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How will future climate depending agronomic management impact the yield risk of wheat cropping systems? A regional case study of Eastern Denmark

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Abstract

One of the major challenges in agriculture is how climate change influences crop production, for different environmental (soil type, topography, groundwater depth, etc.) and agronomic management conditions. Through systems modelling, this study aims to quantify the impact of future climate on yield risk of winter wheat for two common soil types of Eastern Denmark. The agro-ecosystem model DAISY was used to simulate arable, conventional cropping systems (CSs) and the study focused on the three main management factors: cropping sequence, usage of catch crops and cereal straw management. For the case region of Eastern Denmark, the future yield risk of wheat does not necessarily increase under climate change mainly due to lower water stress in the projections; rather, it depends on appropriate management and each CS design. Major management factors affecting the yield risk of wheat were N supply and the amount of organic material added during rotations. If a CS is characterized by straw removal and no catch crop within the rotation, an increased wheat yield risk must be expected in the future. In contrast, more favourable CSs, including catch crops and straw incorporation, maintain their capacity and result in a decreasing yield risk over time. Higher soil organic matter content, higher net nitrogen mineralization rate and higher soil organic nitrogen content were the main underlying causes for these positive effects. Furthermore, the simulation results showed better N recycling and reduced nitrate leaching for the more favourable CSs, which provide benefits for environment-friendly and sustainable crop production.

Introduction

Yield risk of a cropping system (CS) describes the reliability of expected yields under various environmental conditions and can be estimated in multiple ways by considering the yield performance, the temporal/spatial yield variability and the probability of a certain level of yield losses. Regarding climate change, a more detailed understanding of how yield risks of CSs will be affected by future climate is essential to ensure food security. This can be mainly assessed using system modelling and future climate projections (Olesen *et al.*, 2011; Ozturk *et al.*, 2017; Ray *et al.* 2019). In Europe, the yield risk of wheat is expected to increase as shown in recent modelling studies (Trnka *et al.*, 2014; Kahiluoto *et al.*, 2019). While wheat production in Northern European countries may benefit from a longer crop-growing period, more climatic variability continues to challenge their performance (Porter and Semenov, 2005; Ozturk *et al.*, 2017; Ray *et al.*, 2019). For Denmark, higher annual mean temperatures, more precipitation in winter and less in summer, longer and greater frequencies of abnormal weather events, such as heat waves, drought, heavy downpours and storms, are expected in the future (Olesen *et al.*, 2014; Ozturk *et al.*, 2017). These projections are assumed to severely impact regional wheat production and increase temporal yield variability (Olesen *et al.*, 2000; Kristensen *et al.*, 2010; Patil *et al.*, 2012).

In Eastern Denmark, the prevalent local farming types are conventional, arable systems focusing on CSs with winter wheat. This region is relatively homogenous and characterized by favourable soil conditions and high wheat yields of approximately 8.3 t/ha during the recent years 2015–2019 (Statistics Denmark: https://www.statbank.dk). Traditional diverse mixed farms (crop livestock) have been replaced over time by specialized arable farms with lower crop diversity (Schiere *et al.*, 2002). A trend towards higher proportions of cereal-dominated CSs has been observed, which can increase the risk of yield losses (e.g. Berzsenyi *et al.*, 2000; Babulicova, 2014; Babulicova and Dyulgerova, 2018; Nielsen and Vigil, 2018), inter alia, due to higher weed pressure or soil-borne diseases (Petersen *et al.*, 2010).

The extent to which CSs are vulnerable to climate change depends on the actual exposure to climate change (e.g. country/region), their sensitivity, adaptive capacity and the underlying soil conditions in the field (Porter *et al*., 2014). Although there has been increasing attention to climate change adaptation, a better understanding is needed on how yield risk can be reduced under increasing climate variability by improved agronomic management factors (Porter and Semenov, 2005; Reidsma and Ewert, 2008). A few studies based on field experiments showed that more diverse CSs with favourable preceding crops (pre-crop) and catch crop usage may be an adaptation strategy (Berzsenyi *et al*., 2000; Christen, 2001; Cociu, 2012; Macholdt and Honermeier, 2018; Liu *et al*., 2019). Straw management may be another important management factor influencing yield risk. Straw incorporation rather than straw removal increases the soil organic carbon (C) content, total nitrogen (N) content and microbial biomass, which is relevant for long-term soil functionality and sustainable agriculture (Gaind and Nain, 2007; Powlson *et al*., 2011; Macholdt and Honermeier, 2018; Macholdt *et al*., 2020a, 2020b). Besides this, the future yield risk of wheat is expected to differ significantly on the regional scale depending on specific soil and management conditions (Olesen *et al*., 2000). Thus, regional risk assessments of CSs that include agronomic management factors are of direct and increasing relevance to farmers. A regional specific modelling approach with related quantitative risk assessment of modelled yield results offers the opportunity to investigate multiple agronomic adaptation strategies under future climatic scenarios (Ebrahimi *et al*., 2016), which cannot be observed to this extent by retrospective analyses of long-term field experiments.

Through systems modelling, this study aims to quantify the impact of future climate on the yield risk of winter wheat for two common soil types of Eastern Denmark. The agro-ecosystem model DAISY was used to simulate arable, conventional CSs and the study focused on the three main management factors: cropping sequence, usage of catch crops and cereal straw management. The following hypotheses were addressed:

1. The yield risk of winter wheat is higher under future climate scenarios than under recent climate scenarios. (#H1)
2. Cropping sequence: Cereal preceding crops lead to a higher yield risk of subsequent wheat compared with non-cereal preceding crops. (#H2)
3. Catch crop: Catch crops within rotations reduce the yield risk of wheat compared with rotations without catch crops. (#H3)
4. Cereal straw management: Straw incorporation (of all cereal crops in the rotation) diminishes the yield risk of wheat compared with straw removal. (#H4)

Materials and methods

Model simulation approach

The study was conducted in Zealand, one of the five administrative regions of Denmark. The crop production of winter wheat for the case region of Eastern Denmark (Zealand) was simulated under three climate scenarios (recent, near future and far future climate projections) on two of the most prevalent soil types and for 22 CSs with differences regarding cropping sequence (pre-crop effect), usage of catch crops and straw management (Fig. 1). The simulation approach based on the agro-ecosystem model DAISY (open source version 5.93; 64 bit) is described in the following paragraphs.

Agro-ecosystem model DAISY

DAISY is a mechanistic model system, initially developed for Denmark, which simulates water, heat, organic C, organic N, and solute balances (here, ammonium and nitrate) and crop production in the one-dimensional soil–plant–atmosphere system subjected to various management strategies (Hansen *et al*., 1990, 1991, 2012; Abrahamsen and Hansen, 2000). Driving variables in DAISY are weather and management data. A general description of DAISY can be found in Hansen *et al*. (2012), while specific processes relevant for the current study are described in the following.

Water flow in soils is calculated using Richard's equation (Richards, 1931). Solute transport is calculated using the advection-dispersion equation (Bear, 1972). The C balance is simulated considering photosynthesis and build-up of plants, as well as the turnover of plant residues and added organic materials. Assimilated C is lost to maintenance and growth respiration or loss of dead material. The turnover of organic matter is described by two 'added organic matter' pools for each type of added material, two soil microbial biomass (SMB) pools and two soil organic matter (SOM) pools, parameterized in long-term experiments (Bruun *et al*., 2003). N is mineralized or immobilized from each pool depending on the C/N relationship. Mineral N may be in the form of ammonium or nitrate, which may sorp, nitrify, denitrify, be taken up by roots or leach. The robust performance of DAISY in terms of short- and long-term simulation of nutrient and SOM dynamics when compared to field data has been documented in a number of publications (de Willigen, 1991; Diekkrüger *et al*., 1995; Smith *et al*., 1997; Bruun *et al*., 2003, 2006; Gyldengren *et al*., 2020).

The model calculates photosynthesis on an hourly basis based on leaf area and crop architecture and distributes assimilation to the root, leaves, stem and storage organ as a function of growth stage. Photosynthesis may be limited by water or N stress (lack of water/N) or senescence. The water stress model is based on the following assumptions. Potential transpiration rates $E_{t,p}$ are estimated from meteorological data and crop growth. Integrated root water uptake over the whole root zone or actual transpiration is calculated in DAISY using the microscopic approach, and the main controlling factor is the energy status of the water in the soil (Abrahamsen and Hansen, 2000). If the soil is wet, $E_{t,p}$ rates are satisfied, whereas if the soil is (partially) dry, E_a is determined by the transport of water to the roots. Water stress is calculated as a function of the ratio of actual transpiration plus actual evaporation from the intercepted water to their potential transpiration components. These assumptions lead to the following approximation for how the actual photosynthesis rate is reduced from the potential (dimensionless/unitless):

$$F_w = F_p \frac{E_t + E_i}{E_{t,p} + E_{i,p}} \qquad (1)$$

where F_w is water-limited photosynthesis, F_p is potential photosynthesis, E_t and $E_{t,p}$ are actual and potential transpiration, respectively, and E_i and $E_{i,p}$ are actual and potential evaporation of intercepted water, respectively. The water stress term is the second part of the equation, which has values between 0 and 1. The accumulated days where this term is <0 is indicating days of growth lost due to water stress (unit in days).

N uptake may be passive (advection) or active (by diffusion). The demand is calculated according to a potential N content found by multiplying biomass of roots, leaves, stems and storage

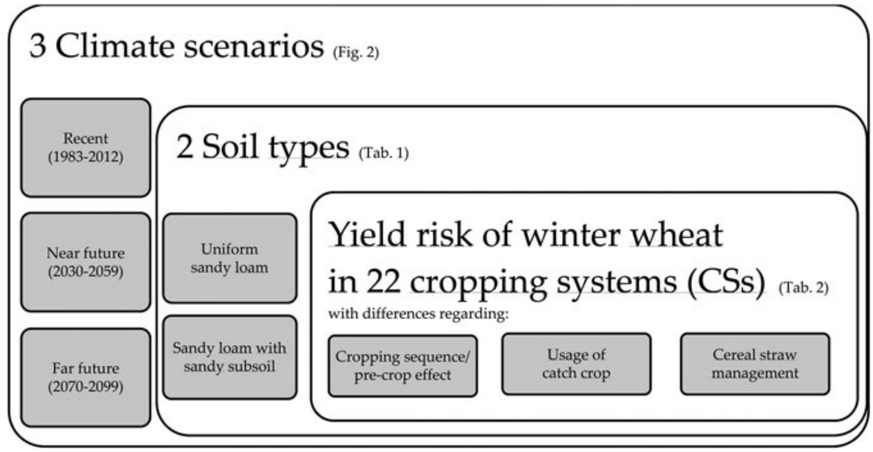

Fig. 1. Schematic representation of the methodological approach used in this case study.

organs with respective potential N concentrations, which depend on growth stage. Similarly, a critical and non-functional level is calculated. If the N content is below the critical level, N stress is calculated as (actual N content minus non-functional N content)/(critical N content minus non-functional N content) (e.g. Gyldengren *et al*., 2020).

