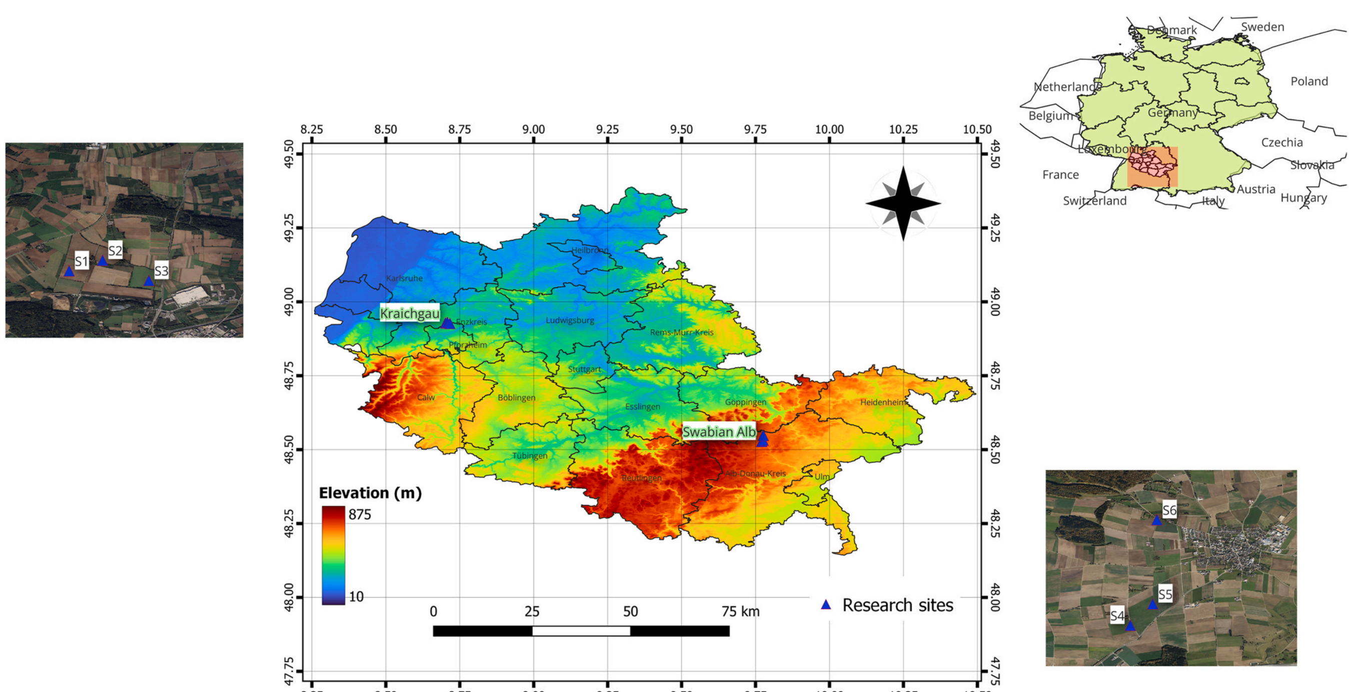

Fig. 1. Locations of six research sites (S1 to S6) in Kraichgau (S1 to S3) and Swabian Alb (S4 to S6) southwest Germany and surrounding districts as the region of interest used in the model application.

Sites at Kraichgau were dominated by WW, WR, and SM, which were also intensively planted at Swabian Alb in addition to WB and spring barley (SB), with the inclusion of cover crops at all sites.

2.2.2. Field management and crop measurement data

Agronomic cultural practices were reported directly by farmers including soil preparation and tillage, organic and inorganic fertilizers application, and pesticides use, freely available from the BonaRes Data Center at https://doi.org/10.20387/bonares-a0qc-46jc (Weber et al., 2022). Field management operations were typical for the intensive conventional farming system in the region described in detail by Weber et al. (2022) (see Section 2.2). At each site, five 4-m^2 plots were randomly selected and marked for crop measurements throughout the growing season. Crop assessments included crop phenology according to BBCH-scale (Meier, 2018), in 4-weeks intervals during winter and biweekly intervals during the main crop growth period in autumn, spring and summer for winter crops and in spring and summer for spring crops. Aboveground biomass (dry matter) at different growth stages was collected in at least three measurements each growing season. Aboveground biomass was measured by destructive sampling of five plants from $0.5 \times 0.5\ m^2$ subplots in all crops and from 1.5 m sections of selected rows in silage maize. At physiological maturity, the total aboveground biomass was separated into straw and grain yields to determine the final grain yield for cereals or seed yield for winter oilseed rape (seeds without pods), except for silage maize where the final yield was the fresh total aboveground biomass.

2.2.3. Weather and soil data

The six research sites were equipped with eddy-covariance stations and data were recorded on CR3000 data loggers (Campbell Scientific Inc., Logan, UT, USA) in half-hourly intervals. Meteorological data included air temperature and humidity at 2-m height, precipitation, global and net radiation, and wind speed. Details of the used instruments and data processing and gap filling are described in Weber et al. (2022). The half-hourly data were aggregated on a daily basis and maximum and minimum air temperature, relative humidity, cumulative solar radiation, cumulative precipitation, and average wind speed were estimated.

Soil matric potential was measured on each site by installing matric-potential sensors (model 253, Campbell Scientific Inc., UK) at 5, 15, 30, 45, and 75 cm soil depth. The obtained soil water holding capacity parameters of field capacity and permanent wilting point were used to set the upper and lower limits, respectively of the soil profile for each site (Table S1). Soil physical and chemical characteristics were measured by analyzing soil samples taken from 0 to 30, 30–60, and 60–90 cm soil layers (Weber et al., 2022). In addition, the soil CO_2 efflux was recorded during some periods in different years 2009, 2010, 2014, and 2015 by a portable infrared gas analyzer (EGM-2 and EGM-4, PP Systems, Amesbury, MA, USA) attached with a soil respiration chamber as well as a soil temperature probe. Bulk density was measured using cylinders in 2017 at the six research sites and organic C content was determined during selected periods by analyzing composited five cores samples taken from 0 to 30, 30–60, and 60–90 soil depths.

2.3. Model calibration and evaluation

Given the weather, soil, and crop management inputs for the cropping system in Table 1 at each research site, the model was set up to run for ten years from 2008 to 2018 utilizing the sequential analysis tool in DSSAT. This tool allows for the analysis of long-term cropping systems that include crop rotation and the associated soil carry-over effect. Accordingly, we implemented the cultural practices of the reported cropping systems in the simulation experiments including the inclusion of CCs. Data from S1, S4, and S6 were used to calibrate the crop coefficients of various crops in the cropping system whereas data from S2, S3, and S5 were used to evaluate the model performance. The model was evaluated against data from all sites for soil CO_2 efflux, soil temperature, and SOC content. For cultivar coefficients, an automatic optimization procedure was implemented in R software and aimed at minimizing the error between observed and predicted data returned by an objective function with multiple target variables including time-series data. A derivative-free grid based search algorithm, Hjkb: Hooke-Jeeves derivative-free minimization algorithm, in the R library *dfoptim* (Varadhan and Borchers, 2018) was used to find the X_{opt} value of each parameter within a specific range in an iterative procedure until the function converged or the maximum number of evaluation was reached (Fig. S2). Parameters' ranges shown in Table S2 were set as indicated by the model default cultivars complemented by coefficients from literature and previous work on the model (Bannayan and Hoogenboom, 2009; Deligios et al., 2013; Attia et al., 2016; Malik and Dechmi, 2019; Attia et al., 2022a). Target variables included crop phenology of anthesis and physiological maturity, time-series aboveground biomass, and final yield.

The model performance was evaluated against observed soil and crop data by computing goodness-of-fit indices such as root mean square error (RMSE), normalized RMSE (nRMSE), and mean percentage error (MPE) utilizing *modeval* function in the R package *sirad* (Bojanowski, 2016). An nRMSE $<$ 10% indicated an 'excellent' prediction, $\geq$ 10% and $<$ 20% indicated a 'good' prediction, $\geq$ 20% but $<$ 30% indicates a 'fair' prediction, and $\geq$ 30% indicates a 'poor' prediction (Bannayan and Hoogenboom, 2009). The MPE indicates the model tendency to over-(positive) or under-(negative) estimate the observed data.

2.4. Design of cover crop inclusion scenarios for model application

A total of 36 improved CC-crop rotation treatments with two or three possible CCs inclusion based on the available cultivation windows between the previous and subsequent main crops were designed and will be referred to as the CC-crop rotation treatments (Fig. S3). The CC-crop rotation treatments were designed to achieve all possible permutations and combinations of non-legume and legume CC inclusion at different positions in the rotation plus crop rotation without CCs as the no-CC control scenario (Table 2). In addition, two additional treatments representing the regular cropping system planted in S1 and S4 were applied to provide the BAU scenario. The full variety of main crops are planted at the BAU, i.e., all winter crops, spring barley and silage maize with the inclusion of at least one CC every four years (Table 1). The cropping systems as reported in Weber et al. (2022) at these sites started actually in 2008 while the simulation study with the CC-crop rotation treatments started in 2006 to allow three cycles of the four-component crop rotations between 2006 and 2020, and therefore, additional main winter crops were planted in 2006 and 2007.

2.4.1. Model application at research sites

All included CCs were planted after the main crops' harvest, which for winter crops WW, WB and WR is in July or August. There were two termination dates depending on the subsequent main crop; (1) for spring crops (SB or SM), the CCs had a long cultivation window and were terminated by in mid-February, (2) for winter crops, the cultivation window was shorter, lasting until mid-October. Planted CCs in the field experiments included a wide range of species such as non-legume broadleaves mustard (*Sinapis alba*), legume green beans (*Phaseolus vulgaris* L), and cereal grasses (*Poaceae* sp.)/mustard mixtures. In the simulation experiments, WR mimics mustard (*Sinapis alba*) and mustard dominated mixtures, green bean (*Phaseolus vulgaris* L.) represents all legume cover crops including beans (*Phaseolus* sp.), peas (*Pisum* sp.), lupines (*Lupinus* sp.), clovers (*Trifolium* sp.) and others as well as legume dominated mixtures, while rye represents all *Poacea* species including e.g., *Lollium perenne* and *Poacea* dominated mixtures.

