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Crop modelling based analysis of site-specific production limitations of winter oilseed rape in northern Germany

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ABSTRACT

Winter oilseed rape production is typically characterised by low nitrogen (N) use efficiency. Defining site-specific fertiliser strategies based on field trials and crop modelling may help to improve the ecological efficiency of this crop. However, no model has been evaluated for winter oilseed rape that simulates the growth of the plant as limited by the interaction of water and N. In this study, the APSIM canola model which was originally developed for the temperate regions of Australia, was adapted for conditions in Germany and tested against measured data (total biomass, grain yield, leaf area index, N-uptake and soil mineral N) at three sites near Göttingen (northern Germany). In the second part of the study, the evaluated model was used in a simulation experiment to explore site-specific climate and soil related production limitations to match fertiliser rates to yield targets. Historical weather data from four sites across northern Germany and a fertile loamy soil with different rooting depths, implicating different plant available water capacities, were used. Model results showed large differences in yield (up to 1000 kg ha^{-1}) and N-balance (>30 kg ha^{-1}) for 200 kg N-fertiliser rate ha^{-1} between restricted (50 cm) and unrestricted rooting depths. Simulated yields for such high N-fertiliser rate were lower for sites with continental climate than for sites close to the coast, reflecting different rainfall patterns. Results indicate that water supply plays a critical role when maintaining high N use efficiency and reaching simultaneously grain yields of 4000 kg ha^{-1}.

1. Introduction

The average yields of winter oilseed rape (*Brassica napus* L.) have reached 4000 kg ha^{-1} in many northern states in Germany since 2000 with the most favourable sites regularly yielding above 5000 kg ha^{-1} (Statistisches Bundesamt, 2014). Under optimal growing conditions (optimal nutrient and water supply, absence of pest and diseases, no weeds) a potential grain yield of 6500 kg ha^{-1} has been suggested by Berry and Spink (2006). However, under rainfed conditions winter oilseed rape production in Germany is frequently affected by water stress, indicated by national yields below 3000 kg ha^{-1} in years with a dry spring period as observed in 2003 and 2011 (Statistisches Bundesamt, 2014). Indeed, oilseed rape is a water demanding crop (Gerbens-Leenes et al., 2009) with studies showing that >300 mm of water must be available from flowering to maturity to support high yields of more than 4000 kg ha^{-1} (Berry and Spink, 2006; Rathke et al., 2006). Available soil moisture at flowering is therefore critical to support the crop under conditions where rainfall is limited. Shallow, sandy or constrained soils with low plant available water capacity (PAWC) therefore have a limited ability to buffer a crop during periods of low rainfall, and it is on these soil types that yields are most severely limited.

Another limiting factor in oilseed rape production is that N-application is restricted by the EU Nitrate Directive in Germany to limit average annual N-balance (N applied minus N removed by harvest) to a three year average of 60 kg ha^{-1}. N-balance measured after winter oilseed rape usually exceeds this limit, and is frequently above 100 kg ha^{-1} (Henke et al., 2007). Large surpluses arise due to typical fertiliser rates in the range of 160 to 200 kg N ha^{-1} in spring. A low harvest index (HI; ratio harvested organ/total biomass) of oilseed rape, typically 0.3, and N harvest index (NHI; ratio N in harvested organ/N in total biomass) of 0.6–0.7 result in a large proportion of the applied N remaining in straw residues on the field. The following crop, commonly winter wheat, is not able to take up the mineralising N in autumn. Despite this overall trend, the N-balance for the same N-fertiliser rate can differ strongly from site to site (Sieling and Kage, 2010), when factors,

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which are largely beyond the scope of management, such as water supply, solar radiation and temperature, limit growth. Matching fertiliser application rates to site-specific attainable yield may help to adapt management practices and improve the N-balance.

In the last twenty years, field trials have been widely conducted in Germany to define site-specific best management practices by setting targets for site-specific yield and improved N use efficiency (Lickfett, 1993; Henke et al., 2008a, 2008b; Rathke et al., 2006). However, field trials are expensive and time consuming and, more importantly, results and also N-response curves statistically derived from these trials are difficult to extrapolate to other sites and years due to the complex nature of the interaction between crop physiology, N-uptake and distribution, temperature driven growth duration, intercepted radiation and water supply (rainfall amount, distribution and storage in the soil) (Henke et al., 2007; Schulte auf'm Erley et al., 2011). For other crops, mechanistic plant growth models have been successfully used to develop complementary insights into soil and climate specific fertiliser practices (e.g. for wheat: Asseng et al., 2000).

During the 1990s, few models for oilseed rape have been developed in Europe and Australia. However, so far, no model has been evaluated for simulating the growth of rainfed oilseed rape limited by N. For example, the respective LINTUL version developed by Habekotté (1997a–1997c) takes only solar radiation and temperature into account and assumes optimal conditions for growth where water and N are not limiting. It further ignores the autumn and winter development phases of winter oilseed rape. A second example is that of the CERES-Maize model adapted for winter oilseed rape in France, but only tested for non-water stressed plants (Gabrielle et al., 1998). For Mediterranean conditions in Italy, a winter oilseed rape model was adapted within the DSSAT framework (Deligios et al., 2013). For conditions in Australia, a canola model was incorporated into APSIM (Robertson et al., 1999) and mainly used to assess temperature effects on plant phenology (Farre et al., 2002). Both models – DSSAT rapeseed and APSIM canola – were developed for warmer climates than the growing conditions of central and northern Europe. Although both models have not been tested for crop N-uptake, they make use of intensively tested modules for soil N and water dynamics, which make them suitable as a basis for model development and adaptation.

Against this background, this study aimed to (1) collect rainfed field trial data from multiple sites and years to (2) adapt the existing APSIM canola model for winter oilseed rape production in Germany and (3) to evaluate the performance of the calibrated model in terms of total biomass, grain yield, leaf area index (LAI), N-uptake and soil mineral N (SMN) dynamics against these field trial data and (4) explore the scope for site-specific N-management in northern Germany for improving the productivity (represented by yield) and reducing the risk of exceeding the N-balance.

2. Materials and methods

2.1. Field experiments

Data for the calibration and the evaluation of the model derived from N-rate × variety field trials conducted at Reinshof in 2010/2011, at Rosdorf in 2012/2013 (Lower Saxony, Germany, University of Göttingen) and a at third experimental site, at Harste in 2006–2012 (Institute of Sugar Beet Research). These three sites are located in the vicinity of Göttingen. The region is located in the transition between maritime and continental climate. Average annual precipitation is 637 mm and average daily temperature is 9.17 °C (Figs. 1 and 2). Daily weather data (including solar radiation, maximum and minimum temperature and rainfall) were obtained from the German weather service station in Göttingen around one km from the Reinshof field trial and five km from the trial at Rosdorf. For Harste, meteorological data were taken from a nearby weather station (Wetterstation Göttingen, 2014).

Fig. 1. Map of Germany presenting the selected sites: Magdeburg (1), Göttingen (2), Bad Salzuflen (3) and Leck (4).

2.1.1. Reinshof

The soil was a Pseudogley with organic carbon content (OC; 0–10 cm) of 1.8% (Table 1). Soil texture was a clayey silt and the pH value was 7 (0.01 M $CaCl_2$; VDLUFA, 1991). Phosphorus (P; 7 mg 100 g^{-1} soil; CAL method), potassium (K; 12 mg 100 g^{-1} soil; CAL method) and magnesium (Mg; 9 mg 100 g^{-1} soil; $CaCl_2$ method) were measured at field trial start and found in sufficient supply (VDLUFA, 1991). The field trial was carried out from 08/2010 to 07/2011. In this study we used data from a factorial experiment with four replicates of three hybrids (cvv. PR46W31, PR46W20, PR46W26) and three N-levels (0, 100, 200 kg ha^{-1}). N-fertiliser was applied in two equally split doses at recommencement of growth after winter dormancy in spring and four weeks later. The crop was shown on 20/08/2010 at a planting density of 50 plants m^{-2}. Soil characterisation including hydrological properties needed to parameterise the soil water balance model in APSIM were taken from Jung (2003) with an assumed rooting depth of 150 cm. SMN (0–90 cm) was low with 30 kg ha^{-1} before sowing (N_{min} method, Wehrmann and Scharpf, 1979). Aboveground residues of the preceding wheat crop were removed. 40 kg ha^{-1} of sulphur (S) were applied as Kieserite on 08/02/2011. Biomass production, N-uptake and SMN were recorded before winter, after winter, at flowering and at harvest (including grain yield and N-uptake). The main phenological development stages were monitored according to the BBCH scale (Lancashire et al., 1991). All biomass values from the field trial, same for Rosdorf and Harste, were presented as dry weight.