Climate scenarios

Three climate scenarios were used in this study (recent, near future and far future climate projections). Each data set contained a 3000-year-long synthetic weather data series, which was generated and published by Rasmussen *et al.* (2018), with hourly weather data for precipitation and daily data for min/max temperature, wind, vapour pressure, diffuse radiation and global radiation. In Fig. 2, the monthly mean air temperature and precipitation for the case region are shown for the three climate scenarios (the related data table is in Appendix Table A1). A climatic trend of increasing CO_2 concentrations was not included. The data set comprises a control scenario based on the recent climate (1983–2012; abbreviated as 'RC' in the following) with 30 years of meteorological data from East Denmark (Copenhagen), which was used for calibration. Furthermore, two future (projected) climate scenarios represent the near future (2030–2059; abbreviated as 'NFC' in the following) and the far future (2070–2099; abbreviated as 'FFC' in the following). The future climate scenarios were based on the global circulation model ECHAM, developed by the Max Planck Institute of Meteorological Germany (Roeckner *et al*., 2003), paired with the regional circulation model HIRHAM5, which was developed by the Danish Meteorological Institute (Christensen *et al*., 2006).

Soil types

In Eastern Denmark, the soil texture is mainly loamy sand or sandy loam (Danish Centre for Food and Agriculture, 2014). In some areas, the parent material is uniform in depth, but in other areas, the parent material consists of mixed texture composition. To represent some of the variation in East-Danish agricultural soils, two model soils were chosen. The main difference between them is the subsoil, where soil 1 is a sandy loam with a uniform soil texture throughout the soil column (abbreviated as 'SL' in the following), while soil 2 is a sandy loam with sandy subsoil that limits root growth to 1 m (abbreviated as 'SL-SS' in the following). Both model soils have a systematic tile drain system at 1.2 m depth with a drain distance of 16/18 m and a discharge to drain ratio of 55/30% (as % of total discharge) on soil 1 and soil 2, respectively, which is representative of Danish soil conditions (Danish Centre for Food and Agriculture, 2014). The lower boundary condition, which is a conceptual description of the interaction between the simulated system and its surroundings, is defined as an aquitard. An aquitard is a layer with low water permeability as opposed to free internal drainage. The hydraulic properties of each soil horizon are determined by the HYPRES model on the basis of soil texture using the Mualem-van Genutchen equations for water flow (Wösten *et al*., 1998). Organic matter initiation was set for C according to the pre-history of the actual fields on which the descriptions are based (6340 kg C input per hectare and year for soil type 1; and 6170 kg C input per hectare and year for soil type 2). The model soil parameters are summarized in Table 1.

Cropping systems

The CS designs (Table 2) were based on common crops grown in conventional, arable farming systems in the case region (Appendix Table A2). Three typical cropping sequences (3-year rotations) were defined: (i) oilseed winter rape–winter wheat–spring barley, (ii) ryegrass (for seed production)–winter wheat–spring barley and (iii) sugar beet–winter wheat–spring barley. Furthermore, a fourth pure cereal cropping sequence, 'winter rye–winter wheat–spring barley', was added. This cropping sequence is not common but is still relevant to have a reference baseline for testing cereal *v.* non-cereal pre-crop effects on the subsequent winter wheat (#H1). Except for the first crop in each rotation, the sequence of the subsequent two crops (winter wheat and spring barley) was kept constant in all CSs to achieve a high level of comparability regarding the test factors.

To evaluate the effect of catch crops (#H2), all four cropping sequences were simulated without and with the usage of catch crops (grown before a spring crop, here before sugar beet and spring barley) according to Danish guidelines (Ministry of Environment and Food of Denmark, 2020a, 2020b). The two most common catch crops for the area, oilseed radish and winter rye, were selected. Due to phytosanitary reasons, oilseed radish was not tested in rotations with oilseed winter rape (e.g. *Plasmodiophora*, *Verticillium* and *Sclerotinia).*

To test the effects of cereal straw management (winter wheat, spring barley and winter rye in CS 17–22), all CSs were simulated with straw removal and straw incorporation (#H3). In the scenario with straw removal, the cereal straw of rye, wheat and barley

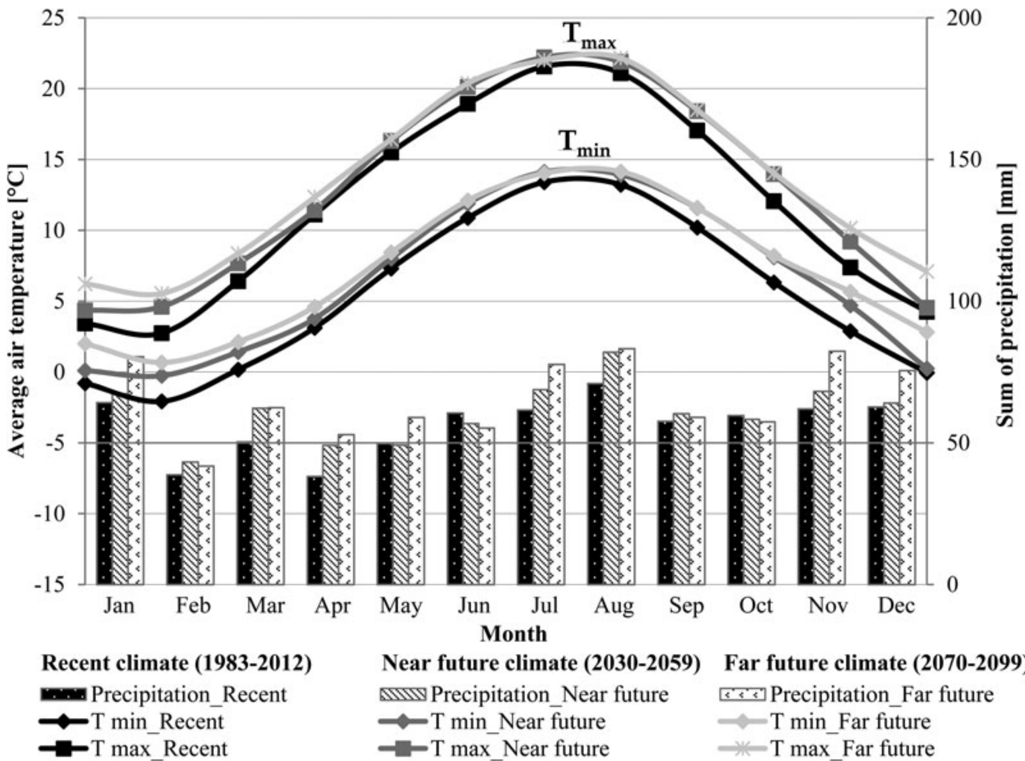

Fig. 2. Climate diagram of the recent (RC), near future (NFC) and far future climate (FFC) scenarios assumed for the case region of Eastern Denmark. *Note*: Weather data set provided by Rasmussen *et al*. (2018), based on the HIRHAM climate model developed by the Danish Meteorological Institute (Christensen *et al*., 2006). The data table for air temperature and precipitation values is shown in Appendix Table A1.

Table 1. Model soil parameters used for the simulations

Soil type	Horizon[a]	Depth (cm)	Clay 0–2 µm (%)	Silt 2–50 µm (%)	Sand 50–2000 µm (%)	Humus (%)	Dry bulk density (g/cm^3)
(1) Uniform sandy loam 'SL'	Ap	30	17.4	25.7	54.0	2.9	1.54
	Bd	36	19.8	21.8	56.6	1.5	1.78
	Bt	80	19.8	21.8	56.6	1.5	1.68
	C	300	17.9	23.8	57.5	0.8	1.87
(2) Sandy loam with sandy subsoil 'SL-SS'	Ap	30	12.3	24.8	59.9	3.0	1.53
	Bd	36	19.8	21.8	56.6	1.5	1.78
	Bt	60	19.8	21.8	56.6	1.5	1.68
	C1	100	8.0	18.6	73.1	0.3	1.65
	C2	300	3.4	5.9	90.5	0.2	1.55

[a]Horizon abbreviations: Ap, plow layer; Bd, plow sole (compacted layer); Bt, subsoil with clay illuviation; C, substratum; maximal root depth: 175 cm for soil 1 and 100 cm for soil 2. Data provided by Gyldengren *et al*. (2020).

was removed from the field, excluding the stubble of 8 cm. In the case of cereal straw incorporation, the stubble, stem and leaves of all cereal crops were simulated as remaining on the field with incorporation during stubble cultivation and ploughing afterwards. In all scenarios, the plant residues (stems/leaves) of the other crops within the rotation were incorporated in the soil. The standard yield level and mineral N fertilization of the main crops used for the simulations are shown in Table 3; further crop-specific management actions are described in Appendix Table A3. Plant disease and weed occurrence are not simulated in the DAISY model. It had to be assumed that plants stayed healthy and that the fields were free from weeds.

Model simulation

The crop modules selected for the study were the Danish standard crop modules ('dk-crops') applied together with standard parameterizations for general agronomic management (tillage, sowing and harvest; see Appendix Table A3). These crop modules are distributed with DAISY and specifically calibrated to generate yield levels and N-response curves in accordance with experience in

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Table 2. Description and differentiation of the simulated cropping systems (CS)

CS	Cropping sequence incl. catch crop (CC) position	Catch crop (CC)	Cereal straw management[a]
1	OR-WW-BY	None	Removed
2			Incorporated
3	OR-WW-(CC)-BY	Winter rye	Removed
4			Incorporated
5	RG-WW-BY	None	Removed
6			Incorporated
7	RG-WW-(CC)-BY	Oilseed radish	Removed
8			Incorporated
9		Winter rye	Removed
10			Incorporated
11	SB-WW-BY	None	Removed
12			Incorporated
13	SB-WW-(CC[1])-BY-(CC[2])	CC[1]: oilseed radish	Removed
14		CC[2]: winter rye	Incorporated
15	SB-WW-(CC[1])-BY-(CC[2])	CC[1]: winter rye	Removed
16		CC[2]: oilseed radish	Incorporated
17	WR-WW-BY	None	Removed
18			Incorporated
19	WR-WW-(CC)-BY	Oilseed radish	Removed
20			Incorporated
21		Winter rye	Removed
22			Incorporated

[a]Referred to the straw of main cereal crops: winter wheat and spring barley (+winter rye in CSs 17–22); WW, winter wheat (*Triticum aestivum* L.); BY, spring barley (*Hordeum vulgare* L.); oilseed radish (*Raphanus sativus* var. *oleiformis*); OR, oilseed winter rape (*Brassica napus* L.); RG, Italian ryegrass (*Lolium multiflorum* L.); SB, sugar beet (*Beta vulgaris* subsp. *vulgaris*); WR, winter rye (*Secale cereale* L.). Standard yield level and mineral N fertilization of the main crops used for the simulations shown in Table 3.