The CC-crop rotation treatments consisted of 4-year crop rotations implemented in three cycles from 2006 to 2020 with two types based on the available cultivation window: (i) rotation with two possible CCs, i.e., WW-WR-CC-WB-CC-SM and (ii) rotation with three possible CCs, i.e.,

Table 2
Cover crop (CC)-crop rotation treatments of non-legume (N) and legume (L) species inclusion in two 4-year crop rotations (i) WW-WR-WB-SM with 2 possible CCs and (ii) WR-WB-WW-SB with 3 possible CCs.

Scenario	Cover crop (CC)-Crop rotation treatments	Number of non–legume† (N) CC	Number of legume (L) CC	Rotation type	
				4–year rotation with 2 possible CCs	4–year rotation with 3 possible CCs
No-CC	N0-L0	0	0	WW‡–WR–WB–SM	WR–WB–WW–SB
Simple	N1-L0	1	0	WW–WR–NCC–WB–SM, WW–WR–WB–NCC–SM	WR–NCC–WB–WW–SB, WR–WB–NCC–WW–SB, WR–WB–WW–NCC–SB
Simple	N2-L0	2	0	WW–WR–NCC–WB–NCC–SM	WR–NCC–WB–NCC–WW–SB, WR–NCC–WB–WW–NCC–SB, WR–WB–NCC–WW–NCC–SB
Ambitious	N3-L0	3	0	–	WR–NCC–WB–NCC–WW–NCC–SB
Simple	N0-L1	0	1	WW–WR–LCC–WB–SM, WW–WR–WB–LCC–SM	WR–LCC–WB–WW–SB, WR–WB–LCC–WW–SB, WR–WB–WW–LCC–SB
Simple	N0-L2	0	2	WW–WR–LCC–WB–LCC–SM	WR–LCC–WB–LCC–WW–SB, WR–LCC–WB–WW–LCC–SB, WR–WB–LCC–WW–LCC–SB
Ambitious	N0-L3	0	3	–	WR–LCC–WB–LCC–WW–LCC–SB
Simple	N1-L1	1	1	WW–WR–NCC–WB–LCC–SM, WW–WR–LCC–WB–NCC–SM	WR–NCC–WB–LCC–WW–SB, WR–NCC–WB–WW–LCC–SB, WR–WB–NCC–WW–LCC–SB, WR–LCC–WB–NCC–WW–SB, WR–LCC–WB–WW–NCC–SB, WR–WB–LCC–WW–NCC–SB
Ambitious	N2-L1	2	1	–	WR–LCC–WB–NCC–WW–NCC–SB, WR–NCC–WB–LCC–WW–NCC–SB, WR–NCC–WB–NCC–WW–LCC–SB
Ambitious	N1-L2	1	2	–	WR–NCC–WB–LCC–WW–LCC–SB, WR–LCC–WB–NCC–WW–LCC–SB, WR–LCC–WB–LCC–WW–NCC–SB
Business-as-usual	The cropping systems of S1 and S4 shown in Table 1.				

† Non-legume CC were rye (Secale cereal L.) and oilseed rape (Brassica napus L.) and legume CC is green beans (Phaseolus vulgaris L.).
‡ WW: winter wheat; WR: winter oilseed rape; WB: winter barley; SM: silage maize; SB: spring barley.

WR-CC-WB-CC-WW-CC-SB. These 36 CC-crop rotation treatments provided 10 CC inclusion treatments based on the type of CC, i.e., non-legume (N) or legume (L), and the frequency of planted CCs in the 4-year rotation to range from none (no-CC) to three CCs (Table 2). Therefore, for instance, the N2-L1 CC treatment refers to the CC-crop rotation treatments that apply three CCs, two non-legume (N2) and one legume (L1). The 10 CC inclusion treatments were then grouped for comparison with the BAU scenario as follows: (i) no-CC scenario, (ii) simple scenario that included all rotations with one or two CCs, i.e., N1-L0, N2-L0, N0-L1, N0-L2, and N1-L1, and (iii) ambitious scenario that included all rotations with three CC, i.e., N3-L0, N0-L3, N2-L1, and N1-L2. In the BAU scenario, 84% of CCs' above ground biomass was incorporated into the soil and 16% were removed for livestock feed to mimic the field situation practiced by farmers as reported in Seitz et al. (2022). In comparison in the simple and ambitious scenarios 100% of CCs' biomass were incorporated into the soil. Initial soil conditions and crop management that included organic and inorganic fertilizers application, tillage operations, among others remained the same for all treatments.

The model was then executed for the 38 treatments from 2006 to 2020 at the research sites S1 to S6 resulting in 3192 simulations using the measured soil and weather data previously used in the model calibration and evaluation at these sites. To determine differences in main crop yields and water productivity as well as key soil N and C variables between site and scenarios, the analysis of variance (ANOVA) was performed for completey randomized design replicated by years as a random source of error in R software. Treatment means were averaged across years and were separated by the protected least significant difference (LSD) at 5% level. Linear orthogonal contrast was performed to test the significance of BAU vs. no-CC, no-CC vs. non-legume CC, no-CC vs. legume CC, and non-legume CC vs. legume CC, i.e., CC-crop rotation treatments that included non-legume only CCs vs. CC-crop rotation treatments that included legume only CCs. The annual change rate of SOC was estimated by computing the slope of SOC over time, i.e., the slope of linear regression over time, for each treatment in Mg C ha^{-1} yr^{-1}. These change rates for the different rotations, i.e., BAU, simple and ambitious, were then contrasted against the no-CC scenario to derive the relative difference in SOC change rate considering the soil profile $\approx$ 100 cm soil depth. Similarly, comparison among scenarios change rate or annual mean of soil variables and crop yield were analyzed and graphed.

2.4.2. Model application at spatio-temporal scale

Spatial application of the model was performed to test and exercise the developed decision support tool at spatio-temporal scale for selected districts covering the two regions of the research sites from 2006 to 2020 (Fig. 1). A point shapefile layer was created to generate 570 points at a 5 km by 5 km grid over the region of interest in the Baden-Württemberg state, southwest Germany. The model was run at each grid point for all the 38 treatments applied at the research sites and shown in Table 2 from 2006 to 2020 resulting in 303,240 simulations. We applied the BAU practices adopted from the research sites to the regional scale in order to compare the proposed improved rotation initiated from the same cropping system as the BAU. Nonetheless, other cropping systems are present in the region. A script in R software was developed to fetch and format gridded weather data from its source at each grid point utilizing *ROracle* package (Mukhin et al., 2021). Gridded weather data were obtained from the German Weather Service (DWD; in German: *Deutscher Wetterdienst*) which provides daily meteorological data based on approximately 2000 weather stations over Germany and interpolated

Table 3
Goodness-of-fit statistics of calibration and evaluation of the DSSAT model simulation of various crops' anthesis and physiological maturity dates, biomass yield through the growing season and cover crop biomass, and grain/seed yield and model evaluation of soil variables in southwest Germany.

Crop	Variables	Calibration					Evaluation				
		n	RMSE	nRMSE	MPE	Corresponding figure	n	RMSE	nRMSE	MPE	Corresponding figure
Winter wheat											
	Anthesis	13	6.6 d	2.7%	1.9%	Fig. 2a	13	14.4 d	6.3%	5.6%	Fig. 2b
	Maturity	13	8.2 d	2.8%	0.6%	Fig. 2a	13	8.7 d	3.1%	1.9%	Fig. 2b
	Biomass	35	3297 kg ha^{-1}	16.4%	9.4%	Fig. S5	36	3488 kg ha^{-1}	15.6%	18.7%	Fig. S6
	Grain yield	13	1273 kg ha^{-1}	14.5%	-1.09%	Fig. 2a	13	1401 kg ha^{-1}	17.1%	12.8%	Fig. 2b
Winter oilseed rape											
	Anthesis	4	16.3 d	6.6%	0.05%	Fig. 2a	5	14.1 d	5.6%	0.19%	Fig. 2b
	Maturity	4	10.7 d	3.3%	-1.3%	Fig. 2a	5	9.1 d	2.9%	0.29%	Fig. 2b
	Biomass	12	4225 kg ha^{-1}	35.6%	14.6%	Fig. S7	14	5966 kg ha^{-1}	29.4%	63.8%	Fig. S7
	Seed yield	4	687 kg ha^{-1}	21.2%	-6.7%	Fig. 2a	5	567 kg ha^{-1}	13.4%	7.2%	Fig. 2b
Winter barley											
	Anthesis	3	10.4 d	4.3%	3.8%	Fig. 2a	2	10.6 d	4.3%	3.08%	Fig. 2b
	Maturity	3	8.4 d	2.9%	1.04%	Fig. 2a	2	4.2 d	1.5%	1.03%	Fig. 2b
	Biomass	9	4187 kg ha^{-1}	24.3%	53.4%	Fig. S8	6	3608 kg ha^{-1}	29.3%	-1.7%	Fig. S8
	Grain yield	3	1091 kg ha^{-1}	13.8%	9.1%	Fig. 2a	2	1125 kg ha^{-1}	12.1%	-12.0%	Fig. 2b
Spring barley											
	Anthesis	2	4.0 d	4.1%	0.08%	Fig. 2a	–				
	Maturity	2	5.7 d	4.1%	-2.4%	Fig. 2a	–				
	Biomass	6	1567 kg ha^{-1}	10.7%	32.9%	Fig. S8	–				
	Grain yield	2	829 kg ha^{-1}	11.4%	4.1%	Fig. 2a	–				
Silage maize											
	Anthesis	6	10.4 d	10.8%	0.3%	Fig. 2a	9	16.6 d	17.2%	-4.8%	Fig. 2b
	Maturity	6	9.7 d	6.4%	4.5%	Fig. 2a	9	13.8 d	9.5%	2.4%	Fig. 2b
	Biomass	18	2997 kg ha^{-1}	9.9%	20.5%	Fig. S9	26	4110 kg ha^{-1}	12.9%	45.1%	Fig. S10
Cover crop											
	Biomass	-					13	866 kg ha^{-1}	28.2%	-14.1%	Fig. 2b
Soil variables											
	Soil respiration	–					412	14.0 kg CO_2 ha^{-1} d^{-1}	26.7%	58.6%	Fig. 3
	Soil temperature	–					354	3.6 C	12.8%	16.1%	Fig. 4
	Soil organic C	–					76	2.4 g kg^{-1}	16.6%	4.8%	Fig. 5