2.1.2. Rosdorf

The soil was a Pseudogley with OC (0–15 cm) of 1.7% (Table 1). Soil texture was a clayey silt and the pH value was 6.5 (0.01 M $CaCl_2$). The nutrient status (5 mg P 100 g^{-1} soil (CAL method), 10 mg K 100 g^{-1} soil (CAL method), 6 mg Mg 100 g^{-1} soil ($CaCl_2$ method) was tested prior to sowing and found in sufficient supply (VDLUFA, 1991). The field trial was conducted from 08/2012 to 08/2013. The hybrid Visby and the variety line Adriana were tested with three N-levels (0, 100, 200 kg ha^{-1}; replicates = 4). N-fertiliser was applied in two equally split doses at recommencement of

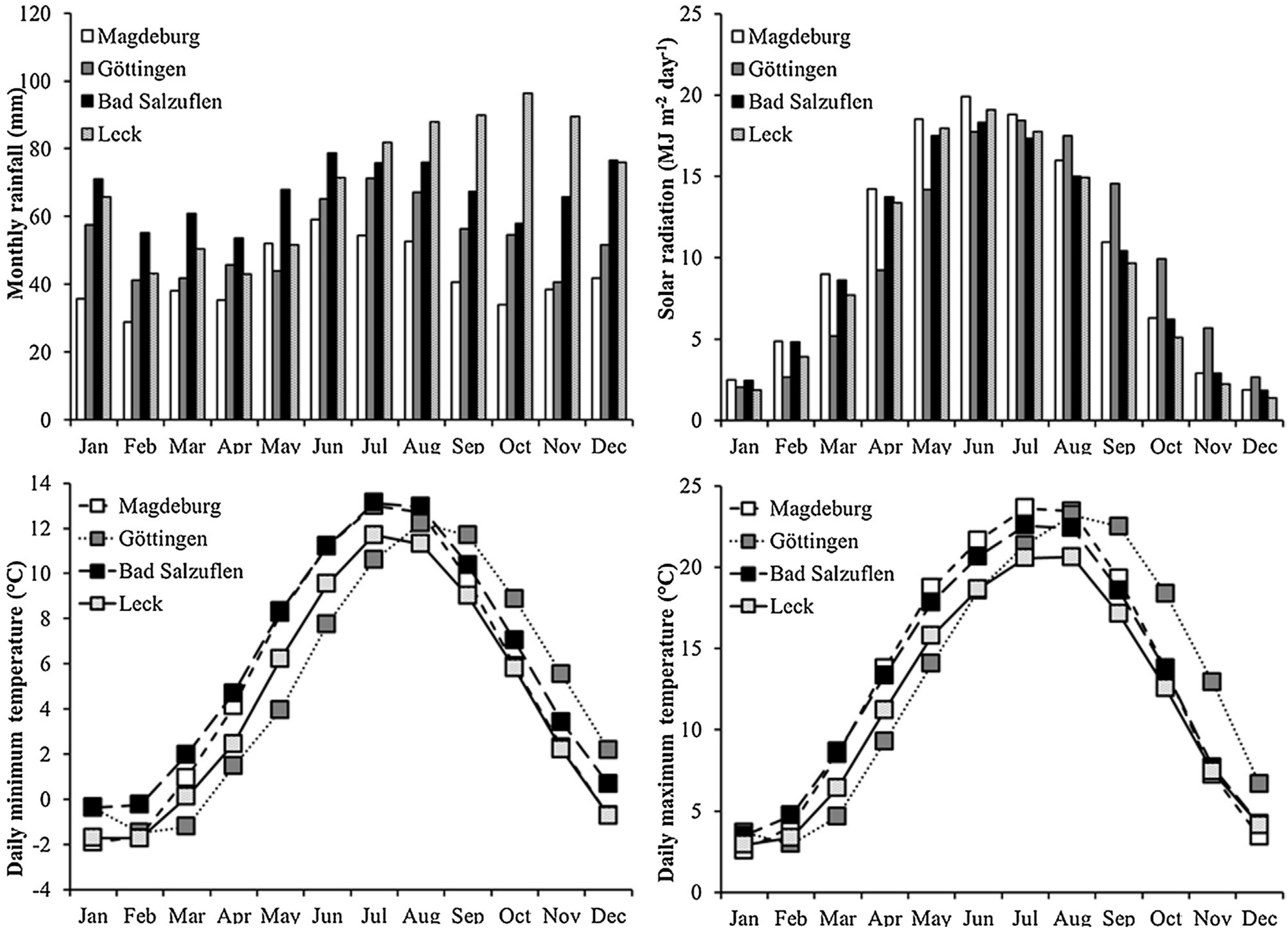

Fig. 2. Climate data (monthly mean rainfall, monthly mean solar radiation (SR), mean minimum and maximum daily temperature based on the years 1961–2012: Magdeburg (annual rain 510 mm; annual SR 3847 MJ m^{-2}, annual mean daily Temp 9.4 °C); Göttingen (637 mm; 3656 MJ m^{-2}, 9.2 °C); Bad Salzuflen (809 mm; 3641 MJ m^{-2}, 9.7 °C; Leck (847 mm; 3503 MJ m^{-2}, 8.2 °C). Source: German Weather Service.

growth after winter dormancy in spring and four weeks later. The crop was sown on 24/08/2012 at a planting density of 45 plants m^{-2} for cv. Visby and 50 plants m^{-2} for cv. Adriana. Hydraulic soil characterisation was done following Dalgliesh and Foale (1998). The lower limit of plant extractable water (known as CLL, similar to permanent wilting point) was assessed by setting a rain out shelter over the flowering oilseed rape. Soil moisture samples measured at harvest under the rain out shelter give the CLL of plant available water capacity. Drained upper limits (DUL, similar to field capacity) were defined by soil moisture samples taken after excessive

Table 1
Soil properties (Bulk density, LL = lower limit of plant available water capacity, DUL = drained upper limit, SAT = saturation, OC = organic carbon) for Rosdorf, Harste and Reinshof used for the parameterisation of APSIM.

Site	Soil layer (cm)	Bulk density (g cm^{-3})	LL (mm mm^{-1})	DUL (mm mm^{-1})	SAT (mm mm^{-1})	OC (%)
Reinshof	0–10	1.5	0.19	0.43	0.44	1.8
	10–30	1.5	0.19	0.43	0.44	1.8
	30–60	1.5	0.20	0.39	0.42	1.0
	60–90	1.5	0.18	0.34	0.38	0.4
	90–120	1.5	0.16	0.28	0.33	0.2
	120–150	1.5	0.16	0.28	0.33	0.1
Rosdorf	0–15	1.4	0.06	0.33	0.37	1.7
	15–30	1.5	0.10	0.33	0.37	1.5
	30–60	1.5	0.25	0.39	0.43	0.8
	60–90	1.5	0.24	0.34	0.38	0.5
	90–120	1.5	0.18	0.28	0.31	0.2
	120–150	1.5	0.28	0.32	0.35	0.1
Harste	0–15	1.4	0.14	0.37	0.48	1.0
	15–30	1.4	0.12	0.34	0.45	0.9
	30–60	1.5	0.11	0.32	0.44	0.4
	60–90	1.5	0.11	0.32	0.44	0.4
	90–120	1.5	0.11	0.32	0.44	0.2
	120–150	1.5	0.11	0.31	0.44	0.1
	150–180	1.5	0.10	0.31	0.43	0.1

Table 2
Minimum, critical and maximum N-concentrations (%) for different organs of winter oilseed rape derived in this study for the calibration of the APSIM winter oilseed rape model. Original values in brackets.

Organ	Level	Plant stage						
		Emergence	Juvenile	Flower initiation	Flowering	Start grain filling	End grain filling	Maturity
Leaf	Min	5.5 (5.5)	2.5 (5.0)	2.5 (4.0)	1.4 (3.0)	0.5 (0.5)	0.5 (0.5)	0.5 (0.5)
Leaf	Critical	6.5 (6.5)	3.6 (6.0)	3.0 (5.5)	3.1 (5.0)	1.5 (5.0)	1.5 (0.5)	0.8(1.0)
Leaf	Max	8.0 (8.0)	7.5 (7.5)	6.5 (6.5)	5.5 (5.5)	5.5 (5.5)	5.5 (5.5)	1.0 (2.0)
Stem	Min	5.5 (5.5)	2.0 (5.0)	2.0 (3.5)	1.4 (3.0)	0.5 (0.3)	0.5 (0.3)	0.3 (0.3)
Stem	Critical	6.5 (6.5)	2.7 (6.0)	2.7 (5.0)	2.5 (4.0)	1.5 (4.0)	1.5 (4.0)	0.5 (0.5)
Stem	Max	8.0 (8.0)	5.5 (7.5)	5.5 (5.5)	4.5 (4.5)	4.5 (4.5)	4.5 (4.5)	1.5 (2.5)
Pod	Min				3.5 (4.0)	2.5 (3.0)	0.5 (2.0)	0.3 (0.5)
Pod	Critical				4.0 (5.0)	3.5 (4.0)	1.5 (3.0)	1.0 (1.0)
Pod	Max				5.5 (5.5)	4.5 (4.5)	2.6 (3.5)	1.5 (1.5)
Grain	Min							2.8 (2.8)
Grain	Critical							3.3 (4.0)
Grain	Max							4.5 (4.5)

rainfall. SMN (0–90 cm) was 70 kg ha^{-1} at sowing (N_{min} method, Wehrmann and Scharpf, 1979). All residues from preceding wheat crop were incorporated by ploughing. S (40 kg ha^{-1}) was in spring 2013 as Kieserite to ensure that it was not limiting. Biomass production, N-uptake as well as SMN (0–90 cm) were monitored before winter, in spring, at flowering and harvest (including grain yield, and grain N-uptake). Furthermore, LAI was measured five times around flowering. Phenological development was monitored according to the BBCH scale (Lancashire et al., 1991).