Table 3. Standard yield level and mineral N fertilization of the main crops used for the simulations

Crop	Standard yield (t/ha)	Mineral N fertilization norm[1] (kg N/ha)
Italian ryegrass for seeds (pre-crop winter wheat)	1.4	140
Oilseed winter rape (pre-crop spring barley)	4.4	201
Spring barley (pre-crop winter wheat)	6.5	126
Sugar beet (pre-crop spring barley)	65.7	113
Winter rye (pre-crop spring barley)	7.7	144
Winter wheat (pre-crop oilseed rape or ryegrass)	8.8	171
Winter wheat (pre-crop sugar beet)	8.8	191
Winter wheat (pre-crop winter rye)	8.8	194

Based on the Danish regulatory system 'N fertilization norm for the growing season 2019/2020' (Ministry of Environment and Food of Denmark, 2020a, 2020b), values corrected depending on the pre-crop (wheat/barley/rye: 0 kg N/ha; ryegrass/oilseed rape: −23 kg N/ha; sugar beet: −3 kg N/ha), year and site specifics with '−15 kg N/ha' according to the soil type in the Ap-horizon (sandy loam) and region (region B) (Ministry of Environment and Food of Denmark, 2020b).

practical Danish agriculture (field trials in farmers' fields, statistics and case studies) (Styczen *et al*., 2004). The same modules were used by Bruun *et al*. (2006) and similar calibration goals were used by Nielsen *et al*. (2019) and Fan *et al*. (2017).

The winter wheat module used builds on the default winter wheat parameterization in DAISY, which has been used in several articles, providing good correspondence between measured and simulated values of biomass production and N dynamics (Abrahamsen and Hansen, 2000), crop production, soil water fluxes and nutrient dynamics (Hansen *et al*., 1990; Diekkrüger *et al*., 1995; Groh *et al*., 2020), and yield estimates (Palosuo *et al*., 2011; Ozturk *et al*., 2017). A new parametrization of winter wheat was recently presented by Gyldengren *et al*. (2020), based on recent experimental data from Eastern Denmark.

As recommended by Hansen *et al*. (2012), the simulated CS performances were tested and validated using the present standardized Danish yield level and allowed fertilizer norms depending on the preceding crop, soil type, year and region (Table 3) (Ministry of Environment and Food of Denmark, 2020a, 2020b). The present norms are determined based on the economic optimum of the different crops at the corresponding soil found in experimental N response field trials. The discrepancy between simulated *v*. Danish norm yields was below 8% (acceptable simulation error) and re-calibration appeared to be unnecessary in this study. Due to the hypothetical and complex approach of this study with a large variety of tested CS designs, measured data based on an appropriate field experiment (for specific calibration) were unavailable.

The parameterization of the organic matter module was calibrated on a Danish long-term experiment (Bruun *et al*., 2003), with and without straw incorporation as well as a range of other fertilization treatments. Plant residue effects of cereal straw and catch crops (ryegrass, rape, grass and oil radish) straw on N-mineralization/immobilization and of SMB N were investigated by Müller *et al*. (2006), and the effects of ryegrass residues on C and N dynamics by Bruun *et al*. (2020). The effect of catch crop use (ryegrass, Brassica) and rooting pattern was compared with data in Pedersen *et al*. (2009). In regard to European model intercomparisons, DAISY was tested successfully and performed well for predicting crop production in typical European crop rotations (Kollas *et al*., 2015; Yin *et al*., 2017). Thus, we can safely assume that the DAISY model can simulate correctly the different CSs and their effects on future crop yields (pre-crop #H1; catch crop #H2; straw #H3).

Lastly, a warming up period of 100 years (control scenario RC) was used to initialize the soil conditions (i.e. water content) in each CS and was not included in the statistical analysis. After the warming up period, the simulations covered each random set of 300 yearlong weather series (3-year rotations), resulting in 100 harvest years of the target crop winter wheat. Each CS was simulated using the same annual weather conditions over the same number of years to test the systems under comparable environmental conditions. The results of the 132 DAISY simulations (3 climate scenarios × 2 soil types × 22 CSs) with respect to the grain

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yield of winter wheat with 100% dry matter content (0% moisture) were used for the subsequent statistical analysis.

Statistical analysis

For a comprehensive yield risk assessment, four complementary parameters were calculated: (a) mean yield performance; (b) temporal yield variability; (c) rank-sum approach considering both mean yield performance and temporal yield variability; and (d) probability of certain yield reductions. The analyses were performed separately for each environmental combination (climate scenario × soil type).

(a) The CS mean yield performances were analysed with a univariate variance analysis with regard to testing for significant ($P < 0.05$) differences between the CSs within a climate scenario and between the climate scenarios within a CS (random factor: year and year × CS; fixed factor: CS; post hoc test: Tukey's-*b*).

(b) To estimate the temporal (year-to-year) yield variability, Shukla's approach was used (Shukla, 1972), where the yield variance (σ_i^2) of winter wheat grown in a certain CS ($i = 1, \ldots, K$) can be described as its variance across years ($j = 1, \ldots, N$) after the main effects of year means have been removed (Piepho, 1994):

$$\sigma_i^2 = \frac{KW_i}{(K-2)(N-1)} - \frac{\sum_{i=1}^{K} W_i}{(K-1)(K-2)(N-1)} \qquad (2)$$

where $W_i = \sum_j (y_{ij} - \bar{y}_i - \bar{y}_j + \bar{y})^2$ with y_{ij} = wheat yield of CS_i in year $_j$ and $\bar{y}_i = \sum_j y_{ij}/N$; $\bar{y}_j = \sum_i y_{ij}/K$; $\bar{y} = \sum_{ij} y_{ij}/KN$

Lower σ_i^2 values indicate lower temporal yield variability or better yield stability, and *vice versa*. As stated by Döring *et al.* (2015), no systematic relationship between lower yield variabilities and increasing mean yields should be present, or the stability results may be misleading. In this analysis, there was no such dependency between the mean yield and yield variability s_i^2 estimations.

(c). Kang's rank-sum (Kang 1988) was calculated, which gives a weight of one to both mean yield performance and temporal yield variability (based on Shukla's yield variance σ_i^2) to identify high-yielding and stable CSs. The CS with the highest wheat yield and lower s_i^2 were assigned a rank of one. Then, the ranks of yield and σ_i^2 were added for each CS, and the CS with the lowest rank-sum was the most desirable one (high and stable yields); in contrast, CSs with high rank-sums were assumed to have low and non-stable yields.

(d). The probability of certain yield reductions was estimated based on Eskridge's approach (Eskridge *et al.* 1991), which predicts the probability $P(i)$ of wheat yield with which a CS_i is not achieving a certain threshold δ (here, the average yield across all CSs over all three climate scenarios) in a randomly chosen year:

$$P(i) = \Phi\left(\frac{\delta - m_i}{s_i}\right) \qquad (3)$$

where Φ is the cumulative density function of the standard normal distribution, δ is the threshold, m_i is the mean, and s_i is the standard deviation. The threshold was set as −10%/−20% under the average yield across all CSs and climate scenarios, separately for the two soil types. The thresholds can be chosen as required and were selected for this study to show the largest differences between CSs, which are also in a relevant range of yield reductions for farming practice.

For statistical analysis, SPSS software (Version 24; IBM SPSS Statistics; Armonk, New York, USA) was used.

Results

Mean yield

In comparison with climate scenarios (#H1), the mean yield of winter wheat decreased slightly from the RC (9.5 t/ha) to the FFC scenario (9.3 t/ha), for the uniform SL (soil 1; Table 4) across all CSs. In contrast, the mean yields of SL-SS (soil 2; Table 5) increased slightly for the FFC (9.3 t/ha) compared with the RC and NFC (9.2 t/ha). The wheat yields ranged from 8.1 t/ha (CS 11) to 10.2 t/ha (CS 4) for both soils under the RC; and from 7.7 t/ha (CS 11) to 10.1 t/ha (CSs 4/6/8/10/20/22) under the FFC scenario.

The following ranking of pre-crops according to their positive effects on the mean yield of the subsequent winter wheat (#H2) was found: ryegrass > oilseed winter rape > winter rye > sugar beet. We noted that this ranking was nearly similar in all three climate scenarios and for both soils. This pre-crop effect on wheat yield was slightly higher in CS when straw was removed and without a catch crop (CC). For example, the wheat yield in the RC scenario (see first column in Table 4) showed the following ranking (t/ha): CS 5 with ryegrass: 9.87 > CS 1 with rape: 8.66 > CS 17 with rye: 8.36 > CS 11 with sugar beet: 8.29. These effects were less and not significant when straw was incorporated and CCs were used in the rotation: see, for example, wheat yields under the RC (e.g. see first column in Table 4; CS 4 with rape: 10.18; CS 10 with ryegrass: 9.98; CS 16 with sugar beet: 10.08; CS 22 with rye: 10.10 t/ha). In CSs with CC usage (#H3), winter wheat showed slightly higher mean yields under all three climate scenarios and for both soils, as in CS 'sugar beet–winter wheat–spring barley' with straw removal under the FFC (e.g. see third column in Table 4; CS 11: 7.71 t/ha *v.* CSs 13/15: 8.24/8.34). No significant differences could be found between the two types of CCs. Regarding cereal straw management (#H4), in all CSs, higher mean wheat yields were obtained (up to >1 t/ha) in simulations with straw incorporation compared with straw removal. This effect was found in all three climate scenarios and on both soils (e.g. see first column in Table 4; CS 1: 8.66 *v.* CS 2: 10.04 t/ha), but was not significant in all cases (e.g. see first column in Table 5; CS 5: 9.47 *v.* CS 6: 9.55 t/ha).

Temporal yield variability

The temporal yield variability was higher under the RC than under the future climate scenarios (#H1; see average across all CS in Table 4: 0.46 *v.* 0.25; in Table 5: 0.71 *v.* 0.29), indicating more stable future wheat yields. The yields showed higher temporal variabilities in the SL-SS (soil 2; see fourth column in Table 5: 0.71) than on the SL (soil 1; see fourth column in Table 4: 0.46), but this was only the case for the RC. Under the NFC and FFC, the results for both soils were lower and in a similar range (see fifth and sixth columns in Tables 4 and 5: 0.25–0.29).