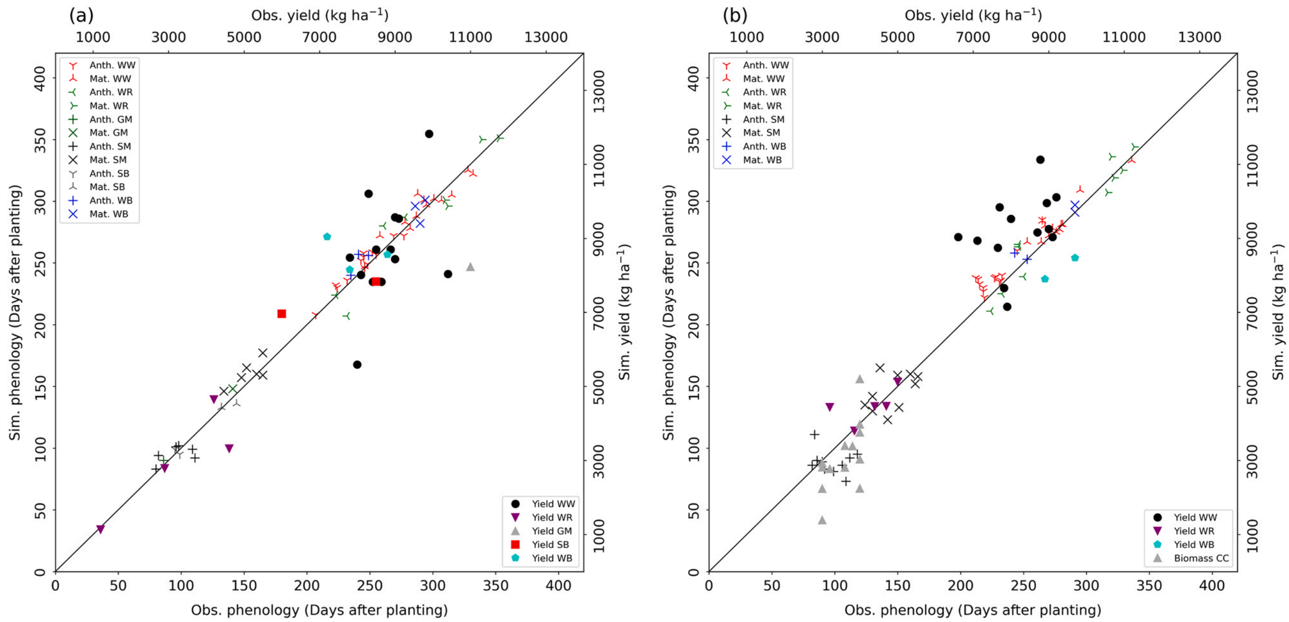

Fig. 2. (a) Model calibration and (b) model evaluation: comparison of observed and DSSAT simulated crops anthesis (Anth.) and physiological maturity (Mat.) and grain/seed yield of winter wheat (WW), winter oilseed rape (WR), winter barley (WB), silage maize (SM), spring barley (SB), and grain maize (GM).

on a raster grid of 1 × 1 km resolution available at https://opendata.dwd.de/climate_environment/CDC/grids_germany/daily/regnie/. Obtained data included minimum and maximum temperature, precipitation, solar radiation, wind speed, and relative humidity. For gridded soil data, WISE soil database was used (Gijsman et al., 2007; Batjes, 2009). This database was developed by the International Soil Reference and Information Centre (ISRIC) SoilGrids Wageningen, Netherlands as part of the World Inventory of Soil Emission Potentials and aggregated from 1 km resolution to 10 km (5-min) resolution for a global high-resolution soil profile database for DSSAT (Han et al., 2019) available at https://doi.org/10.7910/DVN/1PEEY0. Initial conditions and crop management including crop specific planting density, organic and inorganic fertilizer application and tillage operations were adopted from the management practices at the research sites and were fixed across simulations. The simulations were run by an R-based script which automated the model application for several treatments with post-processing of output variables to calculate treatment means and slope of soil organic N and SOC, and ΔYield% at each grid point (Fig. S4). Percent of yield change was calculated as follows: (Yield $_{\text{CC treatment}}$ − Yield $_{\text{no-CC treatment}}$)/ Yield $_{\text{no-CC treatment}}$ × 100. Treatments were then grouped in three scenarios BAU, simple, and ambitious as described in Section 2.4.1. Results were interpolated across the region of interest at 0.5 km resolution using the kriging interpolation method in QGIS (QGIS Core Team, 2016) which is a recommended interpolation method to extend the value of the variable over a continuous spatial extend (Abtew et al., 1993; Attia et al., 2022b). The resulting raster layers for each variable were masked by a vector layer of cropland over the selected districts.

3. Results

3.1. Model calibration and evaluation in simulating crop variables

Table 3 shows the goodness-of-fit statistics of model calibration and evaluation for crop and soil variables across six research sites. Crop phenological variables of anthesis and physiological maturity for WW showed good agreement with predicted data as indicated by nRMSE and MPE < 10% in the model calibration (Fig. 2a) and evaluation (Fig. 2b). The RMSE was 6.6 and 14.4 for anthesis and 8.2 and 8.7 d for physiological maturity in the model calibration and evaluation, respectively. The time series biomass yield and final grain yield were well simulated as indicated by nRMSE and MPE < 20% in the model calibration and evaluation (Figs. S5 and S6). For WR, simulation of crop phenology showed reasonable agreement with simulation with nRMSE < 10% and MPE close to 0 (Fig. 2). The RMSE was about 16 d in anthesis and 10 d in physiological maturity in both calibration and evaluation (Table 3). The biomass yield had high nRMSE > 30% during calibration at S1 and S4 indicating poor prediction even though the overall observed plant growth pattern matched well the simulation which resulted in MPE < 15% (Table 3). The MPE, however, indicated overestimation of time-series aboveground biomass in model evaluation mainly during 2008–2009 season at S5 (Fig. S7). Nevertheless, the nRMSE was about 30% and the model captured the growth dynamics throughout the growing seasons (Fig. S7). Results of model performance of predicting seed yield of WR was much better than biomass yield with nRMSE ranging from 22% to 13% and small MPE between −6.7% and 7.2% during calibration and evaluation, respectively (Table 3, Fig. 2).

For WB, results of model simulation of crop phenology was closely similar to WW with excellent agreement between simulated and observed phenology as indicated by nRMSE < 10% and MPE close to 0 at calibration and evaluation sites (Fig. 2). The time-series aboveground biomass was reasonably simulated but with some overestimation as indicated by MPE of 53.4% during model calibration, nonetheless the model showed better performance in the evaluation with MPE of only −1.7% (Fig. S8). The grain yield was well simulated with nRMSE < 15% and MPE ranging from ± 12% in the calibration and evaluation processes (Fig. 2). For SB, there were only two seasons of data at S4 which were used in the model calibration. Crop phenology, time-series aboveground biomass, and grain yield were well simulated with nRMSE < 5%, 10.7%, and 11.4%, respectively (Fig. 2 and S8). The model also provided reasonable simulation of SM phenology and time-series aboveground biomass during calibration and evaluation with averagely RMSE 12.6 d for phenology and 3.5 Mg ha^{-1} for aboveground biomass (Table 3, Figs. S9 and S10). In addition, the model was evaluated against CC biomass and indicated good agreement between observed and simulated values with RMSE of 866 kg ha^{-1} and a slight underestimation by 14% (Table 3, Fig. 2). Nonetheless, the simulated CCs provided biomass amounts closely similar to the various CC species planted in the field, averaging around 3 Mg ha^{-1} depending on several factors such as the planted species and the length of the growing period.

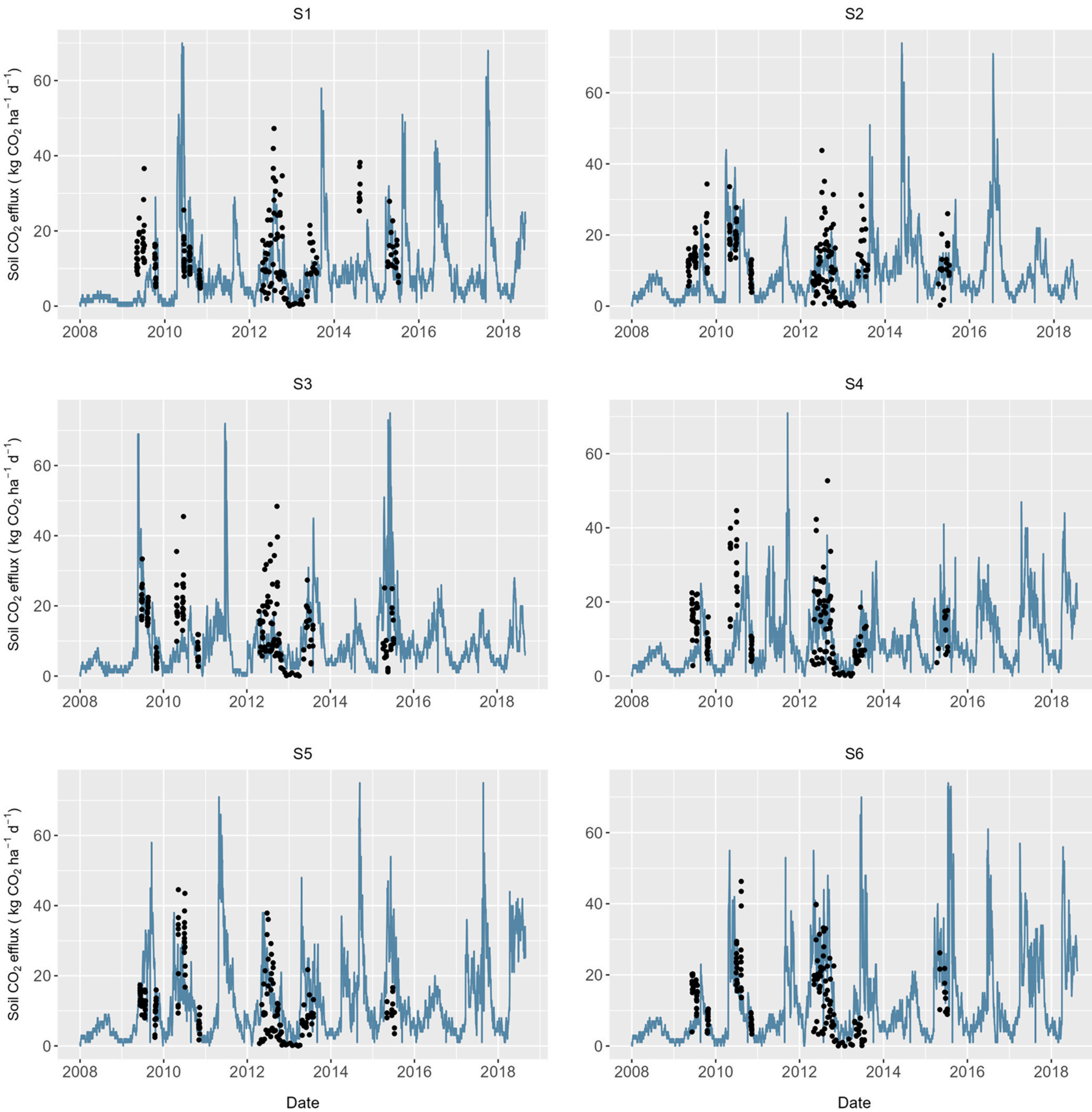

Fig. 3. Comparison between observed (points) and DSSAT simulated (lines) soil CO_2 efflux at six research sites in southwest Germany.