2.1.3. *Harste*

The soil is a Stagnic Luvisol with OC content (0–15 cm) of 1.0% (Table 1). Soil texture is a clayey silt and pH value was 7.1 (0.01 M $CaCl_2$). Hydraulic soil characterisation was based on soil texture analysis using pedotransfer functions following Tsuji et al. (1994) (Table 1). The available data for testing the model derived from a long-term crop rotation experiment with three replicates (2006–2012). Winter oilseed rape was planted every year and, thus, the data set included grain yield from 2006 to 2012 and final total biomass for 2011 and 2012. SMN (0–90 cm) was measured before winter and in spring (N_{min} method, Wehrmann and Scharpf, 1979). From 2006 to 2009 the hybrid Mika was planted and from 2010 to 2012 the cv. Visby. Sowing date was late August/early September. Planting density was 45–50 plants m^{-2}. N-fertiliser splitting (2–5 times, including pre-winter application) and amount (185–260 kg ha^{-1}) differed from year to year and was managed according to SMN levels in spring. Before sowing, 109 kg P ha^{-1}, 142 kg K ha^{-1}, 45 kg Mg ha^{-1} and 1143–1400 kg CaO ha^{-1} were applied. In spring, 20 kg S ha^{-1} and 15 kg Mg ha^{-1} as Bittersalz were applied. All residues from preceding wheat crops were incorporated by deep cultivation.

2.2. *APSIM setup*

APSIM is a widely used farming system model that simulates crop growth and development based on incoming radiation limited by temperature stress, water supply and N availability (Keating et al., 2003). Management decisions such as sowing date, fertiliser application etc. can be specified in a manager module. APSIM (version 7.5r3008) was configured with the modules for canola, soil water (SOILWAT), soil N (SOILN) and surface organic matter (represents residues of the preceding crop) as follows:

2.2.1. *Soil and surface organic matter*

The SOILWAT module was parameterised following standard practices using APSIM: The two parameters that determine first (U) and second stage (Cona) of soil evaporation using the Taylor-Priestly approach were set to 4 and 2 mm day$^{-0.5}$ for loam soils, similar to Hunt and Kirkegaard (2011). Runoff is linked to the setting of the USDA curve number and was defined for all sites as 73. The fraction of water drained to the next soil layer under saturated conditions per day (SWCON) is 0.5 for all layers in the three soils following standard parameterisation for loam. For soil water content below DUL, water movement depends upon the water content gradient between adjacent layers and the soil's diffusivity, defined in APSIM as diffusivity constant and diffusivity slope. For all sites the default values of 88 (diffusivity constant) and 35 (diffusivity slope) were used to represent loam soils.

The OC content which was only measured for the top layer, was assumed to decrease exponentially with depth. FINERT and FBIOM, the different pools of the organic matter are defined according to typical default values (FBIOM; 0–10 cm: 0.05; 10–30: 0.045; 30–60: 0.035; 60–90: 0.015; 90–120: 0.01; FINERT: layer 0–10: 0.4; 10–30: 0.5; 30–60: 0.7; 60–90: 0.8; 90–120: 0.95; unit less, fraction of total OC; Probert et al., 1998; Luo et al., 2014).

Straw remaining from the preceding wheat crop was set according to the values measured and a C:N ratio of 60 was assumed. The amount of straw in the field trials ranged from 6000 to 8000 kg ha^{-1}. The relative potential decomposition rate was 0.05 d^{-1} according to the application of APSIM in the Netherlands by Asseng et al. (2000). Recorded tillage events were implemented in the management script. An annual N-deposition of 24 kg ha^{-1} as suggested by the Deutsches Umweltbundesamt (2014) was evenly distributed over the year on a monthly basis (2 kg ha^{-1} mo^{-1}) in the simulation runs.

2.2.2. *Plant module calibration*

As the APSIM canola model was not previously tested for the study region, we calibrated the model with data from three treatments of the Reinshof trial (cv. PR46W26 at 0, 100, 200 kg N ha^{-1}, respectively). These treatments were excluded from the evaluation of the model afterwards. An existing cultivar in the APSIM data base, cv. French Winter, was selected as a base cultivar which was assumed to be closest to cultivars found in northern Europe. The model output of these calibration runs was compared to observed results. It showed that the N-uptake was overestimated in relation to total biomass production. APSIM's N-uptake is regulated by supply and demand. The demand side is determined by a value for minimum, critical and maximum concentration (%) for the different organs and plant stage. Based on the measured N-concentration in vegetative biomass and grain before winter, at vegetation start, flowering and harvest and in accordance with literature (Barlog and Grzebisz, 2004), the APSIM-standards for N-concentrations for leaf, stem, pod and grain were adjusted (Table 2). Values are close to the ones used by Deligios et al. (2013) for an oilseed rape model built for the Mediterranean climate in the DSSAT framework. Adjusting

Table 3
Cultivar parameter for APSIM.

APSIM parameter	Acronym	Unit	Cultivar					
			French Winter (default)	PR46W26	PR46W31	PR46W20	Adriana	Visby
Harvest Index	hi_max_pot	–	0.30	0.20	0.24	0.25	0.27	0.28
Thermal time requirements:								
End of juvenile to floral initiation	tt_end_of_juvenile	°C days	900	900	900	900	900	900
Floral initiation to flowering	tt_floral_initiation units	°C days	250	250	350	350	350	350
Flowering to start grain	tt_flowering units	°C days	200	350	300	300	250	300
Start grain filling to end grain filling	tt_start_grain_fill	°C days	1000	650	750	750	950	950

the threshold N-concentration levels in the model led to a good match between simulated N-uptake with the observed N-uptake in the calibration treatments.

Two further adjustments were made in the model setup: First, recent work with the APSIM canola model in Australia suggested greater leaf size for modern cultivars than the default ones in the release version of the model (APSIM 7.5r3008). Leaf size was increased to 2000, 7000, 15,000, 18,000 and 19,000 mm^2 (original vales 1500, 4000, 11,000, 14,000, 15,000) which is set in APSIM according to leaf number (1, 3, 5, 9, 13, 16, respectively) (McCormick et al., 2015). Second, senesced leaves were set to be dropped at a daily rate of 1% (original value 0%) by calibrating the model with the observed total biomass values before and after winter.

After these general canola module calibration, which is the same for all cultivars, cultivar specific parameterisations (HI and thermal time requirements for the specific development stages) were done as follows (Table 3): cv. PR46W26 was parameterised by observed HI for the 200 kg N ha^{-1} treatment and thermal unit requirements, which were adapted from observed flowering and harvest day. For differentiating the other cultivars, we used the 200 kg N ha^{-1} treatments at Reinshof for cv. PR46W31 and cv. PR46W20. For cvv. Visby and Adriana, we used the 200 kg N ha^{-1} treatment at Rosdorf. The cv. Mika was assumed to be similar to Visby.

2.3. *Analysis of model performance*

For statistical analysis of model evaluation, the observed data of total biomass, yield, grain N-uptake, total biomass N-uptake, SMN and LAI were compared with the corresponding predicted values. To assess the goodness of fit of these simulated—measured comparisons the root mean square error (RMSE) between predicted and observed data was calculated as follows:

$$\mathrm{RMSE} = \left[\frac{\Sigma(O-P)^2}{n}\right]^{0.5}$$

where O and P are the paired observed and predicted data and n is the total number of observations. Additionally, for comparison, the traditional R^2 regression statistic (least-squares coefficient of determination) forced through the origin was calculated.

2.4. *Simulation experiment*

The scope for site-specific N-fertiliser management was investigated using a simulation experiment for four locations across northern Germany (Fig. 1). For a transect running from Göttingen to Leck, long-term (1961–2012) daily historical weather data (solar radiation, minimum and maximum temperature and rainfall) of four sites were obtained from the German Weather Service (Fig. 1). The highest average annual rainfall (847 mm) and coolest mean daily temperature (8.16 °C) is recorded for Leck. During the critical growing period for oilseed rape growth from flowering to maturity 53% of all season provide more than 200 mm rain. Contrary, in Magdeburg, a continental dry site (510 mm average annual rainfall), only 16% of all seasons have rainfall >200 mm, while more than half of the seasons (57%) have less than 150 mm rainfall during that period (Fig. 8).

A generic loamy soil – of varying depth – similar to a Parabraunerde (USDA classification, Cambisol) was used to represent a common highly productive arable soil in northern Germany. While information on soil texture is easily available, there is often a lack of knowledge concerning the rooting depth of the specific soil. Rooting depth can differ due to subsurface hardpans or rocks and it is correlated strongly with PAWC and, thus, crop growth. Therefore, we applied four different rooting depths to illustrate the effect on crop growth at each site: A rooting depth of 180 cm resulted in a PAWC of 237 mm, which was categorised as high according to AG Bodenkunde (1994). Rooting depths limited to 140 (PAWC 187 mm), 90 (PAWC 123 mm) 50 cm (PAWC 58 mm) are considered to represent moderate, low and very low PAWC, respectively, according to AG Bodenkunde (1994). To single out rooting depth effects, CLL and DUL were not changed. All parameters of the SOILWAT module were kept constant (first (U) and second (cona) stage evaporation 4 and 2 mm $day^{-0.5}$, respectively; runoff 73; SWCON 0.5 for all layers; diffusivity constant 88; diffusivity slope 35. We used a typical OC content in the topsoil of 1.4%. Characterisation of the soil organic matter pools followed the convention as described above.