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Table 4. Colour online. Cropping system (CS)-specific yield performance of winter wheat depending on the climate scenario for the uniform sandy loam (soil type 1; uniform 'SL')

Cropping system (CS) description			CS	Yield performance of winter wheat on the uniform sandy loam (soil type 1) depending on the climate scenario								
				Mean yield** [t/ha]			Yield variability σ^2_i			Kang's rank-sum		
Cropping sequence incl. catch crop (CC) position	Catch crop (CC)	Cereal straw management*		Recent climate	Near future climate	Far future climate	Recent climate	Near future climate	Far future climate	Recent climate	Near future climate	Far future climate
OR-WW-BY	none	removed	1	8.66 AB b	8.40 BC a	8.26 B a	1.14	0.54	0.47	39	40	38
		incorporated	2	10.04 D a	9.83 FG a	9.84 E a	0.71	0.19	0.20	26	23	24
OR-WW-(CC)-BY	Winter rye	removed	3	9.25 C a	9.09 D a	9.05 C a	1.17	0.55	0.50	37	37	35
		incorporated	4	10.18 D a	10.00 G a	10.13 E a	0.64	0.13	0.18	17	11	13
RG-WW-BY	none	removed	5	9.87 D b	9.65 EF a	9.39 D a	0.50	0.36	0.41	27	30	30
		incorporated	6	9.99 D a	9.98 G a	10.09 E a	0.64	0.37	0.46	24	25	23
RG-WW-(CC)-BY	Oilseed radish	removed	7	9.94 D a	9.83 FG a	9.79 E a	0.55	0.33	0.36	26	27	27
		incorporated	8	9.98 D a	10.00 G a	10.11 E a	0.66	0.41	0.51	28	22	24
	Winter rye	removed	9	9.96 D a	9.87 FG a	9.88 E a	0.57	0.33	0.36	26	24	24
		incorporated	10	9.98 D a	10.00 G a	10.12 E a	0.66	0.41	0.52	26	22	24
SB-WW-BY	none	removed	11	8.29 A c	7.89 A b	7.71 A a	0.31	0.29	0.16	33	36	29
		incorporated	12	9.90 D c	9.52 E b	9.17 CD a	0.13	0.11	0.16	14	20	20
SB-WW-(CC¹)-BY-(CC²)	CC¹: Oilseed radish	removed	13	8.83 B c	8.51 C b	8.24 B a	0.19	0.25	0.16	20	30	28
	CC²: Winter rye	incorporated	14	10.08 D a	9.96 FG a	9.88 E a	0.22	0.07	0.06	10	10	9
SB-WW-(CC¹)-BY-(CC²)	CC¹: Winter rye	removed	15	8.92 BC c	8.60 C b	8.34 B a	0.20	0.25	0.18	20	28	28
	CC²: Oilseed radish	incorporated	16	10.08 D a	9.99 G a	9.96 E a	0.23	0.08	0.07	11	9	9
WR-WW-BY	none	removed	17	8.36 A b	8.18 B a	8.15 B a	0.33	0.17	0.18	33	29	34
		incorporated	18	9.97 D b	9.85 FG a	9.77 E a	0.16	0.07	0.10	12	11	16
WR-WW-(CC)-BY	Oilseed radish	removed	19	8.54 AB b	8.38 BC a	8.33 B a	0.30	0.17	0.17	30	29	28
		incorporated	20	10.09 D a	10.00 G a	10.06 E a	0.23	0.09	0.09	9	9	9
	Winter rye	removed	21	8.60 AB b	8.45 BC a	8.41 B a	0.29	0.18	0.17	28	28	25
		incorporated	22	10.10 D a	10.02 G a	10.11 E a	0.24	0.10	0.10	10	6	9
			Average across all CS	9.53	9.36	9.31	0.46	0.25	0.25			

WW, winter wheat (*Triticum aestivum* L.); BY, spring barley (*Hordeum vulgare* L.); oilseed radish (*Raphanus sativus* var. *oleiformis*); OR, oilseed winter rape (*Brassica napus* L.); RG, Italian ryegrass (*Lolium multiflorum* L.); SB, sugar beet (*Beta vulgaris* subsp. *vulgaris*); WR, winter rye (*Secale cereale* L.). [a]Refers to straw of winter wheat and spring barley (+winter rye in CS 17–22); [b]significant ($P < 0.05$) differences between CS within a climate scenario (per column) are displayed by different capital letters and between climate scenarios within a CS (per row) by different small letters. Yield variability: lower values indicate less variable/more stable yields (green cells), and higher values indicate more variable/unstable yields (red cells); Kang's rank-sum: lower rank-sums indicate a good combination of high and stable yields (green cells), and higher ranks indicate lower and variable/unstable yields (red cells).

Table 5. Colour online. Cropping system (CS)-specific yield performance of winter wheat depending on the climate scenario for the sandy loam with sandy subsoil (soil type 2; 'SL-SS')

Cropping system (CS) description			CS	Yield performance of winter wheat on the sandy loam with sandy subsoil (soil type 2) depending on the climate scenario								
				Mean yield** [t/ha]			Yield variability σ^2_i			Kang's rank-sum		
Cropping sequence incl. catch crop (CC) position	Catch crop (CC)	Cereal straw management*		Recent climate	Near future climate	Far future climate	Recent climate	Near future climate	Far future climate	Recent climate	Near future climate	Far future climate
OR-WW-BY	none	removed	1	8.69 BCD a	8.53 BCE a	8.46 BC a	2.13	0.66	0.65	39	40	41
		incorporated	2	9.76 F a	9.65 FG a	9.84 F a	1.88	0.20	0.20	21	17	15
OR-WW-(CC)-BY	Winter rye	removed	3	9.27 DE a	9.20 EF a	9.29 D a	2.13	0.50	0.50	37	36	35
		incorporated	4	9.84 F a	9.75 G a	9.99 F a	1.90	0.20	0.22	21	9	9
RG-WW-BY	none	removed	5	9.47 EF a	9.48 FG a	9.40 DE a	0.50	0.18	0.32	27	18	30
		incorporated	6	9.55 EF a	9.68 FG a	9.87 F a	0.63	0.21	0.35	24	14	24
RG-WW-(CC)-BY	Oilseed radish	removed	7	9.52 EF a	9.60 FG a	9.72 EF a	0.58	0.16	0.27	26	15	24
		incorporated	8	9.53 EF a	9.67 FG a	9.88 F a	0.65	0.22	0.36	26	18	24
	Winter rye	removed	9	9.52 EF a	9.62 FG a	9.77 EF a	0.59	0.17	0.28	26	15	24
		incorporated	10	9.53 EF a	9.68 FG a	9.88 F a	0.65	0.22	0.37	28	16	24
SB-WW-BY	none	removed	11	8.11 A b	7.87 A a	7.72 A a	0.45	0.43	0.25	34	42	31
		incorporated	12	9.50 EF a	9.33 FG a	9.24 D a	0.20	0.14	0.19	14	15	19
SB-WW-(CC¹)-BY-(CC²)	CC¹: Oilseed radish	removed	13	8.84 CD b	8.78 CDE ab	8.56 BC a	0.20	0.29	0.26	19	33	28
	CC²: Winter rye	incorporated	14	9.60 F a	9.64 FG a	9.84 F a	0.40	0.23	0.18	15	23	11
SB-WW-(CC¹)-BY-(CC²)	CC¹: Winter rye	removed	15	8.91 CD a	8.84 DE a	8.67 C a	0.21	0.27	0.26	19	31	26
	CC²: Oilseed radish	incorporated	16	9.61 F a	9.64 G a	9.86 F a	0.41	0.23	0.19	15	23	12
WR-WW-BY	none	removed	17	8.24 AB a	8.16 AB a	8.17 B a	0.42	0.34	0.31	32	40	37
		incorporated	18	9.60 F a	9.66 G a	9.78 EF a	0.30	0.16	0.16	11	9	11
WR-WW-(CC)-BY	Oilseed radish	removed	19	8.40 ABC a	8.38 BC a	8.38 BC a	0.35	0.31	0.29	26	38	35
		incorporated	20	9.64 F a	9.74 G ab	9.96 F b	0.36	0.18	0.18	11	9	6
	Winter rye	removed	21	8.45 ABC a	8.45 BCE a	8.46 BC a	0.33	0.31	0.28	24	36	32
		incorporated	22	9.65 F a	9.75 G ab	9.98 F b	0.37	0.19	0.20	11	9	8
			Average across all CS	9.24	9.23	9.31	0.71	0.26	0.29			

WW, winter wheat (*Triticum aestivum* L.); BY, spring barley (*Hordeum vulgare* L.); oilseed radish (*Raphanus sativus* var. *oleiformis*); OR, oilseed winter rape (*Brassica napus* L.); RG, Italian ryegrass (*Lolium multiflorum* L.); SB, sugar beet (*Beta vulgaris* subsp. *vulgaris*); WR, winter rye (*Secale cereale* L.). [a]Refers to straw of winter wheat and spring barley (+winter rye in CS 17–22); [b]significant ($P < 0.05$) differences between CS within a climate scenario (per column) are displayed by different capital letters and between climate scenarios within a CS (per row) by different small letters. Yield variability: lower values indicate less variable/more stable yields (green cells), and higher values indicate more variable/unstable yields (red cells); Kang's rank-sum: lower rank-sums indicate a good combination of high and stable yields (green cells), and higher ranks indicate lower and variable/unstable yields (red cells).

Regarding the cropping sequence (#H2), the most stable wheat yields were determined for wheat grown after winter rye (CSs 17–22) and sugar beet (CSs 11–16), in particular under the FFC (e.g. see sixth column in Table 4; CS 14/16 with sugar beet: 0.06/0.07). In comparison, the pre-crop ryegrass and oilseed winter rape led to somewhat higher temporal yield variability in the subsequent wheat crop, which was most evident under the RC (e.g. see fourth column in Table 5; CS 1/3 with oilseed rape: 2.13). These effects were found for both soils. The usage of a CC (#H3) gave no conclusive results. In some cases, there was a slightly reduced temporal yield variability in wheat (e.g. see sixth column in Table 4; CS 12: 0.16 *v.* CS 14/16: 0.06/0.07), but there was no clear CC effect in most of the cases and no clear differentiation of yield variability due to the CC type (oilseed radish *v.* winter rye).

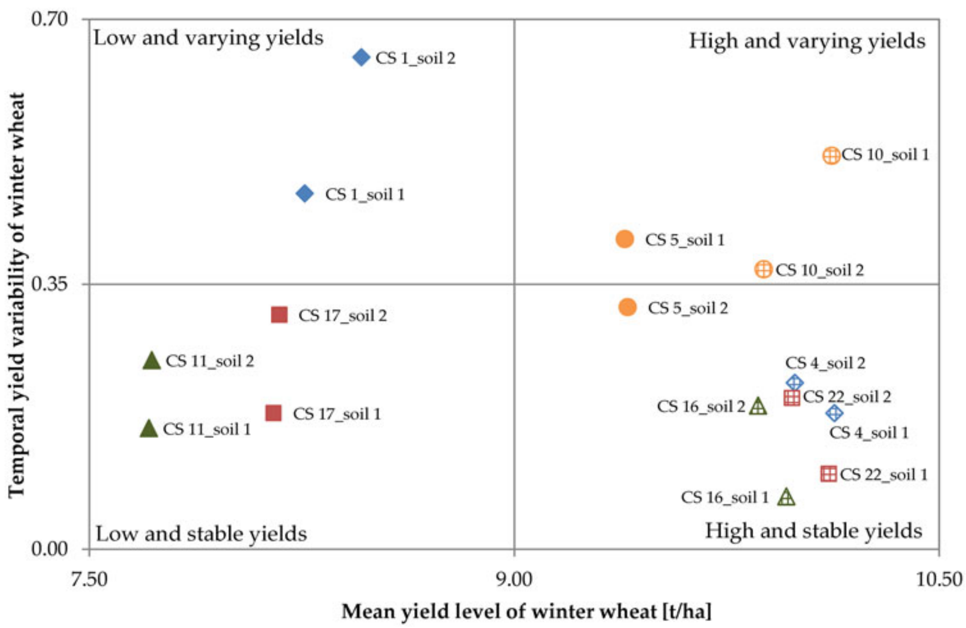

Fig. 3. Comparison of mean yield *v.* temporal yield variability in winter wheat for selected CSs grown under the far future climate (FFC) scenario for uniform sandy loam (soil 1) and sandy loam with sandy subsoil (soil 2). *Note*: Full coloured boxes indicate cropping systems (CSs) without catch crop (CC) usage in the rotation and cereal straw removal; chequered boxes indicate CSs with CC usage in the rotation and cereal straw incorporation. Different boxes indicate different pre-crops: oilseed winter rape (rhombs), Italian ryegrass (circle), sugar beet (triangle) and winter rye (square). The underlying values of the mean yield and temporal yield variability are shown in Table 4 (soil 1) and Table 5 (soil 2).