3.2. *Model evaluation in simulating soil variables*

The model was evaluated for simulating the soil CO_2 efflux, temperature, and SOC content (Table 3). For soil CO_2 efflux, the model reasonably well simulated this variable with nRMSE < 30% but with some overestimation as indicated by the MPE particularly at S3 in 2015–2016 season when the model simulated soil respiration of 75 kg CO_2 ha^{-1} d^{-1} whereas the observations were around 25 kg CO_2 ha^{-1} d^{-1} and at S5 in the same season when the simulated soil respiration was about 50 kg CO_2 ha^{-1} d^{-1}, whereas the observations were about 10 kg CO_2 ha^{-1} d^{-1} (Fig. 3). Nevertheless, the overall magnitude and temporal pattern of observed data matched well the simulated data with RMSE of 14 kg CO_2 ha^{-1} d^{-1} across seasons and sites (Table 3). For soil temperature, the model had good performance with both nRMSE and MPE < 20% indicating good agreement with observed data which is clearly illustrated in Fig. 4 at all sites. The model captured the variations of soil temperature very well with varying 20 °C degree temperature or more between summer and winter seasons at the six sites (Fig. 4).

The SOC in the 30 cm soil layer showed varying trends at different sites with overall RMSE of 2.4 g kg^{-1} and nRMSE of < 20% and MPE of only 4.8% (Table 3, Fig. 5). At S1 and S3, the soil organic C decreased by about 10% at the end of the cropping sequence in 2018 compared with 2008 which was captured by the model. At S2, S4, and S6, there was a more pronounced increase in SOC at the end of the cropping system in 2018 which was also well captured by the model (Fig. 5). Among sites, the SOC was higher at S5 and S6 compared with others ranging about 20 g kg^{-1} which might have contributed to higher soil respiration at these sites at the end of the cropping sequence (Fig. 5).

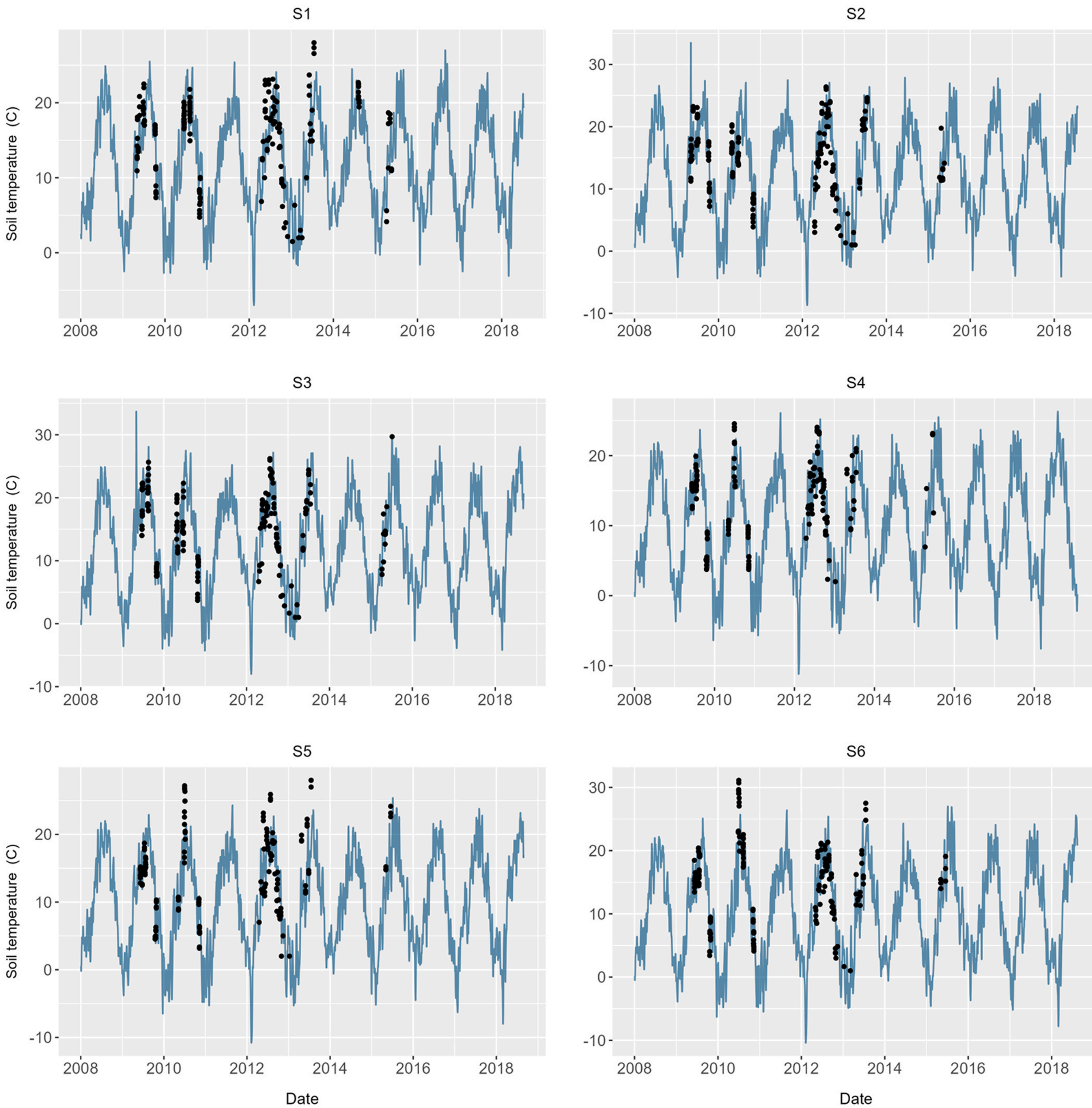

Fig. 4. Comparison between observed (points) and DSSAT simulated (lines) soil temperature at 15 cm soil depth at six research sites in southwest Germany.

3.3. Simulation at the research sites

3.3.1. Impact of cover crop inclusion on soil organic nitrogen and carbon

Table 4 shows the differences among sites and scenarios on soil variables and crop yield. Significant differences among sites were observed for soil organic N with the greatest content at S5 and S6, agreeing with the SOC content whereas the lowest value of SOC was observed at S4 (Table 4). In contrast, the highest net N mineralization and N leaching were recorded at S1 and S4, with S2 and S3 in-between (Table 4). Differences among sites in soil N and C related variables must be attributed to differences in site-specific soil physical and chemical properties (Table S1).

Soil related variables were significantly impacted by the CC-crop rotation treatments averaged across sites and years (Table 4). Significant increase in soil organic N and net N mineralization was observed by the CC-crop rotation treatments encompassing the simple and ambitious scenarios compared with BAU and no-CC scenarios. Simple and ambitious scenarios vs. BAU scenarios increased the annual soil organic N accumulation rate by 14.7% and the mean net N mineralization by 25% (Table 4), suggesting beneficial rotation and cover cropping effects on soil chemical properties. Relative to no-CC, simple and ambitious scenarios had significantly less leached N across years (Table 4), indicating reduced N losses by CC inclusion in the rotation. Further benefits of CCs were attributed to CC species, according the orthogonal linear contrasts, the legume CCs produced significantly higher 17% annual soil organic N rate and 37% net N mineralization compared with non-legume CCs, whereas the non-legume CCs helped in reducing N leaching (Table 4). The SOC followed a similar trend