The simulation experiment was set up for the site-specific climate data and repeated for each year (1961–2012) and each PAWC category. The sowing date was fixed to 30th August and cv. Visby was planted at a density of 50 plants m^{-2}. The APSIM surface organic matter module was initialised with wheat straw of 6000 kg ha^{-1} and with SMN (0–90 cm) of 50 kg ha^{-1}. Surface organic matter and soil-N (including SMN) were reset annually on 20th August. Soil water was set only in the starting year, and from then on APSIM calculated soil water dynamics. A deposition of 24 kg N ha^{-1} $year^{-1}$ was included (Deutsches Umweltbundesamt, 2014). For each combination, twelve levels of N-fertiliser rates (from 0 to 220 kg N ha^{-1} at an interval of 20 kg ha^{-1}) were tested

Table 4
Summary of the APSIM winter oilseed rape model evaluation at Rosdorf, Reinshof and Harste in Germany taking all measured points across the whole growing period into account. Performance at harvest only is presented in Fig. 3a–d.

Model attribute	Unit	Number of paired data points	Observed range	Observed mean	R^2	mb	RMSE
Total Biomass	kg ha^{-1}	50	1001–16,608	4996	0.96	1.01	884
N-uptake	kg ha^{-1}	48	37–204	83.6	0.94	0.90	16.5
LAI		30	0.34–4.94	2.63	0.88	1.04	0.55
Soil mineral N (0–90 cm)	kg ha^{-1}	48	5.4–121.5	19.9	0.93	1.91	16.4

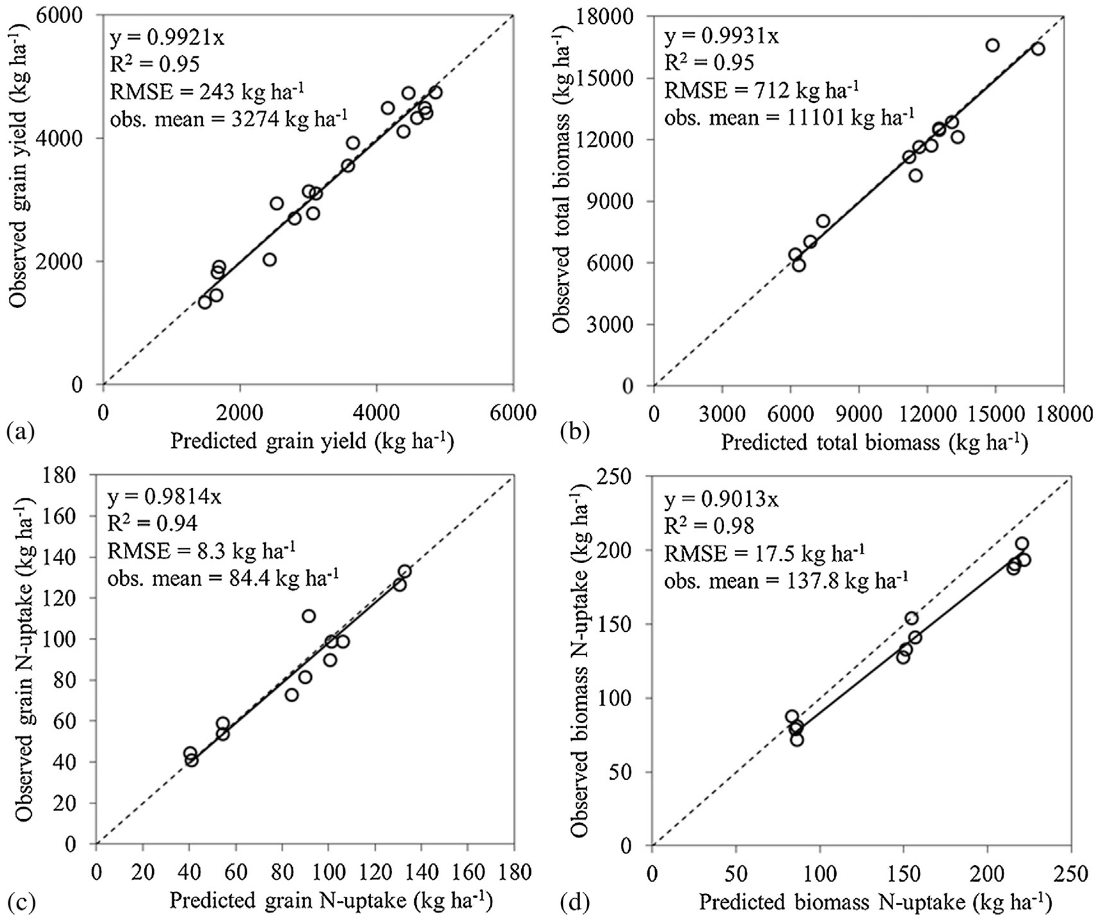

Fig. 3. (a–d) Observed versus predicted (a) grain yield, (b) total biomass, (c) grain nitrogen (N-) uptake, and (d) biomass nitrogen (N-) uptake at harvest. The dotted line represents the 1:1 line. The straight line represents the regression line forced through the origin.

for their effect on grain yield and N-balance. Fertiliser application followed standard practice in the region split into two equal doses both applied in spring. After winter, the first N-dose was applied if the Julian day of the year was >30 and <182 and when the six preceding days >6 °C (daily average). This rule resulted in N-application during February/March. The second dose was applied four weeks later.

3. Results

3.1. Evaluation of the model

Field trial data covered a wide range of grain yield (1348–4754 kg ha^{-1}), total biomass (1001–16,608 kg ha^{-1}), and N-uptake (37–204 kg ha^{-1}) (Table 4; Fig. 3a) and therefore offered the opportunity for detailed testing of the model. At harvest, observed grain yields matched predicted ones with a RMSE of 243 kg ha^{-1} against an observed average of 3274 kg ha^{-1} (% RMSE 7.4) (Fig. 3a). Similar results were found for total biomass (% RMSE 6.4) and N-uptake (% RMSE grain-N 9.8; biomass-N 12.8%) (Fig. 3b–d). The regression line forced through the origin indicated an almost perfect match for predicted and observed grain yield, grain N-uptake and total biomass (Fig. 3a–c). As shown in Fig. 3d, total N-uptake at harvest was slightly over predicted.

Taking all observed points of the whole growing period, the RMSE for total biomass was 884 kg ha^{-1} against an observed average of 4996 kg ha^{-1} (Table 4). Growth simulated over time for Rosdorf and Reinshof is presented exemplary for two cultivars in Fig. 4a–g. Predicted total biomass was close to the four measured points (before and after winter, around flowering and maturity) at both sites (Fig. 4a and b). However, around flowering predictions slightly under estimated production for the zero N-fertiliser treatments at both sites. For total N-uptake across all data points, a RMSE of 16.5 kg ha^{-1} against an observed average of 83.6 kg ha^{-1} was found (Table 4). For the trial at Reinshof, the observed values at flowering exceed the predicted ones (Fig. 4c). For the zero N-fertiliser treatment, this was consistent with the underestimation of biomass at that stage. For the other treatments, the model under predicted N-uptake at that site and development stage. However, despite this exception, the model accurately simulated the N-uptake at the different sampling dates (Fig. 4c and d).

Observed LAI values reflected the strong increase in growth during the first weeks in spring with values below 1 at end of March/early April to values of 5 at end of May for the 200 kg N ha^{-1} treatment at Rosdorf (Fig. 4e). The model simulated LAI with a RMSE of 0.55 against an observed average of 2.63 (Table 4). However, for the run with the zero N-fertiliser application, the model under predicted LAI by about 1 (Fig. 4e). Taking all samples into account, SMN was modelled with a RMSE of 16.4 kg ha^{-1} against an observed average of 19.9 kg ha^{-1}. However, observed values ranged widely from 5.4 to 121.5 kg ha^{-1} (Table 4) and the R^2 forced through the origin showed an agreement of 0.93. The simulated SMN dynamics reflected the observed pattern with a decrease of N before winter and the increase through fertiliser application in spring (Fig. 4f and g).