Cereal straw incorporation (#H4) reduced the temporal yield variability in wheat compared with straw removal, particularly under future climate scenarios (e.g. see fifth column in Table 5; CS 1 with straw removal: 0.65 *v.* CS 2 with straw incorporation: 0.20). This positive straw effect was not evident in CSs 5–10 with the cropping sequence 'ryegrass–winter wheat–spring barley'; here on both soils, a lower yield variability in wheat was determined under straw removal (e.g. see fourth column in Table 5; CS 5 with straw removal: 0.50 *v.* CS 6 with straw incorporation: 0.63).

Combined assessment of mean yield and temporal yield variability

Kang's rank-sum allowed for merging of the previous results of mean yield and temporal yield variability to identify high-yielding and stable CSs (indicated by lower rank-sum), which are mainly pursued in agronomic practice. Low rank-sums occurred most frequently across all three climate scenarios and on both soils for wheat grown in a cereal-CS with winter rye as the pre-crop, straw incorporation and CC usage (CSs 20/22; rank-sums: 6–9). A nearly appropriate combination of high and stable wheat yields (rank-sums: 9–13) was determined for wheat grown in CSs with sugar beet or oilseed winter rape as pre-crop, straw incorporation and CC usage (CSs 4/14/16) but predominantly under future climate scenarios (similar for both soils; Tables 4 and 5). Unfavourable combinations of low and unstable wheat yields (rank-sums > 30) were found in CSs, where the cereal straw was removed and no CCs were included in the cropping sequence (CSs 1/5/11/17; Tables 4 and 5).

In addition, a graphical comparison of the mean yield performance and temporal yield variability in wheat was shown for selected and contrasting CSs grown under the FFC scenario on both soils (Fig. 3). The CSs with CC usage in the rotation and straw incorporation showed higher and more stable future wheat yields (chequered boxes in the right bottom corner), particularly on the uniform SL (soil 1). These results were determined for CSs with the pre-crops of oilseed winter rape (CS 4), sugar beet (CS 16) and winter rye (CS 22). The best combination of a high and stable yield level was found for CS 16 on the uniform SL with a mean yield of 9.96 t/ha and a temporal yield variability of 0.07 (Fig. 3). All combinations of CSs with ryegrass as a pre-crop (CS 5/10) showed high and varying yields of the subsequent wheat (e.g. soil 2: mean yield: 10.12 t/ha; yield variability: 0.52; Fig. 3). The worst combination of low and varying yields was found for CS 1 on the SL-SS (mean yield: 8.46 t/ha; yield variability: 0.65; Fig. 3).

Probability of yield reductions

The probability of wheat yield reductions (risk across all CSs; Table 6) increased slightly from recent to future climate on the uniform SL and decreased slightly for the SL-SS (#H1). Under the RC, the risk was 6–11% higher for SL-SS than uniform SL but on a similar level for both soils under future scenarios (see Table 6; probability of 10% yield reduction: 23–25%). The risk estimations were similar under NFC and FFC. Winter wheat showed different probabilities of yield reductions (risk) depending on the pre-crop (#H2), with the following ranking from higher to lower risk: sugar beet > winter rye > oilseed winter rape > ryegrass (e.g. see first column in Table 6; CS 11: 60% > CS 17: 56% > CS 1: 41% > CS 5: 12%). In CSs 5–10 with the cropping sequence 'ryegrass–winter wheat–spring barley', a lower sensitivity to CC usage and straw management was observed compared with the other CSs (on both soils). Across all CSs, mainly straw incorporation (#H4), as well as CC usage (#H2) to a lesser extent, led to a reduced probability of wheat yield reductions. Furthermore, in each CS with straw removal and no CC (CSs 1/5/11/17), the probabilities for wheat yield reductions were comparably high and increased from recent to future climate, particularly for wheat grown in cropping sequences with sugar beet as a pre-crop (see soil 1 in Table 6; CS 11: 60% RC→85% NFC→92% FFC). In contrast, wheat grown in CSs with winter rye or oilseed winter rape as a pre-crop (#H2), CC usage (#H3) and, in particular, straw incorporation (#H4) showed the lowest probabilities for yield reductions, with risk values remaining at a low level or even decreasing from recent to future climate (see CS 4 in Table 6; soil 1: 1% in all three climate scenarios; soil 2: 13% RC→9% NFC→4% FFC).

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Table 6. Cropping system (CS)-specific probability of yield reductions for winter wheat depending on the climate scenario and soil type

Cropping system (CS) description			CS	Probability of wheat yield falling a given percentage below the average yield across all CS and scenarios (δ = 9.4 t/ha)											
				Uniform sandy loam (soil type 1)						Sandy loam with sandy subsoil (soil type 2)					
				Recent climate		Near future climate		Far future climate		Recent climate		Near future climate		Far future climate	
Cropping sequence incl. catch crop (CC) position	Catch crop (CC)	Cereal straw management*		-10%	-20%	-10%	-20%	-10%	-20%	-10%	-20%	-10%	-20%	-10%	-20%
OR-WW-BY	none	removed	1	41	10	53	13	60	19	43	9	43	11	46	13
		incorporated	2	2	0	3	0	4	0	14	3	10	1	5	0
OR-WW-(CC)-BY	Winter rye	removed	3	20	3	23	4	27	5	25	6	20	4	17	3
		incorporated	4	1	0	1	0	1	0	13	2	9	1	4	0
RG-WW-BY	none	removed	5	12	2	10	1	17	3	12	2	16	4	16	3
		incorporated	6	12	3	5	0	5	0	26	10	14	3	9	2
RG-WW-(CC)-BY	Oilseed radish	removed	7	11	2	7	1	8	1	27	10	15	3	10	2
		incorporated	8	12	3	5	0	5	0	27	11	14	3	9	2
	Winter rye	removed	9	11	2	6	1	6	1	27	10	14	3	10	2
		incorporated	10	12	3	5	0	5	0	27	11	14	3	9	2
SB-WW-BY	none	removed	11	60	13	85	25	92	36	61	11	73	30	84	33
		incorporated	12	5	0	2	0	12	0	24	7	18	4	15	2
SB-WW-(CC[1])-BY-(CC[2])	CC[1]: Oilseed radish	removed	13	29	3	47	5	66	10	38	12	34	9	41	8
	CC[2]: Winter rye	incorporated	14	4	0	1	0	1	0	24	8	15	4	8	1
SB-WW-(CC[1])-BY-(CC[2])	CC[1]: Winter rye	removed	15	25	2	40	3	58	8	36	11	31	8	35	6
	CC[2]: Oilseed radish	incorporated	16	4	0	1	0	1	0	24	8	15	4	7	1
WR-WW-BY	none	removed	17	56	9	73	8	73	11	58	7	64	10	65	8
		incorporated	18	4	0	1	0	1	0	22	7	10	1	4	0
WR-WW-(CC)-BY	Oilseed radish	removed	19	45	5	57	4	60	6	54	16	49	7	49	4
		incorporated	20	4	0	1	0	1	0	22	7	9	1	4	0
	Winter rye	removed	21	41	4	51	3	54	4	51	15	45	6	43	3
		incorporated	22	4	0	1	0	1	0	22	7	9	1	4	0
			Average across all CS	**19**	**3**	**22**	**3**	**25**	**5**	**31**	**9**	**25**	**5**	**23**	**4**

WW, winter wheat (*Triticum aestivum* L.); BY, spring barley (*Hordeum vulgare* L.); oilseed radish (*Raphanus sativus* var. *oleiformis*); OR, oilseed winter rape (*Brassica napus* L.); RG, Italian ryegrass (*Lolium multiflorum* L.); SB, sugar beet (*Beta vulgaris* subsp. *vulgaris*); WR, winter rye (*Secale cereale* L.). [a]Refers to straw of winter wheat and spring barley (+winter rye in CS 17–22).

Table 7. Cropping system (CS)-specific information about the water stress of winter wheat depending on the climate scenario and soil type

Cropping system (CS) description			CS	Water stress of winter wheat on the uniform sandy loam (soil type 1)						Water stress of winter wheat on the sandy loam with sandy subsoil (soil type 2)					
				Recent climate		Near future climate		Far future climate		Recent climate		Near future climate		Far future climate	
Cropping sequence incl. catch crop (CC) position	Catch crop (CC)	Cereal straw management*		Average duration over years with water stress [days]	Frequency of years with water stress [%]	Average duration over years with water stress [days]	Frequency of years with water stress [%]	Average duration over years with water stress [days]	Frequency of years with water stress [%]	Average duration over years with water stress [days]	Frequency of years with water stress [%]	Average duration over years with water stress [days]	Frequency of years with water stress [%]	Average duration over years with water stress [days]	Frequency of years with water stress [%]
OR-WW-BY	none	removed	1	2.8	29	3.2	29	2.9	23	5.4	45	5.8	36	4.5	34
		incorporated	2	3.0	29	3.5	28	2.9	24	5.5	45	5.9	36	4.5	34
OR-WW-(CC)-BY	Winter rye	removed	3	2.9	29	3.4	28	2.9	23	5.5	45	5.9	36	4.5	34
		incorporated	4	3.0	29	3.5	28	2.8	24	5.5	45	5.9	36	4.5	34
RG-WW-BY	none	removed	5	4.6	43	3.5	40	3.5	42	7.2	53	5.6	46	4.8	48
		incorporated	6	4.8	42	3.5	41	3.4	43	7.5	53	5.6	47	4.8	49
RG-WW-(CC)-BY	Oilseed radish	removed	7	4.8	42	3.4	42	3.4	43	7.3	54	5.6	47	4.8	49
		incorporated	8	4.8	41	3.5	42	3.3	44	7.5	54	5.6	47	4.7	50
	Winter rye	removed	9	4.8	42	3.5	41	3.4	43	7.5	53	5.6	47	4.8	49
		incorporated	10	4.8	41	3.5	42	3.4	44	7.7	53	5.6	47	4.8	49
SB-WW-BY	none	removed	11	3.2	38	3.0	33	2.5	31	6.6	51	5.6	43	4.5	44
		incorporated	12	3.7	40	3.4	34	2.7	32	7.1	53	6.0	44	4.6	49
SB-WW-(CC[1])-BY-(CC[2])	CC[1]: Oilseed radish	removed	13	3.5	39	3.2	33	2.5	33	7.4	52	5.7	45	4.6	49
	CC[2]: Winter rye	incorporated	14	3.7	40	3.4	35	2.6	34	7.4	54	5.9	46	4.9	50
SB-WW-(CC[1])-BY-(CC[2])	CC[1]: Winter rye	removed	15	3.5	39	3.3	33	2.7	31	7.4	52	5.8	45	4.6	50
	CC[2]: Oilseed radish	incorporated	16	3.7	40	3.3	35	2.6	34	7.4	54	5.9	46	4.9	50
WR-WW-BY	none	removed	17	3.8	32	3.4	27	2.7	24	7.0	44	5.6	36	4.0	36
		incorporated	18	3.9	34	3.4	29	2.8	25	6.8	48	6.0	36	4.2	37
WR-WW-(CC)-BY	Oilseed radish	removed	19	3.6	34	3.5	27	2.8	24	7.1	45	5.9	36	4.1	37
		incorporated	20	3.9	34	3.4	29	2.8	25	6.9	48	6.1	36	4.2	37
	Winter rye	removed	21	3.7	34	3.5	27	2.8	24	7.1	45	5.9	36	4.1	37
		incorporated	22	3.9	34	3.4	29	2.8	25	6.9	48	6.1	36	4.2	37
			Average across all CS	**3.8**	**36.6**	**3.4**	**33.3**	**2.9**	**31.6**	**6.9**	**49.7**	**5.8**	**41.4**	**4.5**	**42.9**

