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Simulation of spring wheat responses to elevated CO_2 and temperature by using CERES-wheat crop model

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The CERES-wheat crop simulation model was used to estimate the changes in phenological development and yield production of spring wheat (*Triticum aestivum* L., cv. Polkka) under different temperature and CO_2 growing conditions. The effects of elevated temperature (3–4°C) and CO_2 concentration (700 ppm) as expected for Finland in 2100 were simulated. The model was calibrated for long-day growing conditions in Finland. The CERES-wheat genetic coefficients for cv. Polkka were calibrated by using the MTT Agrifood Research Finland (MTT) official variety trial data (1985–1990). Crop phenological development and yield measurements from open-top chamber experiments with ambient and elevated temperature and CO_2 treatments were used to validate the model.

Simulated mean grain yield under ambient temperature and CO_2 conditions was 6.16 t ha^{-1} for potential growth (4.49 t ha^{-1} non-potential) and 5.47 t ha^{-1} for the observed average yield (1992–1994) in ambient open-top chamber conditions. The simulated potential grain yield increased under elevated CO_2 (700 ppm) to 142% (167% non-potential) from the simulated reference yield (100%, ambient temperature and CO_2 350 ppm). Simulations for current sowing date and elevated temperature (3°C) indicate accelerated anthesis and full maturity. According to the model estimations, potential yield decreased on average to 80.4% (76.8% non-potential) due to temperature increase from the simulated reference. When modelling the concurrent elevated temperature and CO_2 interaction, the increase in grain yield due to elevated CO_2 was reduced by the elevated temperature. The combined CO_2 and temperature effect increased the grain yield to 106% for potential growth (122% non-potential) compared to the reference. Simulating the effects of earlier sowing, the potential grain yield increased under elevated temperature and CO_2 conditions to 178% (15 days earlier sowing from 15 May, 700 ppm CO_2, 3°C) from the reference.

Simulation results suggest that earlier sowing will substantially increase grain yields under elevated CO_2 growing conditions with genotypes currently cultivated in Finland, and will mitigate the decrease due to elevated temperature. A longer growing period due to climate change will potentially enable cultivation of new cultivars adapted to a longer growing period. Finally, adaptation strategies for the crop production under elevated temperature and CO_2 growing conditions are presented.

Key words: CERES-wheat model, spring wheat, climate change, CO_2, temperature, Finland, simulation, open-top chamber, early sowing

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Manuscript received April 2001

Introduction

Intergovernmental Panel on Climate Change (IPCC) has estimated that the atmospheric CO_2 concentration will double from current ambient concentration (355 ppm) and the mean temperature will increase between 1.48°C and 5.8°C by the year 2100 (IPCC/WGI 1996). The consequences of potential climate change in northern latitudes will involve changes in agro-ecosystems: Mean temperature will increase during late winter, spring and autumn. In Finland the "SILMU scenario" (The Finnish Research Program on Climate Change, SILMU 1992–1995) estimates that the atmospheric CO_2 concentration will increase from current ambient 355 ppm to 523 ppm and the mean temperature will increase with 2.4°C by the year 2050 and respectively to 733 ppm and with 4.4°C by the end of 2100 (Carter 1996, 1998). In Finland the increase of one degree in mean temperature will expand the growing season for 10 days and move the border of cereal cultivation 100–200 km to the north. In Finland a longer growing season for crops (10–33 d) is estimated: sowing will happen ca. 10–15 days earlier (Carter 1992). Earlier sowing will cause changes in growing conditions especially during vegetative phase, with potential changes in plant phenological development (Saarikko and Carter 1996, Saarikko 1999). It has been estimated that C_3-metabolic pathway plants will increase yield potential between 20 and 53% when current CO_2 concentration will double to 600–700 ppm (Goudriaan et al. 1985, Cure and Acock 1986, Goudriaan et al. 1990).