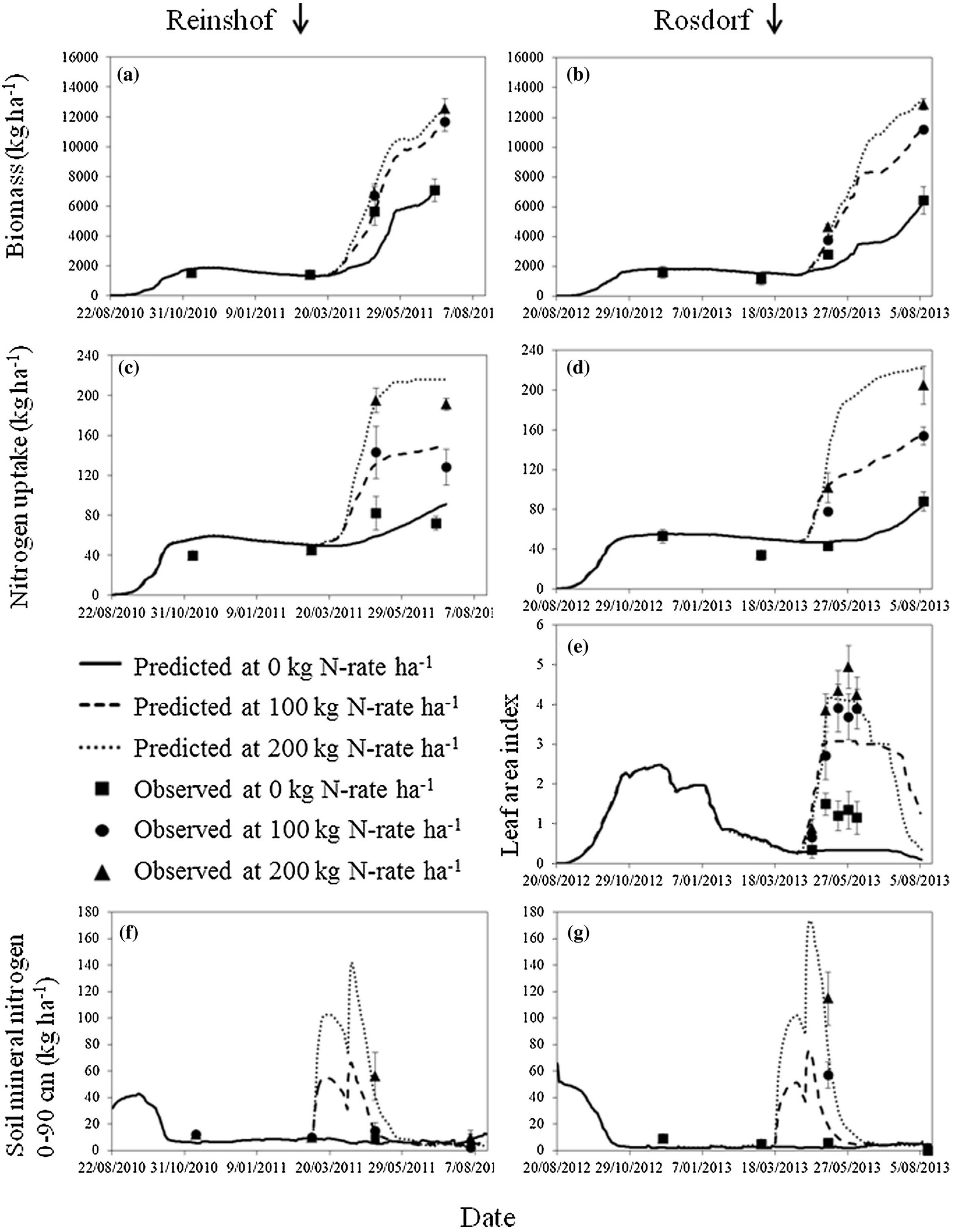

Fig. 4. (a–g) Simulated (as lines) and observed (as points) (a) total biomass growth, (c) N-uptake, and (f) soil mineral nitrogen (0–90 cm) for the treatments with the cultivar PR46W20 as affected by 0, 100, 200 kg nitrogen fertiliser ha^{-1} at Reinshof (2010/2011). Simulated (as line) and observed (as points) (b) total biomass growth, (d) nitrogen uptake, (e) leaf area index, and (g) soil mineral nitrogen (0–90 cm) for the treatments with the cultivar Visby as affected by 0, 100, 200 kg nitrogen fertiliser ha^{-1} at Rosdorf (2012/2013). Bars represent standard deviation ($n = 4$).

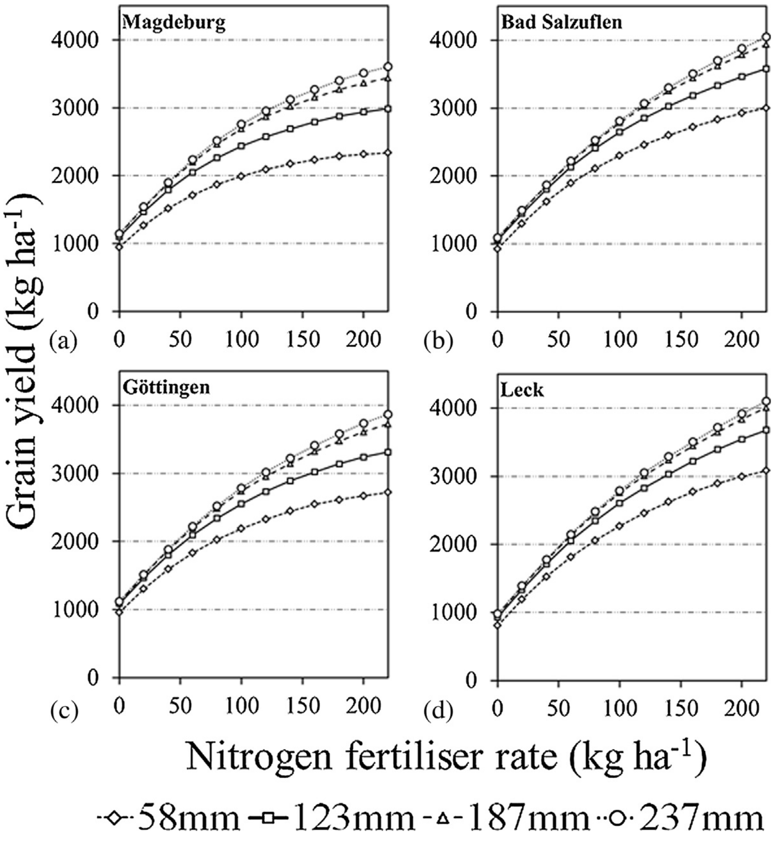

Fig. 5. Nitrogen fertiliser rate versus mean grain yield for (a) Magdeburg, (b) Bad Salzuflen, (c) Göttingen, and (d) Leck and for different plant available water holding capacities (PAWC) (i) 58 mm, (ii) 123 mm, (iii) 187 mm and (iv) 237 mm based on an APSIM simulation experiment for the years 1961–2012.

3.2. Simulation experiment

In the simulation experiment, grain yield and N-balance were strongly affected by N-fertiliser application. Grain yields were around 1100 kg ha^{-1} with zero fertiliser and increased to 4000 kg ha^{-1} for most of the sites with high PAWC when 220 kg N ha^{-1} was applied (Fig. 5). However, the yield gain from additional N-fertiliser diminished at higher N-rates. The average N-balance increased with the amount of N-fertiliser applied and exceeded the EU Nitrate Directive in Germany of 60 kg ha^{-1} for all sites and PAWCs when 160–180 kg N ha^{-1} was applied (Fig. 6).

Comparing sites for the zero fertiliser run, simulated grain yields were highest in Magdeburg (1146 kg ha^{-1}) and lowest in Leck (980 kg ha^{-1}) (Fig. 5). Differences were in the range of 200–300 kg ha^{-1}. Contrary, for all runs with fertiliser rates >160 kg N ha^{-1}, the grain yield was highest in Leck and lowest in Magdeburg. Generally, at these high fertiliser rates, mean grain yields were larger at higher rainfall sites (Bad Salzuflen and Leck) than at low rainfall sites (Göttingen and Magdeburg) (Figs. 2 and 5). At all sites, simulated grain yields reflected the four different PAWC levels (Fig. 5). Although the magnitude differed from site to site, the very low PAWC of 58 mm resulted in average 500 kg ha^{-1} lower yields than the low PAWC of 123 mm. The mean yield difference between the 123 mm PAWC and the 187 mm was around 300 kg ha^{-1}. However, this difference was more pronounced at lower rainfall sites. The mean yield gap between the moderate and the high PAWC soils was marginal at all sites. Seasonal yield variability was largest for the low PAWC (58 mm), especially in Magdeburg and Göttingen (for 180 kg N-fertiliser rate ha^{-1}); yield ranged at these sites from 1000 to 3000 kg ha^{-1} (Fig. 7).

The N-balance exceeded the critical threshold of 60 kg ha^{-1} at all PAWC categories in Magdeburg when ≥180 kg ha^{-1} was applied (Fig. 6). At all other sites, this was only true for the low and very low PAWCs while it stayed close to this limit at the moderate and high PAWC soils (Table 5).

For this 180 kg ha^{-1} N-fertiliser rate, higher NHI and N-uptake were generally simulated for the moderate and high PAWC across sites (Table 5). However, N-concentrations in vegetative and reproductive parts of the crop decreased with higher grain yields and PAWC. For some sites, the model suggested a good relationship between water supply from flowering to maturity (extractable soil water at flowering plus rainfall until maturity) and yield (Fig. 7). In Magdeburg, a lower correlation was simulated for the low PAWC soil and highest for PAWC 237 mm (Fig. 7a). At the other sites, the very low and the low PAWC showed the best relationship between water supply and yield, respectively. At Leck only a weak relationship was suggested (Fig. 7d).