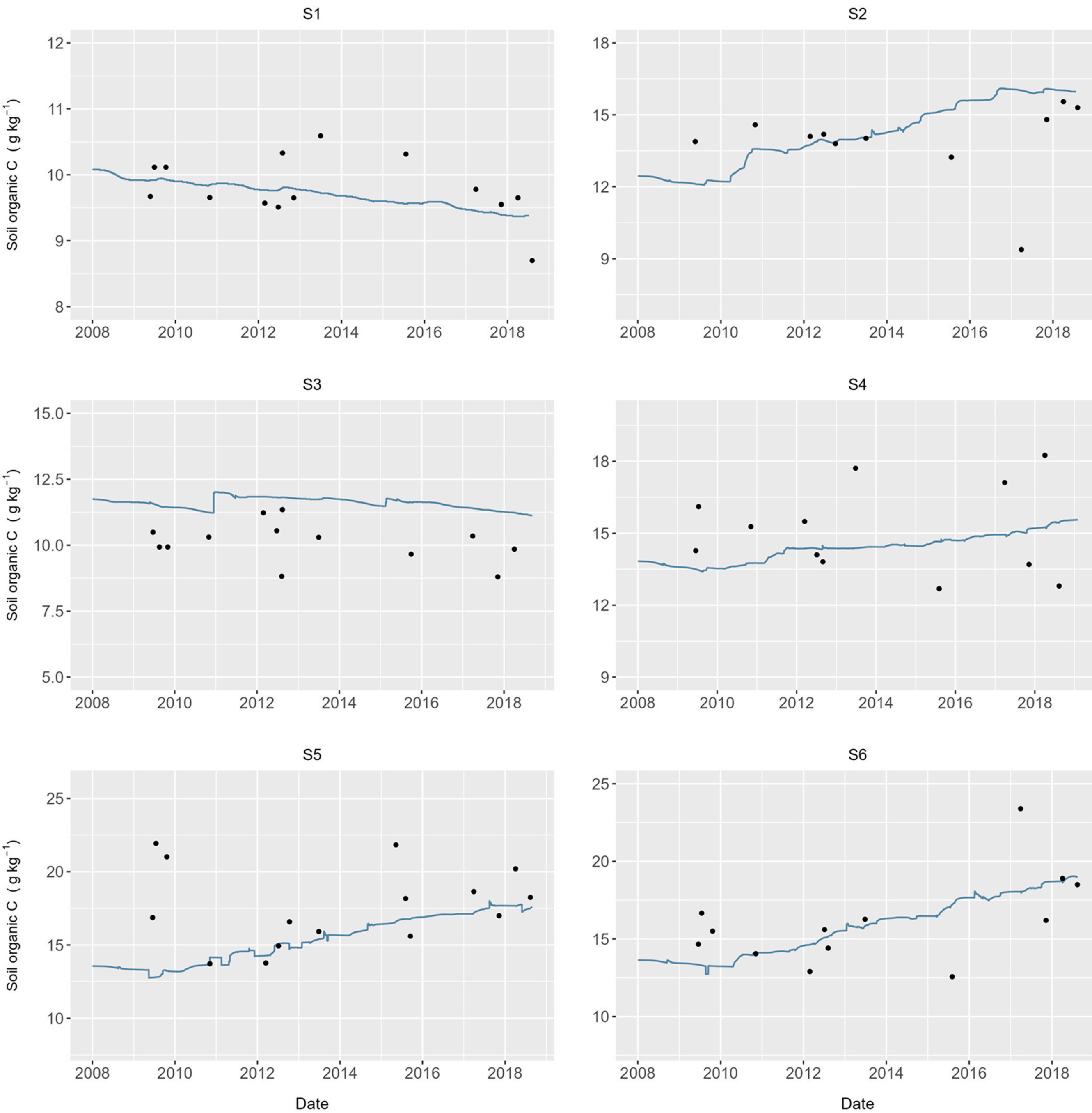

Fig. 5. Comparison between observed (points) and DSSAT simulated (lines) soil organic C in the 0–30 cm soil depth at six research sites in southwest Germany.

observed for soil organic N with the highest SOC content realized by the simple and ambitious scenarios (Table 4). The difference in annual rate of SOC change by CCs scenarios compared with BAU and no-CC were about 0.16±0.05 Mg C ha^{-1} yr^{-1} and 0.12±0.06 Mg C ha^{-1} yr^{-1}, respectively (Table 4). By looking at the contrast of no-CC vs. non-legume CC, the SOC difference was insignificant, indicating that the SOC increase was especially attributed to legume CCs.

3.3.2. *Crop yield and water productivity*

Site differences in crop yield indicated advantage for S6 in grain/seed yield of WW, WR, and SB whereas S4 had higher WB grain yield and SM biomass yield (Table 4). Significant yield differences among sites ranged from 2 to 3 Mg ha^{-1} for WW, WR, and WB and > 3 Mg ha^{-1} for SM and SB (Table 4). The impact of CC-crop rotation treatments on main crop yield and water productivity was positively significant for most crops compared with the BAU scenario (Table 4 and Fig. 6). The ambitious scenario produced 2.3 Mg ha^{-1} and 0.8 Mg ha^{-1} higher WW grain yield compared with BAU and no-CC scenarios, respectively. There were no-significant differences among scenarios for CC biomass production with legume CCs producing about 0.5 Mg ha^{-1} higher biomass than non-legume CCs (Table 4). For WR seed yield, the no-CC and simple scenarios had the highest yield followed by the ambitious scenario and the lowest yield by the BAU. Contrast analysis indicated no benefits of CCs inclusion on WR seed yield compared with no-CC, suggesting that higher WR seed yield in the CC-crop rotation treatments vs. BAU is more likely due to rotational effects, i.e., different pre-crops and respective soil water and N stocks rather than actual CCs effects. The greatest WB grain yield was produced by the ambitious scenario but without being significantly

Table 4
Soil variables of soil organic N (SON), net N mineralization, N leaching, and soil organic C (SOC) and crop yield of winter wheat (WW), cover crop (CC) biomass, winter oilseed rape (WR), winter barley (WB), silage maize (SM) biomass, and spring barley (SB) averaged over 10 cropping seasons from 2008 to 2018 as affected by various CC inclusion scenarios described in Table 2 at six research sites in southwest Germany.

Site	Soil variables				Crop yield					
	SON stock change rate†	Net N mineral-ization	N leached	SOC stock change rate	WW	CC biomass	WR	WB	SM	SB
	—kg N ha^{-1} yr^{-1}—	—kg N ha^{-1}—		—Mg C ha^{-1} yr^{-1}—	—kg ha^{-1}—					
S1	94.02 B‡	44 A	12.0 A	1.6452 BC	7974 D	3239 A	2352 D	7719 CD	18544 B	5962 E
S2	95.31 B	43 A	9.8 B	1.6361 BC	8571 B	3117 AB	2736 C	6811 E	16697 C	6607 D
S3	96.15 B	44 A	7.7 CD	1.7606 B	9489 A	2877 BC	3659 B	860 BC	18310 BC	8590 B
S4	98.16 B	44 A	11.6 A	1.6112 C	8019 D	2146 E	2821 C	8720 A	20682 A	4353 F
S5	117.04 A	37 B	8.2 C	2.0859 A	8579 C	2728 CD	2187 D	8082 B	17530 BC	7980 C
S6	112.95 A	37 B	6.7 D	2.0036 A	9622 A	2516 D	4435 A	7512 D	17560 BC	9939 A
Scenario										
BAU	89.17 B	35 C	8.4 C	1.6283 B	6952 D	2361	2285 C	7879 AB	20125 A	8551 A
No-CC	97.91 AB	35 C	11.2 A	1.6738 AB	8477 C	-	3288 A	7435 B	15242 C	6347 D
Simple§	104.12 A	41 B	9.6 B	1.8218 A	8798 B	2751	3153 A	7707 B	18204 B	7060 C
Ambitious	100.63 A	46 A	8.3 C	1.7583 AB	9258 A	2852	2908 B	8105 A	-	7641 B
Contrasts		Orthognal linear contrast								
BAU vs. no-CC	–8.74 ns¶	0.38 ns	-2.7 *	-0.0455 ns	-1525 ***	-	-1002 **	443 ns	4883 **	2203 *
No-CC vs. non-legume CC	3.27 ns	-0.82 ns	2.9 *	-0.0094 ns	-199 ns	-	240 ns	188 ns	-831 ns	-514 ns
No-CC vs. legume CC	–12.77 *	-14 ***	1.0 ns	-0.2309 *	-713 *	-	184 ns	-948 *	-4473 **	-1195 *
Non-legume CC vs. legume CC	-16.05 ***	-14 ***	-1.8 *	-0.2271 **	-514 *	-486 **	-55 ns	-1136 ***	-3642 **	-681 *

† Annual change rates of SON and SOC were estimated by computing the slope of SON and SOC over time, respectively.

‡ Least significant difference at the 95% confidence level; means of site or scenario followed by the same letter are not significantly different. Columns that do not contain letters indicate no significance difference between treatments.

§ Simple scenarios are those having one or two cover crops N1-L0, N2-L0, N0-L1, N0-L2, and N1-L1; ambitious scenarios are those having three cover crops N3-L0, N0-L3, N2-L1, and N1-L2.

¶ ns, not significant;

***$p < 0.001$;

**$p < 0.01$;

*$p < 0.05$.

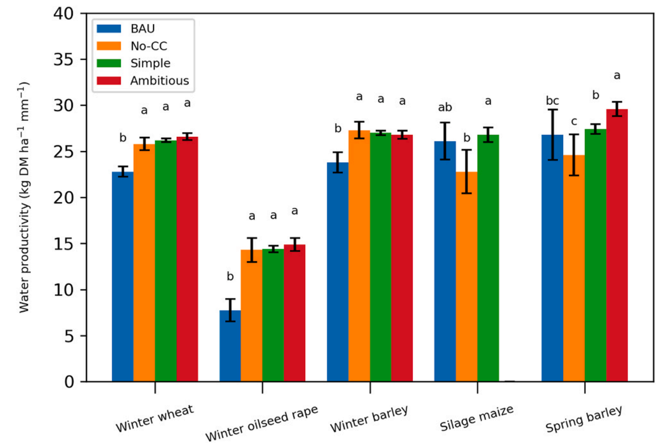

Fig. 6. Water productivity of various field crops in response to crop rotation with and without CCs and BAU scenarios. Error bars represent the standard error of the mean. Scenarios within each crop with the same letter are not significantly different according to the LSD test at 0.05 significance level.

different from the BAU scenario which was at par with no-CC and simple scenarios. Further, the BAU scenario was superior to others for SM biomass yield and SB grain yield. Within the CC-crop rotation treatments, inclusion of only non-legume CCs did not benefit the main crop yield whereas significant yield increase was observed by legume CCs for the grain yields of WW, WB, and SB, and the biomass yield of SM (Table 4).