The IGBP (International Geosphere-Biosphere Programme) Wheat Network validated several crop models with the same genotype and weather datasets (IGBP/GCTE 1993). The spring wheat cv. Katepwa grown in Minnesota (USA) was used in the validation. The grain yield variation was significant between all models under ambient temperature and CO_2 conditions. The SUCROS model (Spitters et al. 1989) grain yield estimate for cv. Katepwa was 4.4 t ha^{-1} and respectively AFRCWHEAT2 (Porter et al. 1993) 4.6 t ha^{-1} and CERES-wheat 3.5 t ha^{-1} (Godwing et al. 1989, Hanks and Ritchie 1991). Porter et al. (1993) validated the AFRCWHEAT2, CERES-wheat and SWHEAT crop models under non-limiting growing conditions. The modelling results with AFRCWHEAT2 model (Semenov et al. 1993) indicated a general increase of 25–30 % on winter wheat yield and biomass levels under elevated CO_2 (700 ppm) and with different nitrogen application. However, the elevated temperature (2–4°C) decreased the grain yield because of accelerated phenological development in generative phase and thus shorter grain filling period. When the condition of both effects, the elevated temperature and CO_2 was simulated, the grain yield remained the same as for current ambient conditions. In Finland Laurila (1995) validated the CERES-wheat for Finnish growing conditions with Swedish and German wheat cultivars. Rosenzweig and Parry (1994) simulated with CERES-models linked with General Circulation Models (GCM) the world cereal trade and production for elevated CO_2 concentration and temperature during climate change by the end of year 2060. The simulation results suggest that without the net effect of increased CO_2 (555 ppm), the world cereal production will decrease by 11 to 20 per cent. With the inclusion of elevated CO_2 effect, the world cereal production will decrease by 1 to 8 per cent.

The overall objective of the present study was to estimate the effects of elevated CO_2, temperature and earlier sowing on spring wheat (cv. Polkka) phenology and grain yield production by using the CERES-wheat model. The specific objectives of the present study consisted of following procedures: (i) Parameterisation of the CERES-wheat model, consisting of (i.1) calibration of the model for Finnish long-day growing conditions under current temperature and CO_2, (i.2) validation of the model with independent wheat data conducted under ambient and elevated temperature and CO_2, (i.3) sensitivity analysis: the sensitivity of grain yield on CO_2 and temperature changes both in the potential and non-potential models and (ii) impact assessment for

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elevated CO_2, temperature and earlier sowing effects on spring wheat phenological development and grain yield potential under potential and non-potential growing conditions by using the calibrated and validated model.

Material and methods

Both the calibration and validation procedures for the CERES-wheat model were accomplished by using independent data sets from different data sources according to Thornley and Johnson (1990). During the validation procedure, the model was used to simulate the phenological development and grain yield responses of cv. Polkka to different elevated CO_2 and temperature conditions. Moreover, the effects of earlier sowing dates were simulated. Both the potential (i.e. without stress factors reducing the yield potential) and non-potential growth under Finnish long-day growing conditions were simulated.

Experimental data

Calibration data

MTT Agrifood Research Finland official variety trial data (1985–1990) for cv. Polkka (Svalöf, Sweden) was used in the calibration of the CERES-wheat model for the ambient CO_2 and temperature levels and Finnish long day growing conditions (Järvi et al. 2000, Kangas et al. 2001). The mean ambient temperature is between 10–15°C during the growing season in Southern Finland (Hakala 1998a). The Finnish Meteorological Institute provided the required weather data (global radiation, precipitation, diurnal maximum and minimum temperatures) for the CERES-wheat model.

Validation data

During 1992–1994 the cv. Polkka was grown inside open-top chambers (OTC) under elevated (700 ppm) and ambient (350 ppm) CO_2 concentrations and under ambient and elevated (+3°C, inside greenhouse) temperature growing conditions. The average nitrogen fertilization was 120 kg N ha^{-1} in the experiment (1992–1994). The open-top chamber experimental design is described by Hakala (1998a). The cv. Polkka was sown 2–3 weeks earlier in the elevated OTC experiment (+3°C) in order to simulate future conditions with elevated temperature (3°C), and with a growing season 10–33 days longer than at present (Carter 1992, Hakala 1998a, b). The cv. Polkka photosynthesis and Rubisco kinetics measurements with elevated CO_2 and increased temperatures are published by Hakala et al. (1999). The plant physiological measurements were used in the validation of the CERES-wheat model. The observed values were compared with the corresponding estimates of potential and non-potential models.