Taking the inter-annual variability into account, the N-balance differed strongly from year to year. Fig. 8 shows that the N-balance with a fertiliser rate of 180 kg N ha^{-1} was always above the critical threshold of 60 kg N ha^{-1} in dry seasons (rainfall from flowering to maturity < 200 mm) at all sites. For rainfall >200 mm and PAWCs of 123, 187 and 237 mm the N-balance was already close to the critical threshold. The difference between the sites is defined mostly (beside stored soil water at flowering) by the frequency of the rainfall class (<150, <200, <250, >250 mm); in Magdeburg, more than half of the seasons (57%) fell into the category of < 150 mm, in Leck only 20% of all seasons had less than 150 mm rainfall. We further explored the water limitations by plotting the mean and standard deviation of the water stress factor for photosynthesis (no water stress = 1, severe water stress = 0) in APSIM (Fig. 9). In Magdeburg, winter oilseed rape suffered strongly in almost all years indicated by the high standard deviation, even at high PAWC values. In Leck, a stress factor of below 0.8 was hardly reached for the PAWC 187 and

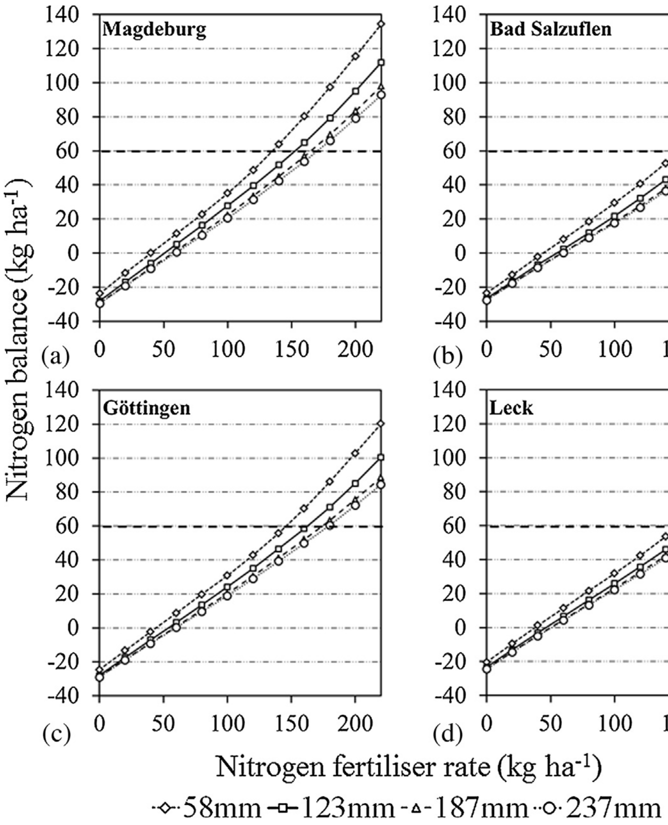

Fig. 6. Nitrogen fertiliser rate versus mean nitrogen balance for (a) Magdeburg, (b) Bad Salzuflen, (c) Göttingen, and (d) Leck and for different plant available water holding capacities (PAWC) (i) 58 mm, (ii) 123 mm, (iii) 187 mm and (iv) 237 mm based on an APSIM simulation experiment for the years 1961–2012. The 60 kg N ha^{-1} threshold for the nitrogen balance defined by the EU Nitrate Directive in Germany is marked in bold.

237 mm. Across all sites with the exception of Magdeburg, mean water stress was strongest during flowering (Thermal time units 1750–2050 degree-days).

4. Discussion

4.1. Model performance

The performance of the model taking all observed points for total biomass and N-uptake into account was excellent (Table 5, Fig. 3a–d) and comparable to other model evaluations (e.g.: Asseng et al., 2000). LAI was well simulated, but only few measurements from one site were available (Fig. 4e).

Observed biomass growth and N-uptake before winter for both sites were in a typical range for conditions in Germany (Henke et al., 2008b) and were well simulated (Fig. 4a–d). In Germany, the winter period is characterised by biomass and N-losses of oilseed rape plants due to frost. In the model, frost effects induced by critical temperature values resulting in leaves dropped at a constant rate. N-content in senesced leaves is fixed by the default model setting

Table 5
Simulated mean winter oilseed rape grain yield, N-balance, total plant N-uptake, grain N-uptake, N harvest index (NHI), N-concentration in the straw and the grain, and the harvest days after emergence at four different sites and four categories of plant water holding capacities (PAWC). The simulation scenario using APSIM based on a fertilisation rate of 180 kg N ha^{-1} rate. Mean (n = 50) and standard deviation (in brackets).

Site	PAWC (mm)	Grain yield (kg ha^{-1})	N-balance (kg ha^{-1})	Total N-uptake (kg ha^{-1})	Grain N uptake (kg ha^{-1})	NHI	N-concentration in straw (%)	N-concentration in grain (%)	Harvest day after emergence (days)
Magdeburg	58	2284 (526)	97 (19)	149 (12)	83 (19)	0.55 (0.10)	1.1 (0.5)	3.6 (0.1)	324 (8)
	123	2876 (449)	79 (14)	162 (10)	101 (14)	0.62 (0.07)	0.8 (0.3)	3.5 (0.2)	324 (8)
	187	3268 (384)	70 (12)	167 (10)	110 (12)	0.66 (0.05)	0.7 (0.2)	3.4 (0.2)	324 (8)
	237	3404 (336)	66 (11)	169 (10)	114 (11)	0.67 (0.05)	0.6 (0.2)	3.4 (0.2)	324 (8)
Bad Salzuflen	58	2832 (429)	79 (14)	158 (9)	101 (14)	0.64 (0.07)	0.8 (0.3)	3.6 (0.1)	320 (7)
	123	3333 (302)	66 (10)	168 (8)	114 (10)	0.68 (0.04)	0.6 (0.1)	3.4 (0.2)	320 (7)
	187	3623 (188)	59 (7)	173 (7)	121 (7)	0.70 (0.03)	0.6 (0.1)	3.3 (0.1)	320 (7)
	237	3702 (143)	57 (6)	175 (7)	123 (6)	0.71 (0.02)	0.5 (0.1)	3.3 (0.1)	320 (7)
Göttingen	58	2612 (483)	86 (17)	154 (12)	94 (17)	0.61 (0.09)	0.9 (0.4)	3.6 (0.1)	326 (7)
	123	3140 (393)	71 (12)	165 (9)	109 (12)	0.66 (0.06)	0.7 (0.2)	3.5 (0.2)	326 (7)
	187	3475 (275)	63 (9)	170 (8)	117 (9)	0.69 (0.04)	0.6 (0.1)	3.4 (0.2)	326 (7)
	237	3581 (218)	60 (7)	172 (8)	120 (7)	0.70 (0.03)	0.6 (0.1)	3.3 (0.2)	326 (7)
Leck	58	2894 (401)	78 (14)	155 (11)	102 (14)	0.66 (0.07)	0.7 (0.2)	3.5 (0.2)	336 (8)
	123	3396 (304)	67 (11)	164 (11)	113 (11)	0.69 (0.04)	0.6 (0.1)	3.3 (0.2)	336 (8)
	187	3650 (239)	62 (9)	168 (12)	118 (9)	0.70 (0.03)	0.5 (0.1)	3.2 (0.2)	336 (8)
	237	3720 (227)	60 (9)	170 (12)	120 (9)	0.71 (0.02)	0.5 (0.1)	3.2 (0.2)	336 (8)

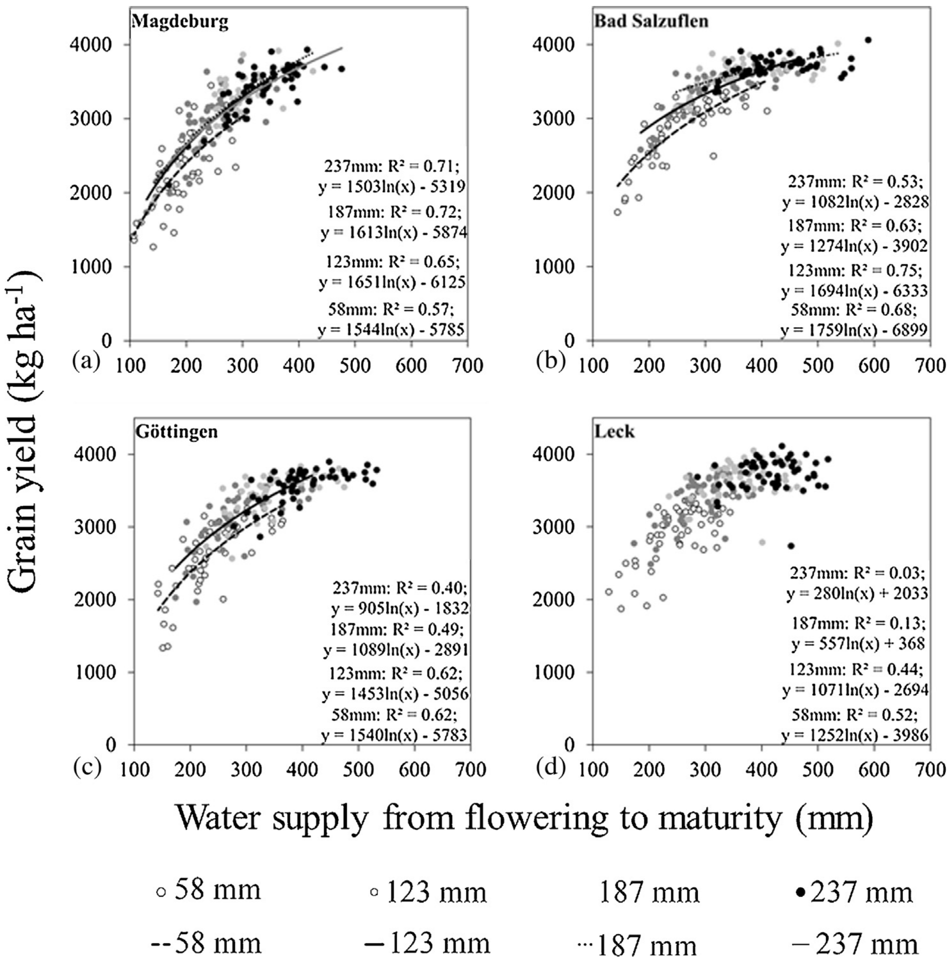

Fig. 7. Water supply from flowering until maturity (extractible soil water at flowering and rainfall from flowering until maturity) versus grain yield for (a) Magdeburg, (b) Bad Salzuflen, (c) Göttingen, and (d) Leck and for different plant available water holding capacities (PAWC) (i) 58 mm, (ii) 123 mm, (iii) 187 mm and (iv) 237 mm based on a simulation experiment for the years 1961–2012 for each site. N-fertiliser rate was 180 kg N ha^{-1}. Regression line was only drawn for $R^2 \geq 0.55$.

at 1.5%. Biomass production during winter is reduced due to low radiation and the critical minimum temperature value of 0 °C. This framework for winter conditions worked sufficiently indicated by a good match between simulated and observed biomass and N-uptake at vegetation start in spring (Fig. 4a–d). Simulated LAI was 2.5 before winter and dropped to 0.5 which is a commonly observed value for winter oilseed rape at vegetation start in spring (Grosse et al., 1992) (Fig. 4e).