Fig. 6 illustrates the water productivity defined as the produced aboveground biomass dry matter per hectare per mm of rain for main crops in response to BAU and CC inclusion scenarios. The simple and ambitious scenarios significantly increased the water productivity of WW by 8.6% compared with BAU and no-CC scenarios. Advantage of CC-crop rotation treatments was also observed for WR and WB as the BAU scenario achieved 47% WR and 12% WB less water productivity compared with others (Fig. 6). The BAU scenarios, however, had similar water productivity to others for WB and higher water productivity than no-CC for SM. For SB, there was no significant difference between BAU and other scenarios except the ambitious scenario which increased the water productivity by 19% compared with BAU and no-CC scenarios. Although the grain yield of SB was significantly higher in the BAU scenario than no-CC or simple scenarios (Table 4), they had similar water productivity (Fig. 6), indicating positive rotation and CCs effects on

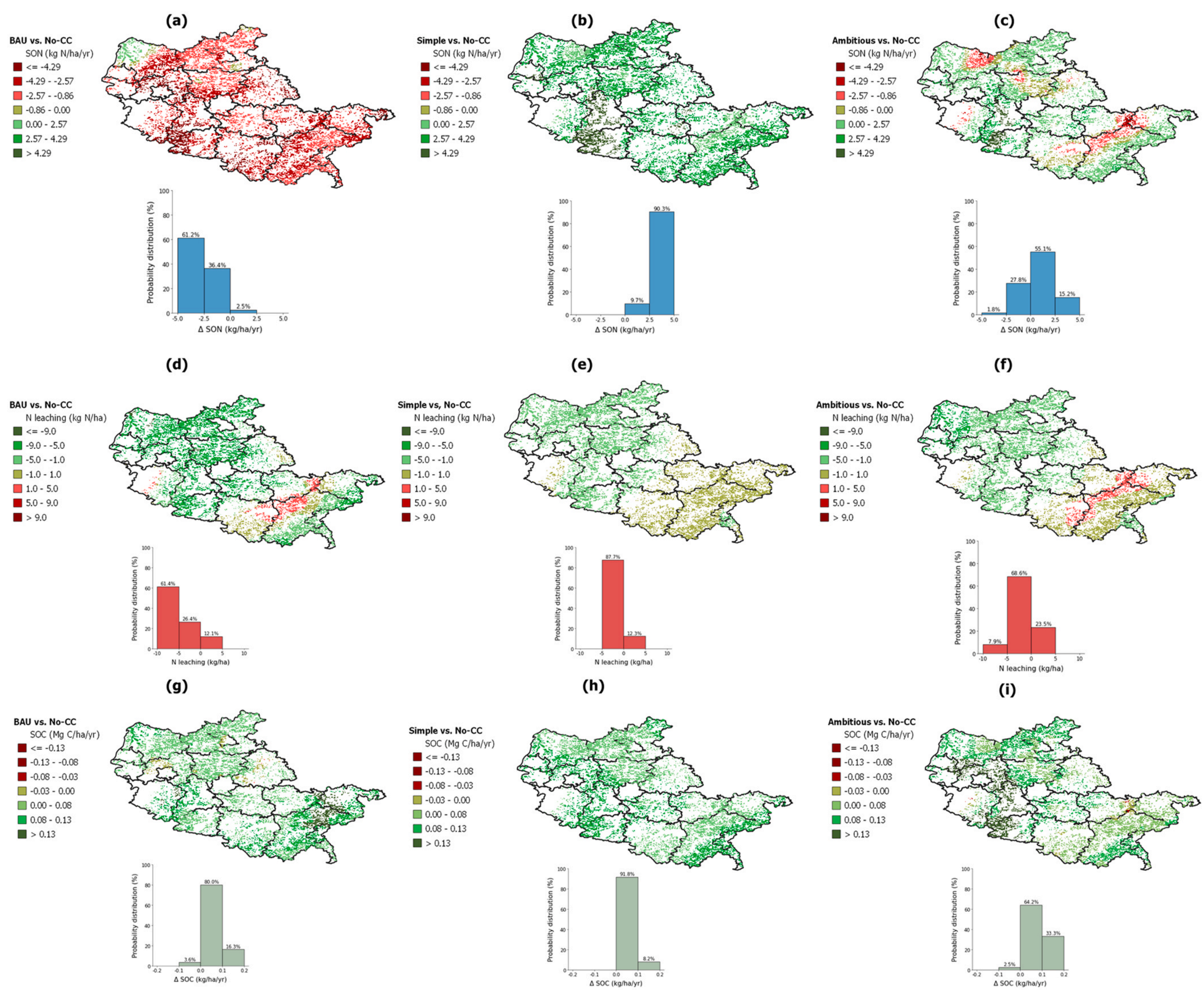

Fig. 7. Contrasts of BAU vs. no-CC, simple vs. no-CC, ambitious vs. no-CC effects on annual change rate of soil organic N (SON), mean N leaching, and annual change rate of SOC.

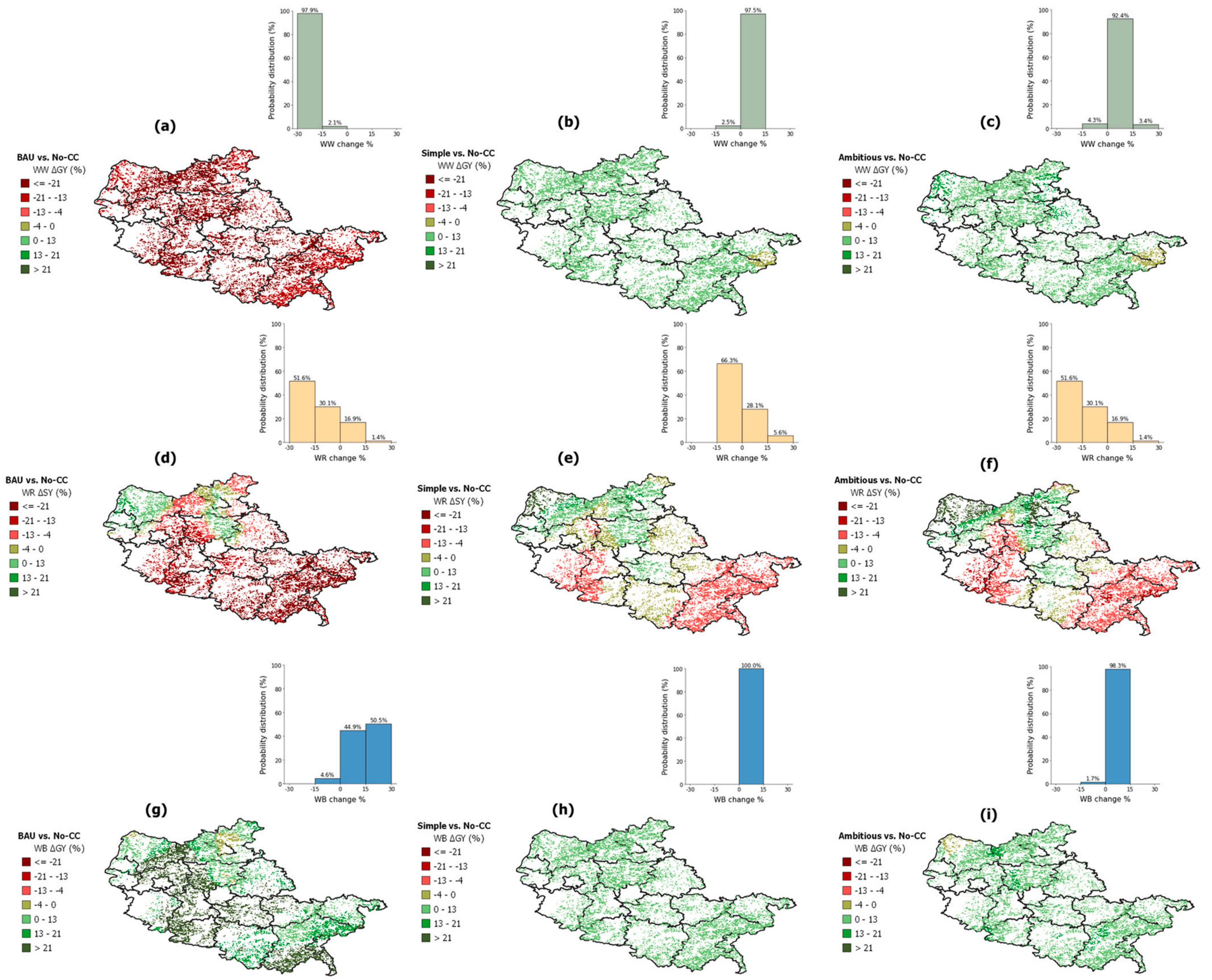

Fig. 8. Percent of grain yield change (ΔGY) of winter wheat (WW), seed yield change (ΔSY) of winter oilseed rape (WR), and grain yield change of winter barley (WB) in response to contrasts of BAU vs. no-CC, simple vs. no-CC, and ambitious vs. no-CC.

biomass yield. These results indicate that inclusion of CCs did not reduce, but actually increased, the water productivity of main crops in the rotation.

3.4. *Simulation at spatial scale*

3.4.1. *Spatial pattern of cover crop effects on soil organic N and C*

Fig. 7 depicts the relative differences of soil organic N and C related variables on spatial scale in the region of interest around Kraichgau and Swabian Alb shown in Fig. 1 in response to BAU, simple, and ambitious scenarios relative to no-CC scenario. The BAU scenario had the lowest annual soil organic N accumulation rate compared to others (Fig. 7a), whereas the simple and ambitious scenarios on-average increased the annual soil organic N by 9.7% and 2.3% compared with the BAU and no-CC scenarios, respectively (Fig. 7b, c). Less concentration of soil organic N within each scenario was mainly observed in the high elevation area named the *Mittlere Kuppenalb* in the southeastern part of the Swabian Alb characterized with mountains forming a hilly plateau at 800–850 m a.s.l. (Fig. 1). Higher mean N leaching was observed in this area by BAU vs. no-CC of about 5 kg N ha^{-1}, indicating N losses vulnerability (Fig. 7d). The inclusion of CCs vs. no-CC reduced N leaching by 5 kg N ha^{-1} in approximately 87% of the total area particularly in the middle and northwest of the region of interest (Fig. 7e, f). These results suggest beneficial crop rotation and CCs effects on increasing the soil organic N content and reducing the susceptibility of N leaching which was more pronounced in areas vulnerable to N losses.

The difference in the rate of SOC change between the BAU vs. no-CC was mostly very small, i.e., 0–0.01 Mg C ha^{-1} yr^{-1} in 80% of the region of interest (Fig. 7g). Annual SOC change rates were higher in the simple scenario than BAU as indicated by simple vs. no-CC values to range from 0.05 to 0.1 Mg C ha^{-1} yr^{-1} in 91% of the region of interest up to 0.13 Mg C ha^{-1} yr^{-1} in middle-western zone about 8% of the total area (Fig. 7h). Ambitious showed the strongest difference in SOC change rates compared to no-CC, which was always > 0.05 Mg C ha^{-1} yr^{-1} higher, in 97% of the total area up to 0.15 Mg C ha^{-1} yr^{-1} in the western areas, except in the high elevation area southeast near the Swabian Alb where the difference in SOC change rates ranged from −0.02–0.03 Mg C ha^{-1} yr^{-1} (Fig. 7i). The mean difference in SOC change rates were 0.077 ±0.013 Mg C ha^{-1} yr^{-1} and 0.083±0.042 Mg C ha^{-1} yr^{-1} for simple vs. no-CC and ambitious vs. no-CC, respectively. Results of SOC change rate indicate that diversification of crop rotations and inclusion of CCs promotes SOC sequestration or loss mitigation.