WW, winter wheat (*Triticum aestivum* L.); BY, spring barley (*Hordeum vulgare* L.); oilseed radish (*Raphanus sativus* var. *oleiformis*); OR, oilseed winter rape (*Brassica napus* L.); RG, Italian ryegrass (*Lolium multiflorum* L.); SB, sugar beet (*Beta vulgaris* subsp. *vulgaris*); WR, winter rye (*Secale cereale* L.). [a]Refers to straw of winter wheat and spring barley (+winter rye in CS 17–22).

Water stress of winter wheat

From the RC to the FFC scenario, the water stress of winter wheat, measured as the duration in and frequency of wheat-growing seasons, decreased (Table 7; see average across all CS for e.g. soil 2; duration: 6.9→4.5 days; frequency: 49.7→42.9%). This trend was found for both soils, with higher water stress on the SL-SS (soil 2: 6.9 days under RC) than on the uniform SL (soil 1: 3.8 days under RC; average across all CS in Table 7). Regarding the pre-crop effect, the water stress of winter wheat was lowest in CSs with preceding oilseed rape, followed by CSs with sugar beet, winter rye and ryegrass as pre-crop (e.g. see first column in Table 7; CS 1: 2.8 > CS 11: 3.2 > CS 17: 3.8 > CS 5: 4.6 days). No clear effect of CC usage within the rotation was found. Compared to straw removal, the straw incorporation had no effect or led to a minimal increase in water stress of winter wheat in some cases (e.g. see first column in Table 7; CS 11 with straw removal: 3.2 > CS 12 with straw incorporation: 3.7 days).

Net nitrogen mineralization

The net N mineralization, both in wheat-growing seasons and over the entire rotation, was highest in CSs with ryegrass, followed by oilseed rape, and lower in CSs with sugar beet and winter rye (e.g. see first column in Table 8; CS 1: 80 > CS 5: 120 > CS 11: 60 > CS 17: 51 kg N/ha). This ranking was similar in all three climate scenarios and on both soils, with somewhat higher net N

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Table 8. Cropping system (CS)-specific information about the net nitrogen (N) mineralization in winter wheat-growing seasons and accumulation over the rotation depending on the climate scenario and soil type

Cropping system (CS) description			CS	Uniform sandy loam (soil type 1)						Sandy loam with sandy subsoil (soil type 2)					
Cropping sequence incl. catch crop (CC) position	Catch crop (CC)	Cereal straw management[a]		Average sum of net N-mineralization in wheat growing seasons [kg N/ha]			Average net N-mineralization cumulated over the rotation [kg N/ha]			Average sum of net N-mineralization in wheat growing seasons [kg N/ha]			Average net N-mineralization cumulated over the rotation [kg N/ha]		
				Recent climate	Near future climate	Far future climate	Recent climate	Near future climate	Far future climate	Recent climate	Near future climate	Far future climate	Recent climate	Near future climate	Far future climate
OR-WW-BY	none	removed	1	80	75	73	270	270	268	81	84	82	276	276	274
		incorporated	2	111	124	123	367	372	369	115	141	139	379	385	383
OR-WW-(CC)-BY	Winter rye	removed	3	94	93	94	322	334	337	99	108	108	336	350	352
		incorporated	4	160	145	147	430	443	445	138	165	165	450	465	466
RG-WW-BY	none	removed	5	130	130	121	325	332	334	132	142	134	330	341	344
		incorporated	6	179	183	182	437	449	459	179	197	200	444	460	475
RG-WW-(CC)-BY	Oilseed radish	removed	7	143	148	144	379	399	409	147	161	161	390	414	429
		incorporated	8	191	199	203	502	521	537	193	213	222	514	535	559
	Winter rye	removed	9	146	152	150	384	405	418	149	165	167	394	420	438
		incorporated	10	194	202	208	506	526	543	195	217	227	517	539	565
SB-WW-BY	none	removed	11	60	65	66	200	190	182	61	49	43	196	189	182
		incorporated	12	53	60	62	309	297	284	58	116	106	310	302	291
SB-WW-(CC^1)-BY-(CC^2)	CC^1: Oilseed radish CC^2: Winter rye	removed	13	80	93	97	280	286	283	88	86	78	298	313	308
		incorporated	14	81	90	91	412	421	418	93	158	155	440	462	461
SB-WW-(CC^1)-BY-(CC^2)	CC^1: Winter rye CC^2: Oilseed radish	removed	15	75	86	88	283	288	285	81	87	81	301	314	310
		incorporated	16	75	82	80	414	424	422	86	158	157	442	463	462
WR-WW-BY	none	removed	17	51	54	53	159	159	156	51	57	55	161	161	158
		incorporated	18	108	116	112	329	331	331	113	133	127	341	345	346
WR-WW-(CC)-BY	Oilseed radish	removed	19	57	61	61	186	188	187	57	65	63	190	193	192
		incorporated	20	121	134	132	380	392	398	128	153	151	399	413	421
	Winter rye	removed	21	59	64	64	190	193	193	59	67	67	194	199	198
		incorporated	22	125	138	138	386	399	406	131	158	157	405	420	428
			Average across all CS	**108**	**113**	**113**	**339**	**346**	**348**	**111**	**131**	**129**	**350**	**362**	**366**

WW, winter wheat (*Triticum aestivum* L.); BY, spring barley (*Hordeum vulgare* L.); oilseed radish (*Raphanus sativus* var. *oleiformis*); OR, Oilseed winter rape (*Brassica napus* L.); RG, Italian ryegrass (*Lolium multiflorum* L.); SB, Sugar beet (*Beta vulgaris* subsp. *vulgaris*); WR, Winter rye (*Secale cereale* L.). [a]Refers to straw of winter wheat and spring barley (+ winter rye in CS 17–22).

mineralization under the FFC scenario than RC; and higher on the SL-SS (soil 2; e.g. RC: 111 kg N/ha; FFC: 129 kg N/ha) than on the uniform SL (soil 1; e.g. RC: 108 kg N/ha; FFC: 113 kg N/ha) (see average across all CS in Table 8). The difference between the soils is caused by SL-SS being better drained, thus less moist and warmer, favouring mineralization. The usage of CC within the rotation resulted in all CSs in higher net N mineralization (e.g. CS 5 without CC: 130 *v.* CS 7/9 with CC: 143/146 kg N/ha), but there was no clear differentiation between the two CC used (oilseed radish/winter rye). A clear effect was also found for straw management. In all CSs, the straw incorporation led to increased net N mineralization – both in wheat-growing seasons and cumulated over rotation – compared to straw removal. This effect was found in all soil × climate scenarios (e.g. first column in Table 8; CS 1 with straw removal: 80 kg N/ha *v.* CS 2 with straw incorporation: 111 kg N/ha).

Soil organic matter content

Across all CS, the SOM content decreased for C, and slightly for N, from the RC to the FFC scenario (see last row in Table 9; e.g. soil 1: 322.3 RC→317.6 NFC→315.2 t C/ha FFC). The level of C and N content in the SOM was higher on the uniform SL (322.3 t C/ha; 17.7 t N/ha in recent climate) than on the SL-SS (146.7 t C/ha; 11.9 t N/ha in recent climate; Table 9). The higher SOM-content on the uniform SL is in line with the lower mineralization described above. The CSs with oilseed rape showed the highest SOM, followed by systems with ryegrass or sugar beet, and were lowest in cereal CSs with winter rye (e.g. see first column in Table 9; CS 1: 314.9 > CS 5: 306.4 > CS 11: 303.6 > CS 17: 295.4 t C/ha). A similar ranking was found on both soils. The CC within rotations led to a slight increase in SOM (C and N content) compared to no CC usage, but no clear differentiation between CC species. Straw management showed a greater impact, with straw incorporation resulting in higher SOM (C and N content) than straw removal (e.g. see fourth column in Table 9; CS 5: 16.3 t N/ha straw removed *v.* 18.2 t N/ha straw incorporated). Overall, cereal CS without CC usage and straw removal showed the lowest SOM contents, with a decreasing trend over time (see Table 9; soil 2 – CS 17: 123.1→116.4 t C/ha; 9.7→9.1 t N/ha). In contrast, in CSs with a more diversified cropping sequence, CC usage and straw incorporation (e.g. CS 4/8/10/14/16), higher SOM contents were found, slightly decreasing from the RC to the FFC scenario (e.g. see Table 9; soil 2 – CS 10: 157.6→153.8 t C/ha; 12.9→12.5 t N/ha).

Discussion

More stable future wheat yields due to lower water stress

The overall decreasing trend towards lower temporal yield variability under the future climate, as shown for nearly all CSs and for both soils (Tables 3 and 4), was mainly related to the lower water stress of wheat within the wheat-growing periods and less frequent years with water stress (Table 7). The lower water stress is due to higher annual net precipitation, which is increasing by 24% from the RC to the FFC scenario, especially during the months of November to May (see Appendix Table A1), although there are also higher temperatures and consequently higher evapotranspiration of wheat plants. Ozturk *et al.* (2017) and Rasmussen *et al.* (2018) estimated an increasing annual sum of precipitation for Denmark under the future climate but also with a higher variation in precipitation from one year to the next and more frequent heavy rainfall events. However, the indirect effects of climatic changes were not considered by the model (e.g. effects of rainfall on lodging or *Septoria* disease), which could instead increase yield variability, and the observed positive trend in the present study could be levelled out.