In the period after winter when temperatures stay continuously >0 °C, winter oilseed rape grows rapidly: Over a period of 3 to 4 weeks, it produces most of the aboveground biomass (Malagoli et al., 2005). Observed biomass increased from 1500 kg ha^{-1} at vegetation start to more than 6000 kg ha^{-1} at flowering for the 200 kg N ha^{-1} fertilisation treatment at Reinshof (Fig. 4a and c). The simulation runs captured this development well for biomass and N-uptake (Table 4). LAI increased from 0.5 in early spring to 5 m m^{-2} at flowering for the highest N-fertiliser simulation run in Rosdorf (Fig. 4e). The underestimation of the model of LAI and biomass production at flowering for the zero N-fertiliser treatment at Reinshof indicates that the model may overestimate the effect of N stress at low N-fertiliser rates when decomposing organic material was the major source of N (Fig. 4a). Simulated and observed SMN contents were high in spring due to the fertiliser application (Fig. 4f and g), but due to the high demand of the plant for its rapid growth, N was taken up at a very high rate. As shown in Fig. 4f and g, the model captured the dynamics; however due to the fast N-uptake rate, differences of just a few days result in higher error terms (RMSE) for SMN (Table 4) as for example also observed in Asseng et al. (2000).

During grain filling, oilseed rape drops most of its leaves. This was reflected by the model in the decreasing LAI (Fig. 4e). Dropped leaves were compensated by grain production in terms of total biomass of a plant. From the leaves, N was then re-translocated to the grains leading to overall decreasing N-content in the vegetative biomass in the field and in the simulation (Fig. 4a–d). While the prediction of N-uptake in grains by the model was generally good, the amount of N (kg ha^{-1}) in the vegetative parts at harvest was overestimated (Fig. 3d). We conclude that the N-loss via leaves dropped during the period from flowering to maturity was higher in reality than predicted by APSIM. This process needs further consideration, in particular via testing against measured N-content and total amount in the senesced leaves, when the model is used to investigate post-harvest soil N-dynamics.

Further possible improvements in model performance may be achieved by better simulating plant dormancy during the winter periods. Especially in warmer winters with temperatures >0 °C over a long period, the current setup could lead to an overestimation of total biomass production as the current model parameter will result in growth. However, we consider that this overestimation is of little consequence for total biomass and grain yield at harvest since winter oilseed rape produces most of its biomass in spring. Generally, after a comprehensive test against a wide range of data points for total biomass, grain yield, N-uptake, LAI, and SMN, the model showed excellent correlation with observed data (Table 4,

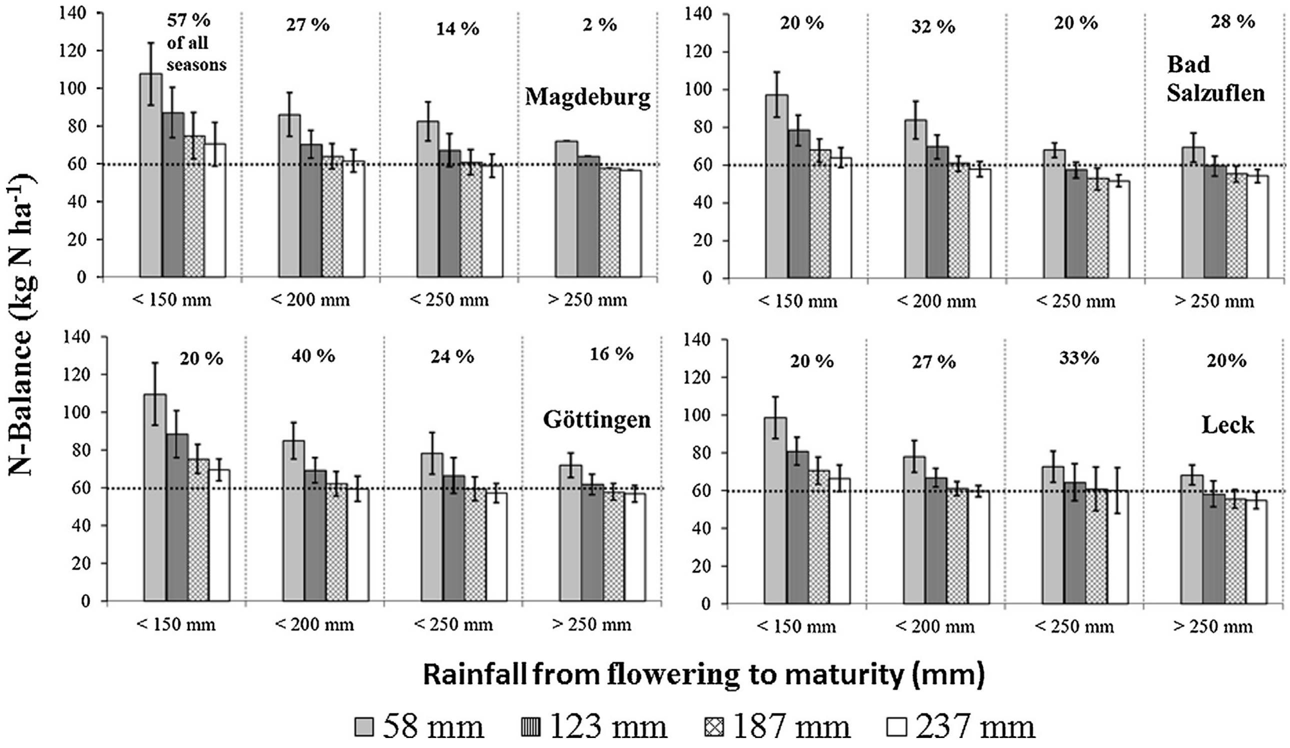

Fig. 8. Simulated N-balance averaged according to years with rainfall classes for the period from flowering to maturity: <150, <200, <250 and >250 mm. Frequency of seasons out of all season (1961–2012), which fall into the respective rainfall class, are presented as percentage. Results based on a simulation experiment for the years 1961–2012 for each site and plant available water capacity (PAWC 58, 123, 187 and 237 mm). N-fertiliser rate was 180 kg N ha^{-1}.

Fig. 3a–d). Based on these results, we concluded that it was valid to use APSIM canola for simulation experiments investigating the relationship between fertiliser application, grain yield and grain N-uptake.

4.2. Simulation experiment

The purpose of the simulation experiment was to explore soil and climate related production limitations for winter oilseed rape cultivation across northern Germany and assess how such limitations can be related to N-fertiliser rate, yield and N-balance. As presented in Fig. 4, the model suggested that mean yields at all sites differed strongly with rooting depth and therefore PAWC. Furthermore, long-term mean yields under higher N-fertiliser rates (>160 kg N ha^{-1}) were related to the average annual rainfall (Figs. 1 and 5). For example, yields were highest in Leck (average rainfall 847 mm) and lowest in Magdeburg (average rainfall 510 mm). Simulated yields for these sites reflected generally the finding that winter oilseed rape yields are higher in the cooler, and high rainfall areas of far northern Germany than in more central locations with drier and warmer continental climate (Statistisches Bundesamt, 2014; Leck: 4000 kg ha^{-1}; Magdeburg: 3500 kg ha^{-1}; Fig. 2). These observed and simulated values confirm results from Saskatchewan (Canada), where Kutcher et al. (2010) showed that district average canola yields follow precipitation patterns.