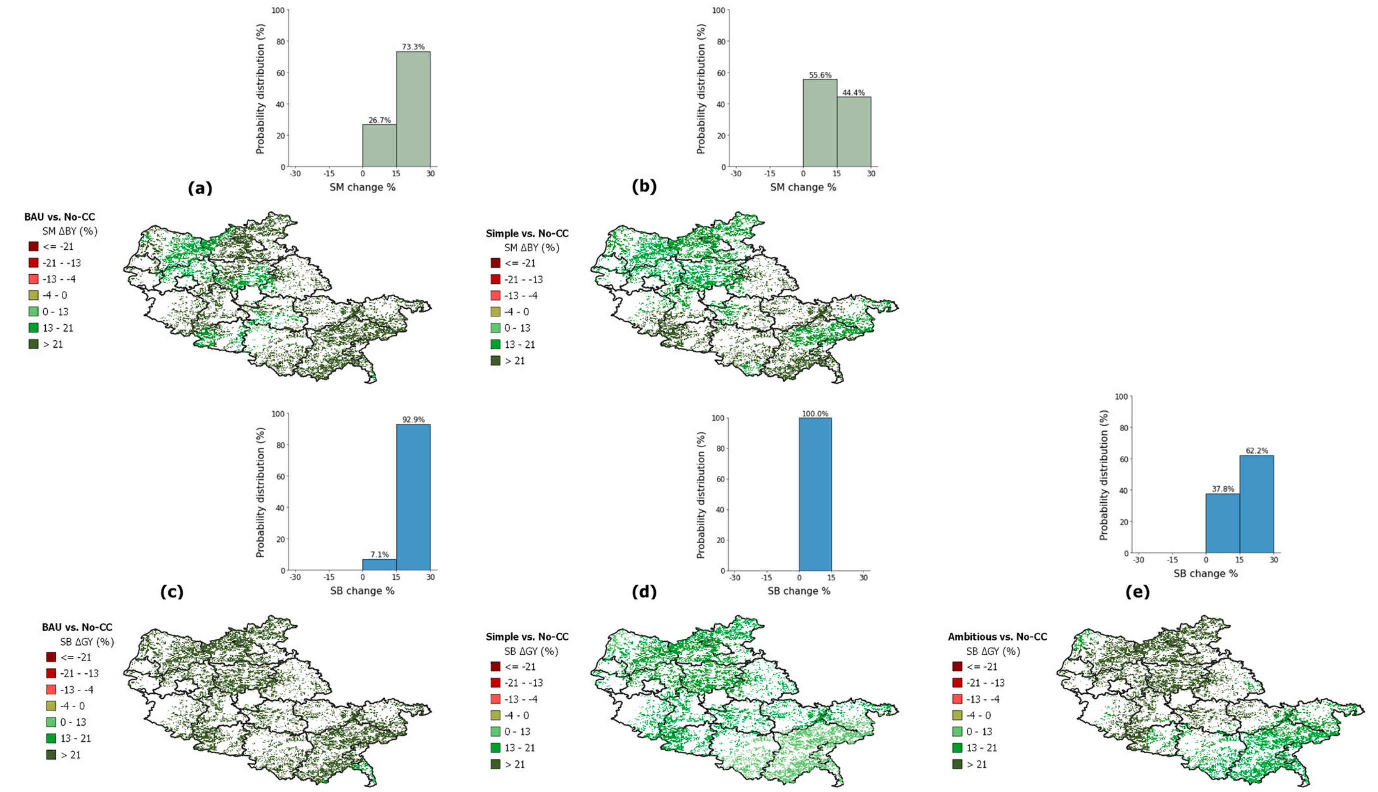

Fig. 9. Percent of biomass yield change (ΔBY) silage maize (SM) and grain yield change of spring barley (SB) as affected by contrasts of BAU, no-CC, and CCs inclusion in crop rotation.

3.4.2. Spatial pattern of crop yield response to diverse crop rotation under cover cropping

The differences in main crops' yields in BAU, simple, and ambitious scenarios vs. no-CC scenario are presented as percent of change as shown in Figs. 8 and 9. For WW, the BAU scenario always had lower yield than the no-CC scenario with an average 20% yield reduction regardless of the spatial location (Fig. 8a). In contrast, the simple and ambitious scenarios had 3% and 8% higher yield than no-CC scenario, respectively, suggesting combined crop rotation and cover cropping advantage on WW grain yield which was more pronounced in the northern axis than the southern axis of the region of interest (Fig. 8b, c). For WR, the region of interest can be divided in three main axes: south, middle, and north where high yield decrease, e.g., $> -23\%$, has occurred in the southern axis while less intensity of yield reduction occurred in middle and north axes by the BAU compared with no-CC (Fig. 8d). Similar attitude and spatial pattern were observed for the simple and ambitious scenarios but with less intensity of yield decrease (Fig. 8e, f). For both scenarios, the only positive response of WR seed yield was observed in the north axis of the region of interest. In general, WR results showed site-specific responses with strong spatial variability in response to cover cropping. In contrast, the BAU scenario did well for WB grain yield, SM biomass yield, and SB grain yield showing an average yield increase of 14%, 17%, and 24%, respectively, in comparison with no-CC scenario regardless of spatial location (Figs. 8g, 9a, c). Nevertheless, the inclusion of CCs did not reduce the productivity of these crops as the simple and ambitious scenarios have also increased the yield but to a lower extent than BAU. For instance, the simple and ambitious scenarios have increased WB grain yield by 6% and 8%, respectively (Fig. 8h, i). Similarly, the SM biomass yield was generally $14\pm3\%$ higher in the simple vs. no-CC in 100% of the region of interest (Fig. 9b) as well as the SB grain yield which was increased by $10\pm3\%$ in the simple scenario and by $17\pm5\%$ in the ambitious scenario (Fig. 9d, e) compared with the no-CC scenario.

4. Discussion

4.1. DSSAT parameterization

One of the main objectives of the present work was to parameterize the DSSAT modeling system for simulating crop rotations in southwest Germany and to obtain a plausible set of calibrated crop coefficients' parameters to be further used on a larger scale. The optimized values, even when constrained on bound limits, are plausible and give good results with respect to phenology, aboveground biomass, and final yield for several crops. By looking at the comparison of simulated vs. observed time-series aboveground biomass, the CERES module had consistent performance for cereal crops dynamically capturing plant growth throughout the growing seasons at most sites and seasons with few exceptions. Crop phenology was, in general, well predicted as well as the grain yield estimates for cereal crops with no clear indication of a relationship between the simulation accuracy of phenology and yield, agreeing with the findings of Palosuo et al. (2011). Among the calibrated cereal crops, aboveground biomass results of WB showed the highest percent of error which may be attributed to the limited available data to train the model. The above ground biomass yield of SM was well predicted at most sites and seasons, except at the end of the 2017 growing season in S4 when the observed aboveground biomass SM was greatly, i. e., ≈ 10 Mg ha^{-1}, higher than simulated data. Yet, there was a good match between the simulated and the reported field average of SM biomass yield in 2017 at this site, suggesting final yield overestimation on the research plots. Nevertheless, the dynamics of time-series aboveground biomass was well predicted by the model across seasons and sites (Figs. S5, S6, and S8-S10).

The CROPGRO module was used for the simulation of WR following calibration of crop-coefficients parameters (Table S2). Another research in a warmer climate in south Europe has adapted the soybean module for oilseed rape simulation utilizing and modifying the initial crop coefficients of soybean (Deligios et al., 2013). Thus, in the present study, the model simulation using the initial coefficients has resulted in crop failure due to freezing effects such that required adjustment of parameters controlling responses to temperature in the species file (Table S2). Central and Northern European WR requires vernalization before flowering with high sensitivity to day length (Robertson et al., 2002). Therefore, in addition to parameters determining the duration between flowering and first pod and between first seed and physiological maturity, adjustment of those controlling crop responses to light extinction coefficient and temperature were necessary to avoid freezing death. As a result, the model simulation of crop phenology and final seed yield was greatly improved, although there are some discrepancies in the time-series aboveground biomass prediction which may potentially be further improved by including more dataset in the optimization process in future studies. In this context, more spatial information on vegetation characteristics, such as leaf area index or aboveground biomass estimated from remote sensing, and more datasets could allow to improve data assimilation, with a refinement of the distribution of calibrated parameters (Jin et al., 2018). Several researchers have used remote sensing to estimate crop canopy state variables such as leaf area index and biomass (Fang et al., 2008; Jin et al., 2015) or to estimate soil properties such as soil moisture (Hosseini and McNairn, 2017) for input in crop models. Accurate field scale WR leaf area index retrieval was achieved using multi-source and high spatial resolution remote sensing data (Wei et al., 2017). That said, further research on remotely sensed model-data fusion can improve the estimation accuracy of canopy state variables and yield of the present crops for improved model optimization.

4.2. Crop rotation and cover cropping impact on agroecosystem services

A considerable body of research highlights the multiple ecosystem services by CCs including its benefits on soil properties and main crop yield (Abdalla et al., 2019; Seitz et al., 2022; Chahal and Van Eerd, 2023; Peng et al., 2023; Van Eerd et al., 2023). In the present research, we tested the impact of the inclusion of CCs in diverse crop rotations on soil parameters and main crop yield at specific research sites and regional scale. We also compared the sole effect of diverse crop rotation without the inclusion of CCs (no-CC scenario) with the BAU practices. For the soil N-related variables, a diverse crop rotation incorporating CCs significantly increased the soil organic N and N mineralization compared with BAU scenario, and had comparable N leaching amount observed at the research sites and on spatial scale (Table 4, Fig. 7a). Compared to no-CC, both enhanced soil organic N and reduced N leaching were observed, particularly in areas vulnerable to N losses through leaching (Fig. 7b-c, e-f). Beneficial rotational effects on soil organic N in the present study agree with previous research where a significant increase in soil organic N was observed by crop rotation vs. monoculture (Havlin et al., 1990; Raphael et al., 2016). The positive rotation effect on soil organic N is likely attributed to the return of diverse residue with different C/N ratio to the soil which was more pronounced with the inclusion of legume CCs (Table 4). A low C/N ratio residue results in N mineralization, hence more available N and soluble C to microorganisms that decompose the roots resulting in soil microbial-derived C stabilization. Previous research has highlighted the effectiveness of soil microbial-derived C in SOC stabilization by increased soil aggregates and minerals such that explains the added benefits of legume CCs vs. non-legume CCs on soil properties in the present research (Dungait et al., 2012; Peng et al., 2023). This was demonstrated by significantly higher 17% soil organic N rate, 38.3% N mineralization, and 13.2% SOC rate by legume vs. non-legume CCs (Table 4), suggesting different efficiencies due to species type. Nevertheless, non-legume CCs had also significantly reduced N leaching by 33.7% compared with no-CC, agreeing with previous research where non-legume, legume, and legume-non-legume mixed can all reduce N leaching but with different efficiencies (Abdalla et al., 2019).