Yield risk strongly depends on management factors

The future yield risk of wheat does not necessarily increase under climate change for Eastern Denmark, but it largely depends on the management factors or CS design, as demonstrated for the effects

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Table 9. Cropping system (CS)-specific information about the soil organic matter (SOM) content (carbon and nitrogen) depending on the climate scenario and soil type

Cropping system (CS) description			CS	Soil organic matter content (SOM) on the uniform sandy loam (soil type 1)						Soil organic matter content (SOM) on the sandy loam with sandy subsoil (soil type 2)					
Cropping sequence incl. catch crop (CC) position	Catch crop (CC)	Cereal straw management*		SOM_Carbon [t C/ha]			SOM_Nitrogen [t N/ha]			SOM_Carbon [t C/ha]			SOM_Nitrogen [t N/ha]		
				Recent climate	Near future climate	Far future climate	Recent climate	Near future climate	Far future climate	Recent climate	Near future climate	Far future climate	Recent climate	Near future climate	Far future climate
OR-WW-BY	none	removed	1	314.9	309.8	306.6	17.1	16.6	16.3	140.0	135.0	132.2	11.3	10.8	10.6
		incorporated	2	338.8	331.5	326.9	19.2	18.6	18.2	160.5	153.6	149.8	13.1	12.5	12.2
OR-WW-(CC)-BY	Winter rye	removed	3	320.5	316.4	313.7	17.6	17.2	17.0	145.0	140.7	138.4	11.7	11.3	11.1
		incorporated	4	344.5	337.6	333.8	19.8	19.1	18.8	165.7	159.1	155.9	13.6	13.0	12.7
RG-WW-BY	none	removed	5	306.4	303.9	302.9	16.3	16.1	16.0	132.7	129.9	129.2	10.6	10.4	10.3
		incorporated	6	326.9	323.0	321.6	18.2	17.8	17.7	150.5	146.6	145.6	12.2	11.9	11.8
RG-WW-(CC)-BY	Oilseed radish	removed	7	312.0	310.4	310.0	16.8	16.7	16.6	137.7	135.7	135.7	11.1	10.9	10.9
		incorporated	8	333.1	329.7	328.6	18.7	18.4	18.3	156.2	152.6	151.9	12.7	12.4	12.4
	Winter rye	removed	9	313.3	311.9	311.8	16.9	16.8	16.8	138.8	137.0	137.3	11.2	11.0	11.0
		incorporated	10	334.6	331.5	330.7	18.9	18.6	18.5	157.6	154.2	153.8	12.9	12.6	12.5
SB-WW-BY	none	removed	11	303.6	298.7	295.5	16.0	15.6	15.3	129.9	124.7	122.1	10.4	9.9	9.6
		incorporated	12	328.8	321.6	317.0	18.3	17.7	17.2	151.7	144.9	141.3	12.3	11.7	11.4
SB-WW-(CC^1)-BY-(CC^2)	CC^1: Oilseed radish CC^2: Winter rye	removed	13	313.0	309.6	306.8	16.9	16.5	16.3	139.3	135.8	133.4	11.2	10.9	10.7
		incorporated	14	338.9	333.6	329.9	19.2	18.7	18.4	161.7	156.9	153.9	13.2	12.8	12.5
SB-WW-(CC^1)-BY-(CC^2)	CC^1: Winter rye CC^2: Oilseed radish	removed	15	312.9	309.3	306.6	16.9	16.5	16.3	139.0	135.2	133.1	11.2	10.8	10.6
		incorporated	16	338.5	333.1	329.9	19.2	18.7	18.4	161.3	156.3	153.6	13.2	12.8	12.5
WR-WW-BY	none	removed	17	295.4	291.2	288.7	15.3	14.9	14.7	123.1	118.6	116.4	9.7	9.3	9.1
		incorporated	18	334.3	327.0	323.6	18.8	18.2	17.9	157.0	150.2	147.4	12.8	12.2	11.9
WR-WW-(CC)-BY	Oilseed radish	removed	19	299.1	295.3	292.9	15.6	15.3	15.1	126.5	122.4	120.3	10.0	9.7	9.5
		incorporated	20	339.2	332.3	329.6	19.3	18.7	18.4	161.5	155.0	152.7	13.2	12.6	12.4
	Winter rye	removed	21	300.3	296.6	294.5	15.7	15.4	15.2	127.5	123.5	121.7	10.1	9.8	9.6
		incorporated	22	340.8	334.1	331.7	19.4	18.8	18.6	163.0	156.6	154.6	13.4	12.8	12.6
			Average across all CS	**322.3**	**317.6**	**315.2**	**17.7**	**17.3**	**17.1**	**146.7**	**142.0**	**140.0**	**11.9**	**11.5**	**11.3**

WW, winter wheat (*Triticum aestivum* L.); BY, spring barley (*Hordeum vulgare* L.); oilseed radish (*Raphanus sativus* var. *oleiformis*); OR, oilseed winter rape (*Brassica napus* L.); RG, Italian ryegrass (*Lolium multiflorum* L.); SB, sugar beet (*Beta vulgaris* subsp. *vulgaris*); WR, winter rye (*Secale cereale* L.). [a]Refers to straw of winter wheat and spring barley (+winter rye in CS 17–22).

of cropping sequence (pre-crop), CC usage and straw management. If a CS is not favourable and is characterized by consequent straw removal and no CCs are grown within the rotation (CSs 1/5/11/17), higher yield risks were observed for wheat. This management effect interacts with the climate, so the effect is pronounced in the future climate scenario. Thus, it is possible that farmers will face more frequent yield reductions and decreasing, or less stable wheat yields under the projected future climate scenario than currently. This finding has also been observed in a recent climate change impact study of Denmark by Ozturk *et al.* (2017), where wheat yield decreased in continuous wheat CSs, despite increasing CO_2 concentration in the atmosphere. One of the major determining factors of crop yield is the N supply, which also has a great impact on yield variability and yield risk. In this context, one reason for the lower yields and higher risk in these non-favourable CSs (CSs 1/5/11/17) within the present study is the relatively low net N mineralization in growing seasons with wheat and over the entire rotation, which even decreased from the RC to the FFC scenario (Table 8). These non-favourable CSs also had a lower SOM level with decreasing trend over time (Table 9), and the N recycling within the rotation was not as effective (higher N losses; Appendix Table A4). These findings are in line with the long-term effects of straw removal observed by Xu *et al.* (2019), which led to lower and more variable wheat yields and lower soil organic C storage (compared with straw return). Thus, from an agronomic and environmental point of view, these not so favourable CSs lead to higher production risk and are not preferable under the present and particularly under the future climate conditions.

In contrast, favourable CSs with a more diverse cropping sequence, CC usage and straw incorporation (CSs 4/8/10/14/16/20/22) maintained their capacity and helped to reduce the yield risk both now and in the future. Based on the modelling results, an increasing, or at least stable yield trend (from recent to future climate), combined with lower temporal yield variability and less probability of yield reductions can be expected for wheat grown in this kind of system. These findings are confirmed by studies of Lin (2011), Gaudin *et al.* (2015) and Degani *et al.* (2019), who showed that CSs with additional added organic material and crop diversity provide a systems approach for improving resilience and stress resistance, as well as maintaining crop yields with reduced external inputs under greater climate variability and extreme events. In contrast, St-Martin *et al.* (2017) found diverging results from long-term experiments across Europe and stated that winter wheat in more diverse CSs led to higher yields but did not find consistent benefits of reduced temporal yield variability.

The greater and stable yield performance in the more favourable CSs within the present study was caused, inter alia, by the higher soil organic N content (Table 9), better N recycling (less nitrate leaching; Appendix Table A4) and higher net N mineralization (Table 8). Similar first indications of higher SOM content supporting yield and yield stability of winter wheat, and *vice versa*, have also been shown in a Serbian study by Seremesic *et al.* (2011). Furthermore, the residual N remaining in the soil or mineralizing in the following growing seasons is a key factor in determining subsequent wheat yields in the absence of diseases or other restrictions (Christen, 2001; Kirkegaard *et al.*, 2008; Angus *et al.*, 2015). A study by Kyveryga *et al.* (2013) showed that in years with favourable growing conditions, crops were able to respond to higher N availability, resulting in higher environmental adaptability and a lower risk of yield loss (Kyveryga *et al.*, 2013). Knapp and van der Hejden (2018) also confirmed that a larger supply of plant-available N could be a very important factor in reducing interannual yield variability if plant growth is not limited by other constraints. Regarding the potential pre-crop effects, Evans *et al.* (2003) showed that based on a crop rotation experiment in Wales (UK), the allocation of residual N and the total N content within the soil significantly affects the yield of the subsequent crops. This finding can be confirmed by Kollas *et al.* (2015) and within the present study, where the higher net N mineralization rate (Table 8) and higher soil organic N content (Table 9) also explain the better yield performance of wheat grown after ryegrass and oilseed winter rape rather than grown after sugar beet or winter rye. Compared with ryegrass and oilseed winter rape, the pre-crop winter rye led to lower temporal yield variability in wheat. This result is in line with the findings of Engström and Lindén (2009) based on a rotational experiment in south Sweden, where wheat yields were more unstable/variable after oilseed winter rape compared with a cereal pre-crop. Another crop rotation experiment from Germany showed contrasting results, with higher temporal yield variability of winter wheat grown after winter rye and more stable wheat yields with previous oilseed winter rape (Macholdt and Honermeier, 2018). These findings are based on field experiments and cannot be easily transferred to the modelling results. The full spectrum of crop rotational benefits, for example, plant healthiness and reduced weed pressure (Angus *et al*., 2015), cannot be shown in a modelling approach like this, where all plants stayed healthy and biotic stressors were not be considered, such as soil-borne root pathogens or weeds. Thus, the simulated pre-crop effects were partly underestimated, and the better yield stability of wheat in the cereal-CSs (CSs 17–22) might not hold under real field conditions. The same issue can occur in cereal-CSs under field conditions, when the straw of only cereal crops (rye, wheat, barley) was incorporated, with related potential increases of fungal diseases (Babulicova, 2014; Xu *et al*., 2019).

In the present study, a clear differentiation between the two CCs (oilseed radish and winter rye) could not be determined. Thus, future research projects focusing on the analysis of a broad range of CC species and their potential impact on the yield risk of subsequent crops or entire CSs are needed.

However, for all CSs, a decreasing SOM trend from the RC to the FFC scenarios was observed (Table 9), partly due to the increased temperature. A different equilibrium level has to be expected when the temperature is higher, because it increases SOM breakdown. Thus, CS management seemed insufficient for maintaining the SOM content over a long-term period in future climates, which is an important indicator of soil quality and agronomic sustainability in agro-ecosystems (Seremesic *et al*., 2011; Liu *et al*., 2019). More temporal and spatial diversification of CSs by introducing legumes or perennial crops in the cropping sequences combined with more frequent CC usage or green manure (Liu *et al*., 2019; Macholdt *et al*., 2019), cover crops and intercropping (Raseduzzaman and Jensen, 2017), etc., would be conceivable ways to make CS improvements with regard to resilience, which are worthwhile investigations for follow-up research studies.