Fig. 7 presents the relationship between water supply and yield, and, indeed, for most sites with the exception of Leck a good correlation ($R^2 > 0.62$) was found. While the coefficient decreased for Bad Salzuflen and Göttingen with higher PAWC, the coefficient increased for Magdeburg. This indicates for Magdeburg that the water stress for the low PAWC was already severe before flowering (mean 0.83 at 1600 Degree-days; Fig. 9) and looking only at the period from flowering to maturity might not be sufficient to explain the water limitations at that site. According to the simulation results, high yielding winter oilseed rape (>3500–4000 kg grain yield ha^{-1}) is frequently affected by water limitation, even on fertile loamy soils with some rooting depth restriction. It is acknowledged that oilseed rape has a high demand for water (Gerbens-Leenes et al., 2009), but literature, which takes water stress into account when developing fertiliser strategies for oilseed rape, is limited in Germany. Nevertheless, it is addressed in extension material (Alpmann, 2009) and is mentioned for oilseed rape for soils of low PAWC (Rathke et al., 2006). As average yields have risen now to levels where water stress can likely occur (>3500–4000 kg ha^{-1}), the simulation experiment demonstrates the importance of taking rainfall amount and distribution as well as the PAWC of a soil into account to determine the attainable yield of a site. For the N-balance, APSIM simulations ranged from 50 to 125 kg N ha^{-1} for 180 kg N-fertiliser ha^{-1}; such variability was observed under field conditions as well (Henke et al., 2008a, 2008b). The N-balance of 60 kg N ha^{-1} was exceeded in average at fertiliser rates of more than 160 kg N ha^{-1}. For soils of a low PAWC, this was already the case for 140 kg ha^{-1}. Nevertheless, the N-balance differed from year to years according to seasonal rainfall (Fig. 8). For instance, for the 180 kg N ha^{-1} rate, the N-balance was hardly exceeded for the PAWC > 187 mm when rainfall was >200 mm. The main difference between the sites was that in Leck more than 53% of all seasons provided sufficient rainfall (>200 mm) from flowering to maturity to remain below the critical threshold for the N-balance for the PAWC > 123 mm, while in Magdeburg, it occurred only in 16% of all seasons. This shows that crop modelling using weather forecast data in spring has the potential to provide improved N-fertiliser recommendations (e.g. Asseng et al., 2012). However, in-season decision making in fertiliser rate is difficult in winter oilseed rape cultivation as the application takes place early in spring to meet the high N-demand during the juvenile phase (Rathke et al., 2006). In the future as reliability of these seasonal forecasts improves, better N-management may be possible.

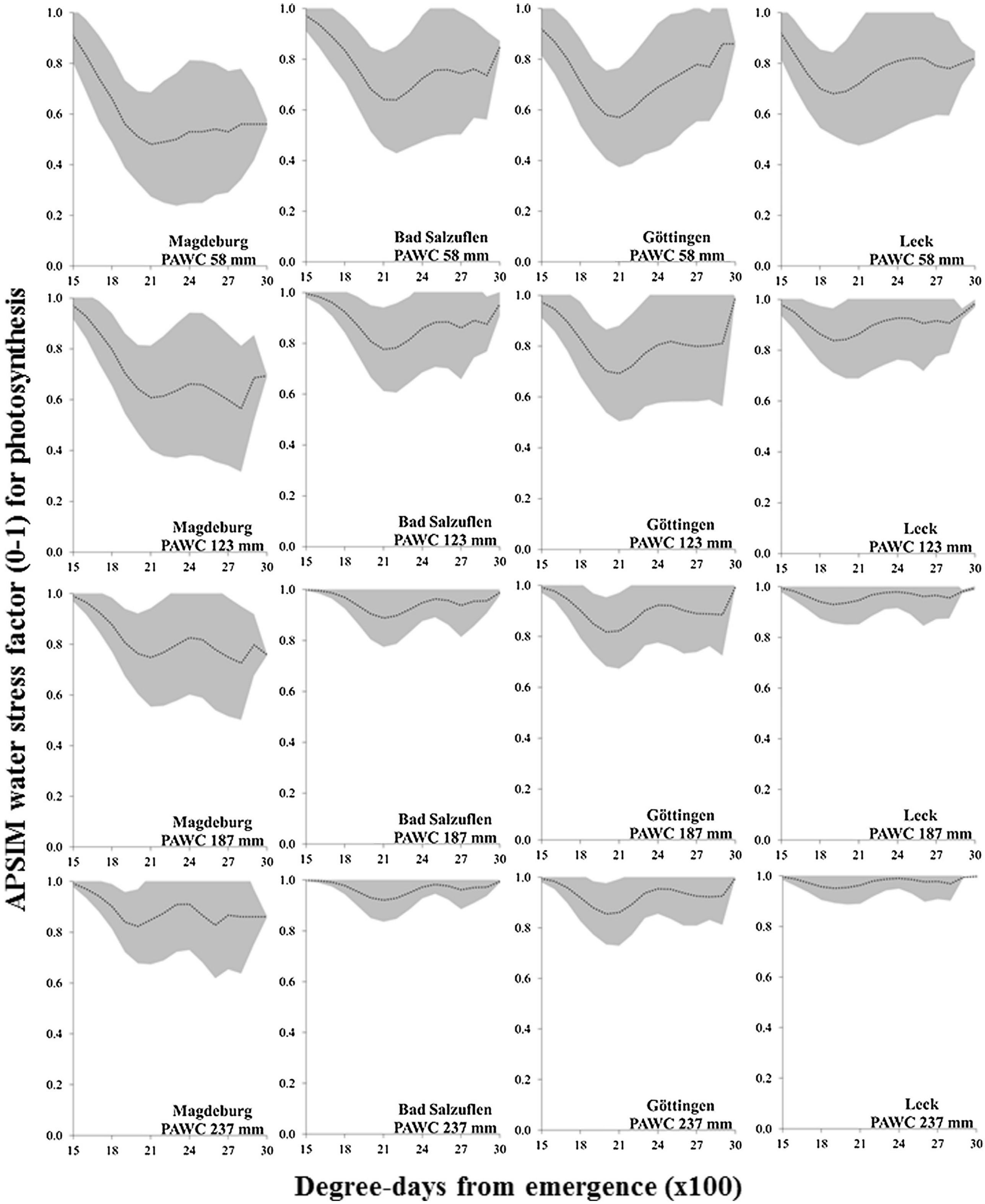

Fig. 9. Simulated factor for mean water stress for photosynthesis as the mean (dotted line; 0 = severe stress, 1 = no stress) and the standard deviation (grey). Results based on an APSIM simulation experiment for the years 1961–2012 for each site and plant available water capacity (PAWC). N-fertiliser rate was 180 kg N ha^{-1}.

While we found in the simulation experiment that N-balance was well related with the PAWC of a soil, a relationship between N-balance and sites was less obvious and needed a more integrative interpretation (Fig. 6). For example, the model suggested a trend of higher yields in Leck than in Göttingen, but the N-balance was the same for both sites at high PAWCs and at the 180 kg N ha^{-1} fertiliser rate. Mean simulated N-uptake was slightly higher at Göttingen (172 kg ha^{-1}) than at Leck (170 kg ha^{-1}) (Table 5). For Göttingen, the model simulated around 5–10 kg more N mineralised per hectare and per growing season (data not shown) due to higher temperatures than for Leck (Fig. 2). However, in Göttingen, biomass production is more limited by water, although the overall N-uptake is similar. Thus, the N-concentration in the plant is higher in Göttingen than in Leck where mean N-concentrations in the grain (3.2%) and in the straw (0.51%) were below critical values (Tables 2 and 5). Therefore, the plant suffered from N-stress more frequently in Leck than in Göttingen. This resulted in more efficient translocation of the available N into the grains indicated by the slightly higher NHI of 0.71 to 0.70 which are typical values for winter oilseed rape in Germany (Sieling and Kage, 2010). Nevertheless, all these differences were very small. According to the model, reduction of the average N-balance in Leck would only be possible by a high soil N-mineralisation which would result into a higher yield and N-content in the grain without additional fertiliser application or by improved HI due to breeding progress. Currently, semi-dwarf varieties have been bred which are supposed to have a higher HI and should be theoretically able to reduce the N-surplus. Interestingly, Sieling and Kage (2007) did not find differences to conventional varieties in terms of yield or N-utilisation over a series of field trials at one location near Kiel (northern Germany). However, crop modelling could provide a better understanding under which circumstances (weather, soil) such varieties perform better. At present, the APSIM canola model simulates HI ultimately on a fixed term (Table 4). An improvement by including the yield determining parameters (grain weight, grain numbers) in the model and how they are affected by climate and management would be needed to better capture the HI (Weymann et al., 2015).

The presented simulation experiment does, however, illustrate the complex relationship between yield, N-balance, soil depth, PAWC, temperature and precipitation. By integrating cultivar specific differences (for instance, HI and root growth (nitrogen uptake capacity) of semi-dwarf varieties) stronger into the model, such an approach could be even more effective in analysing the N-balance. Surprisingly, so far, there is limited literature on a systematic approach trying to connect the different factors (management, soil, climate, genotype) for improving the N-balance (Sieling and Kage, 2010, 2007).

5. Conclusions

We presented the first evaluation of a winter oilseed rape model for central and northern Europe, which includes simultaneous growth limitation by water and N-supply. The model evaluation showed sufficient to excellent results for biomass, N-uptake, SMN and LAI. Thus, it was used to analyse grain yield and N-balance as affected by different N-fertiliser rates at four sites in northern Germany and at four different rooting depths of a loamy soil. Simulated yield was well related with water supply from flowering to maturity at low PAWC and low rainfall sites. Such analysis helps to identify site-specific yield targets which can be reached by an appropriate fertiliser rate. We suggest such an approach complementary to field trial activities for developing site-specific management strategies, which maintain high grain yield levels and improve N-balance in winter oilseed rape cultivation.

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