Cover cropping had a positive influence on SOC change rate compared with the no-CC scenario at research sites and spatial scale (Fig. 7h, i). Average SOC change rate of cover cropping relative to no-CC was 0.15±0.05 Mg C ha^{-1} yr^{-1} representing ≈ 8% increase which closely matches that reported by Seitz et al. (2022) who compared mean 10-years annual SOC accumulation rates of CCs on all German croplands vs. no-CC. Hu et al. (2023) conducted a global meta-analysis on the impact of CCs on SOC fractions and found 12% higher SOC compared with bare soil management. Higher frequencies of planting CCs by the ambitious scenario resulted in SOC stock increase in our study but there was no significant difference in the rate of SOC change between the simple and the ambitious scenarios (Table 4). Results of regional simulation, instead, showed spatial variations in response to increased CCs inclusion in the crop rotation. While the simple scenario had always positive SOC change rate compared with no-CC ≈ 0.05±0.013 Mg C ha^{-1} yr^{-1} at the spatial scale, the ambitious vs. no-CC results showed more spatial variations regarding the difference in the SOC change rate. The difference between ambitious vs. no-CC in annual SOC change rate ranged from neutral ≈ 0.01 Mg C ha^{-1} yr^{-1} in the high elevation area *Mittlere Kuppenalb* southeastern the Swabian Alb to ≈ 0.11 Mg C ha^{-1} yr^{-1} middle-west and north of the region of interest (Fig. 7h, i). This could be attributed to the effect of three non-legume CCs treatments in the ambitious scenario (Table 2), e.g., N3-L0 treatments, in areas with less available N such that decreases the decomposition rates of roots exudates and rhizodeposition which are easily decomposable C sources (Torbert et al., 2000). Positive N balance is considered as fundamental for C sequestration because it affects the production of phytomass and the microbial metabolism, and consequently plays a crucial role in SOC dynamics (Raphael et al., 2016). Others have reported a significant decrease in SOC of averagely 0.3% due to unfertilized vs. minerally and organically fertilized arable European soils (Körschens et al., 2013). In this respect, agreeing with our results, Chaplot and Smith (2023) debated the potential of CCs to increase SOC sequestration in nutrient deficient situations pointing out to the importance of dual increase of C and nutrient inputs for long-term sustainability while balancing out the environmental risks by excessive nutrient application. In the present study, the inclusion of legume CCs averagely increased the annual soil organic N accumulation by 20% and the annual SOC change rate by 10% when compared with BAU scenario on regional scale (Fig. S11c, i), although there was an increased annual N leaching rate by legume only CCs (Fig. S11f). Instead, the N1-L2 vs. BAU had increased the annual soil organic N accumulation by 10% with 28% less annual N leaching rate than N0-L3 (Fig. S11a, d, f). This indicates that the inclusion of CCs should consider the CC species type for better ecosystem services and increased crop yield. Abdalla et al. (2019) argued that legume-non-legume CCs mixture should be selected to avoid yield reduction by CCs and increase the SOC sequestration. According to our findings, this could be also achieved by alternating non-legume and legume CCs in the crop rotation (Fig. S11g). In a recent study on root and shoot biomass of CCs as affected by cereal-brassica and cereal-legume-brassica CCs mixtures compared with single type CCs, total root biomass did not significantly vary among CCs with legumes sometimes unable to compete with oil radish or winter rye as its biomass share was consistently lower than sole planting (Kemper et al., 2023). To this end, the more available N by legume CCs might have contributed to the microbial derived C and therefore protection of SOC (Liang and Zhu, 2021).

Crop yield responses to crop rotation diversity with and without CCs inclusion varied among crops, agreeing with previous research (Chahal and Van Eerd, 2023). Variations in crop yield responses were mainly attributed to several factors that could be differentiated to management and environmental factors. For example, species type, available cultivation window, amount of produced aboveground biomass, and residue management of CCs (Alvarez et al., 2017) and tillage and N inputs of main crop (Dozier et al., 2017) are among the important management factors that control the crop yield responses to cover cropping. Others have emphasized on the importance of site-specific adaptation of these management options in reference to spatial soil and climate variations (Abdalla et al., 2019). This explains the spatial differences in crop yield responses to the tested scenarios in the present study (Figs. 8 and 9). WW had consistently lower yield by the BAU when compared with no-CC which could be attributed to rotational effects by the no-CC scenario that increased WW yield by 22–28% compared with consecutive monoculture in the BAU scenario (Table 4). These results agree with previous research that reported 17–45% spring wheat yield increase due to rotating 2-year spring wheat-fababean/chickpea/sunflower compared with monoculture continuous wheat (López-Bellido et al., 1996) and that reported 22% WW yield increase due to rotating 2-year rotation of WR-WW compared with monoculture continuous WW in a Pulaski sandy loam soil (Bushong et al., 2012). Others have reported 23–39% WW increase due to crop rotation with and without CC (red clover) compared with monoculture in a Brookston clay loam soil (Agomoh et al., 2020) which is closely similar to that observed in the present study of 22–43% WW yield increase due to crop rotation with and without CCs at research sites and spatial scale (Table 4, Fig. 8a-c).

For WB, SM, and SB, the BAU had similar or higher yield compared to others which could be attributed to the less frequent appearance of these crops in the BAU scenario such that has masked the rotational effects. The inclusion of legume CCs; however, showed significant yield increase of these crops in some areas that are vulnerable to N losses in comparison with the BAU scenario (Fig. S12b-d). In addition, the inclusion of CCs in the crop rotation increased the yield of these crops relative to no-CC at the research sites and the spatial scale. For WR, unlike the research sites, more spatial variations were observed for the seed yield to averagely decrease by 3% in response to cover cropping compared with no-CC (Fig. 8e-f). The potential causes of this decrease is unclear, at first, we speculated that the planting of oilseed rape as CC in the simple and ambitious scenarios has resulted in monocultural effects on WR yield. However, the legume-only CC treatments did also not increase the yield (Fig. S12a), indicating that it may be related to management by environment interaction that resulted in wide spatial variations with the majority of areas negatively responding to CCs inclusion. Several studies have reported a reduction in main crop yield following CCs due to less N availability by the return of high C/N residue and/or to the less available water in the soil profile (Wagner-Riddle et al., 1994; Nielsen et al., 2016; Delgado et al., 2021; Chahal and Van Eerd, 2023). Therefore, our findings support that stated by Abdalla et al. (2019) that the management practices related to cover cropping should be adapted to specific soil, management and regional climate conditions.

4.3. Limitations and research needs

Considering the reported spatial variabilities in response to the applied CC-crop rotation treatments, there is a need for testing site-specific agronomic management practices. In the current analysis, we adopted the management practices reported by farmers in an attempt to mimic the conventional farming system and compare it with a proposed set of CCs inclusion in diverse crop rotations. Yet, the present management options should be tested in synchronization with other conservation agriculture principles such as no-tillage for better development of sustainable agricultural practices. In another temperate environment, the SOC was increased by 24%-66% by no-tillage vs. moldboard plow whereas the microbial biomass C and N concentrations were significantly decreased with the increased tillage intensity (Sangotayo et al., 2023). Therefore, evaluating the model performance in simulating soil related variables corresponding to varying levels of soil surface disturbance needs to be further researched. This will allow for a comprehensive evaluation of conservation agriculture principles in the long-term. In addition, as suggested by other researchers, exploring the effects of quantity and quality of produced biomass by different types of CCs including species mixtures on soil characteristics needs to be further examined and implemented in agroecosystems models (Peng et al., 2023; Van Eerd et al., 2023). Such knowledge will allow for assessing site-specific cover cropping in relation to within field soil variability, management and climatic conditions.

5. Conclusions

Two main pillars of conservation agriculture, crop rotation and cover cropping, were tested in a comprehensive simulation study at both field and regional scale using an extensive crop rotation dataset. Improved crop rotations were found to enhance soil organic N and C even without the inclusion of CCs, and showed significant advantage for WW yield compared to the BAU practices. The inclusion of CCs in the improved crop rotation further provided additional agroecosystem services, such as increased annual soil organic N and SOC rates, especially when alternating legume and non-legume CCs. Cash crop yield and water productivity have also benefited from crop rotation, particularly WW and WR, compared with the BAU scenario. Relative to no-CC, the inclusion of CCs in the rotation showed positive impacts on crop yield for all crops with on-average 6–14% yield increase, except WR that showed a wide range of spatial variability. Overall, results of the present study highlight the potential of simultaneously improving SOC change rates and consequently crop yields, while reducing N leaching by adopting site-specific management recommendations. Crop model-data fusion has proven efficacy in devolving site-specific management recommendations adapted to regional soil and climate conditions.

CRediT authorship contribution statement

Ahmed Attia: Conceptualization, Methodology, Software, Formal analysis, Data curation, Visualization, Validation, Writing - original draft, Writing - review & editing. **Carsten Marohn:** Methodology, Formal analysis, Writing - review & editing. **Ashifur Rahman Shawon:** Software, Formal analysis, Data curation. **Arno de Koc:** Software, Data curation. **Jörn Strassemeyer:** Methodology, Administration, Funding acquisition. **Til Feike:** Conceptualization, Methodology, Administration, Funding acquisition, Resources, Writing - review & editing.

Declaration of Competing Interest

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

Data availability

Data will be made available on request.

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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.agee.2024.109167.

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