Limitations of this study

The impact of climate change on the yield risk of wheat was assessed with a focus on changes in air temperature and precipitation, while the content of CO_2 in the atmosphere was not considered. A comparable climate change study by Kristensen *et al*. (2010) reported prospective negative effects of increased temperature, particularly during grain filling, on winter wheat yield in Denmark when increased CO_2 in the atmosphere was not considered. They estimated a 3.5% decline in dry matter yield for wheat due to a 1°C rise for a sandy loam (Kristensen *et al*., 2010), which is similar to the observed slight decrease in wheat yield (across all CSs) on the uniform SL used in the present study (soil 1; Table 4). A further climate change study by Ozturk *et al*. (2017) also indicated a decrease in wheat yield for Denmark under future climate conditions in scenarios where the increase in CO_2 in the atmosphere was ignored. When the CO_2 increase was combined with increased temperature, initially, a positive trend towards slightly higher yields was simulated. However, after prolonged exposure to increased CO_2 concentrations, the stimulatory effect slows down, and the positive yield trend stagnates, which was also observed for spring wheat in a FACE (free-air CO_2 enrichment) experiment under different soil N conditions by Wall *et al*. (2000). Based on their findings, under higher CO_2 concentrations, an acclimatory response (downregulation) in the photosynthetic apparatus of field-grown wheat can be assumed if N is not in ample supply (Blackshaw *et al*., 2017; Ozturk *et al*., 2017).

`In addition to the importance of climate and agronomic management, differences in the yield risk of wheat are closely related to soil conditions, which were exemplarily shown in this study by two common soil types for the case region of Eastern Denmark. There is a wide range of soils, and even within a field, there is often soil heterogeneity. Since soil texture (bulk density) and hydraulic parameters remain fixed throughout this study, the effects in these scenarios should be considered conservative. It should be noted that other soil conditions and climate predictions may lead to different results.

It is expected that breeding progress and warmer temperatures will allow farmers to grow new crop species and genotypes, which are better adapted to future agroclimatic conditions and help to reduce the production risk. This aspect, as well as an economic risk assessment (Stanger *et al*., 2008), was not part of the present study but should be the subject of future research, for which comprehensive data sets and experimental results are needed. Given the limitations, this study was useful for providing initial and regional estimates of how future climate-depending agronomic management will impact the yield risk of wheat CSs.

Conclusion

For the case region of Eastern Denmark, the future yield risk of wheat does not necessarily increase under climate change mainly due to lower water stress; rather, it depends on appropriate management (hypothesis H1 partly accepted). The cropping sequence had an impact on the subsequent wheat performance, but rye, as a preceding cereal crop, did not generally lead to higher risk than non-cereal preceding crops (hypothesis H2 rejected). The major determining factor for the yield risk of wheat was residue management with related N supply and added organic material during the rotations. Here, wheat grown in systems with cereal straw removal and no CC usage led to a higher yield risk in future climate scenarios. In contrast, more favourable CSs with CC usage and straw incorporation maintained their capacity and resulted in a lower yield risk of wheat under future climate scenarios (hypotheses H3 and H4 accepted).

This study quantifies the risk-reducing impact of appropriate management pronounced under a changing climate, even under current farming conditions. Further studies are needed to validate the robustness of the results and their transferability to different crops, production systems or site conditions. A better understanding of how agronomic management practices can help C sequestration and guard against increasing yield risk in the future would be an appropriate complement.

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Appendix

Table A1. Monthly averages of minimum and maximum air temperature (T min; T max) and monthly average sum of precipitation used for the simulations under recent, near future and far future climate scenarios in the case region of Eastern Denmark

	Recent climate (RC)			Near future climate (NFC)			Far future climate (FFC)		
Month	T min (°C)	T max (°C)	Precipitation (mm)	T min (°C)	T max (°C)	Precipitation (mm)	T min (°C)	T max (°C)	Precipitation (mm)
January	−0.8	3.4	64.2	0.1	4.4	67.3	2.0	6.2	80.4
February	−2.1	2.7	38.8	−0.3	4.6	43.2	0.7	5.5	41.8
March	0.2	6.4	50.4	1.4	7.7	62.2	2.1	8.4	62.4
April	3.1	11.1	38.1	3.8	11.4	49.1	4.6	12.3	52.9
May	7.3	15.5	49.8	8.0	16.3	49.2	8.4	16.4	58.9
June	10.9	18.9	60.6	11.9	20.1	56.8	12.1	20.4	55.2
July	13.4	21.6	61.6	14.1	22.2	68.8	14.0	22.0	77.7
August	13.2	21.1	71.0	13.9	21.9	82.0	14.1	22.2	83.2
September	10.2	17.0	57.6	11.6	18.4	60.3	11.6	18.5	59.0
October	6.3	12.1	59.6	8.1	14.0	58.3	8.2	14.0	57.4
November	2.9	7.4	62.0	4.7	9.2	68.2	5.7	10.2	82.3
December	0.0	4.3	62.7	0.2	4.5	64.1	2.8	7.1	75.5
Annual average[a]/ sum[b]	5.4	11.8	676.4	6.5	12.9	729.5	7.2	13.6	786.7

Weather data set generated by Rasmussen *et al.* (2018), projections based on the HIRHAM climate model developed by the Danish Meteorological Institute (Christensen *et al.*, 2006).
[a]Average of temperature values; [b]sum of precipitation values.

Table A2. Main crops with more than 10 000 hectares of cultivated area grown in 2019 in Eastern Denmark (Region Zealand)

Main crop	Cultivated area 2019 (ha)
Grass (seed production)	43 366
Spring barley	1 16 785
Sugar beet	28 971
Oilseed winter rape	38 070
Winter rye	10 180
Winter wheat	1 39 881
Sum of main crops (as listed above)	3 77 253
Agricultural area in total for Eastern Denmark (Zealand)	4 67 017

Data available online at Statistics Denmark (https://www.statbank.dk).

Table A3. Description of the crop-specific management actions used for the simulations

Crop (as main or catch crop)	Soil tillage	Sowing date	Split-application times and % of mineral N fertilization[a]	Harvest
Oilseed winter rape (as main crop)	Stubble cultivation (after harvest of pre-crop); ploughing; seedbed preparation (mid-August)	Late August	Late August (10%), mid-April (90%)	Mid-August; at full maturity; plant residues remain on field
Ryegrass for seeds (as main crop)	None	Early May; undersown in spring barley (pre-crop)	Early August (25%), late September (50%), late April (25%)	Late August; at full maturity; plant residues remain on field
Spring barley (as main crop)	Stubble cultivation (after harvest of pre-crop); ploughing; seedbed preparation (mid-March)	Early April	Early April (30%), Late April (70%)	Mid-July; at full maturity; straw incorporated or removed
Sugar beet (as main crop)	Stubble cultivation (after harvest of pre-crop); ploughing; seedbed preparation (mid-March)	Mid-April	Mid-April (40%), Mid-May (60%)	October; at full maturity; plant residues remain on field
Winter rye (as main crop)	Stubble cultivation (after harvest of pre-crop); ploughing; seedbed preparation (early September)	Mid-September	Early April (40%), early May (60%)	Mid-August; at full maturity; straw incorporated or removed
Winter wheat (as main crop)	Stubble cultivation (after harvest of pre-crop); ploughing; seedbed preparation (early September)	Mid-September	Early April (40%), early May (60%)	Mid-August; at full maturity; straw incorporated or removed
Winter rye (catch crop)	Stubble cultivation (of pre-crop)	Latest on 20 August; in one work step with stubble cultivation	None	No harvest; incorporation of plant biomass
Fodder radish (catch crop)				

Dates of operations were adjusted to account for increasing temperature under near/far future climate scenarios: ploughing +12/+20 days; sowing +12/+18 days; first fertilizer applications −4/−6 days; second fertilizer application −8/−12 days; harvest −11/−18 days (Henriksen *et al*., 2013; Ozturk *et al*., 2017).
[a]Standard yields and specific N fertilizer amounts for the main crops are shown in Table 3.

Table A4. CS-specific information about the average denitrification and N leaching (accumulated over the rotation) depending on the climate scenario and soil type

Cropping system (CS) description: Cropping sequence incl. catch crop (CC) position	Catch crop (CC)	Cereal straw management*	CS	Uniform sandy loam (soil type 1): Average denitrification cumulated over the rotation [kg N/ha]: Recent climate	Near future climate	Far future climate	Uniform sandy loam (soil type 1): Average N leaching cumulated over the rotation [kg N/ha]: Recent climate	Near future climate	Far future climate	Sandy loam with sandy subsoil (soil type 2): Average denitrification cumulated over the rotation [kg N/ha]: Recent climate	Near future climate	Far future climate	Sandy loam with sandy subsoil (soil type 2): Average N leaching cumulated over the rotation [kg N/ha]: Recent climate	Near future climate	Far future climate
OR-WW-BY	none	removed	1	50	61	73	15	18	20	40	48	57	21	27	29
		incorporated	2	76	90	106	22	22	24	66	72	86	35	34	36
OR-WW-(CC)-BY	Winter rye	removed	3	52	63	74	9	9	10	40	49	59	11	10	11
		incorporated	4	76	91	105	18	15	18	59	72	85	30	24	25
RG-WW-BY	none	removed	5	45	55	66	37	34	34	35	42	51	51	47	45
		incorporated	6	66	82	98	53	47	40	52	65	78	77	66	56
RG-WW-(CC)-BY	Oilseed radish	removed	7	47	58	67	29	24	21	36	45	53	38	31	25
		incorporated	8	65	81	96	44	38	31	50	63	76	65	55	43
	Winter rye	removed	9	47	58	69	30	25	21	36	45	54	40	32	26
		incorporated	10	66	82	97	45	38	32	50	64	77	66	56	45
SB-WW-BY	none	removed	11	43	51	62	13	15	17	30	36	44	29	35	36
		incorporated	12	71	82	96	14	16	18	52	61	72	35	40	39
SB-WW-(CC^1)-BY-(CC^2)	CC^1: Oilseed radish CC^2: Winter rye	removed	13	47	56	67	3	3	4	33	41	50	6	7	8
		incorporated	14	71	82	94	5	3	5	51	61	72	13	11	10
SB-WW-(CC^1)-BY-(CC^2)	CC^1: Winter rye CC^2: Oilseed radish	removed	15	47	56	66	3	3	4	33	41	49	6	8	8
		incorporated	16	72	83	95	5	4	5	51	62	73	14	12	11
WR-WW-BY	none	removed	17	34	41	49	9	8	9	26	32	38	13	13	13
		incorporated	18	66	81	94	16	14	14	53	64	76	25	23	23
WR-WW-(CC)-BY	Oilseed radish	removed	19	35	43	49	5	3	4	26	32	38	6	4	4
		incorporated	20	67	80	92	9	6	5	53	64	75	13	8	6
	Winter rye	removed	21	36	43	51	5	3	4	26	33	39	6	4	3
		incorporated	22	67	81	93	9	6	5	53	65	76	13	8	6
			Average across all CS	**57**	**68**	**80**	**18**	**16**	**16**	**43**	**53**	**63**	**28**	**25**	**23**

WW, winter wheat (*Triticum aestivum* L.); BY, spring barley (*Hordeum vulgare* L.); oilseed radish (*Raphanus sativus* var. *oleiformis*); OR, oilseed winter rape (*Brassica napus* L.); RG, Italian ryegrass (*Lolium multiflorum* L.); SB, sugar beet (*Beta vulgaris* subsp. *vulgaris*); WR, winter rye (*Secale cereale* L.).
[a]Refers to straw of winter wheat and spring barley (+winter rye in CS 17–22).

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