CERES-wheat model description

The dynamic and mechanistic CERES-wheat (Crop Estimation through Resource and Environment Synthesis) crop simulation model (v. 2.10) (Ritchie and Otter 1985, Godwing et al. 1989, Hanks and Ritchie 1991, Hodges 1991) was selected for this study because the model was well validated and tested against data from different winter and spring wheat experiments (IGBP/GCTE 1993). For the latest version of the CERES-wheat model refer to DSSAT (Decision Support System for Agrotechnology Transfer) web-site http://www.icasanet.org or http://agrss.sherman.hawaii.edu/dssat/dssat/info.htm. The CERES-wheat model can be used for potential (potential model) and for non-potential simulations (non-potential model). In the potential model, the wheat plant is growing under favourable environment. In the non-potential model, subroutines controlling soil water balance and use of nutrients simulate the effect of water and nutrient stress limiting grain yield (Hanks and Ritchie 1991, Hodges 1991). The phenology submodel (PHENOL) simulates plant physiological

Table 1. Growth stages and corresponding threshold temperatures in the CERES-wheat model (Godwin et al. 1989).

Growth stage	Phase	T_b (°C)
7.	End of previous crop to planting in crop rotation	1.0
	Vegetative phase	
8.	Planting to germination	
9.	Germination to emergence	2.0
1.	Emergence to floral initiation	0.0
	Generative phase	
2.	From floral initiation to begin of ear growth	
	(double ridge phase, terminal spikelet)	0.0
3.	From begin of ear growth to anthesis	0.0
4.	Anthesis to begin of grain fill	0.0
5.	Grain filling period	1.0
6.	Full maturity*1)	1.0

*1) Full maturity of cv. Polkka occurs ca. five days after the yellow ripening stage (Järvi et al. 2000).
T_b = threshold temperature (°C).

processes controlling vernalization, photoperiodism and phenological development (Ritchie and Otter 1985). The CERES-wheat model contains nine growth stages (Table 1). The growth stage classification resembles Feeke's (Large 1954) and Zadok's (Zadoks et al. 1974) growing scales describing both vegetative and generative growth.

The genetic coefficients

In the CERES-wheat model the genetic coefficients define the phenological development and biomass and yield potential for different spring and winter wheat genotypes (Ritchie and Otter 1985). The phenological genetic coefficients used in the model are PHINT (Phyllochron interval or leaf appearance rate), P1V (Vernalization coefficient), P1D (Photoperiodism coefficient) and P5 (Grain filling period).

The phyllochron interval (PHINT) defines the appearance rate of leaves and tillers. It varies with cultivar, latitude and time of planting; a general average value is ca. 95.0 dd (Tables 2 and 3). The P1V coefficient controls sensitivity to vernalization. The P1D coefficient controls sensitivity to photoperiod. The photoperiodic effect on wheat phenological development is modelled assuming daylengths shorter than 20 hours/day can delay development in stage 1 (Table 1). Mean photoperiod and sunshine hours in MTT experimental sites are presented in Table 4. A threshold daylength of 18 hours has been identified for genotypes adapted to Finnish long day growing conditions (Kontturi 1979, Saarikko and Carter 1996). Daylengths below the threshold delay vegetative phase from sowing to heading. The thermal time controls the phenological development in generative phase from heading to full maturity. The mean photoperiod (1992–1994) in the OTC experiment from sowing to anthesis was between 19 and 20 h. According to Hakala (1989a), the photoperiod was long enough not to affect the phenological development in the vegetative stage.

The yield component coefficients in the model are G1, G2 and G3 (Table 2). The G1 coefficient affects the grains/ear (GPP) and grains/m^2 (GPSM) yield components. The G2 coefficient affects the 1000-seed weight (SKERWT). The G3 coefficient (Spike number) affects the lateral tiller production (TPSM). Table 3 demonstrates default genetic coefficients for spring and winter wheat genotypes grown in different continents (Ritchie and Otter 1985, Godwin et al. 1989, Hanks and Ritchie 1991, Hodges 1991). The CERES-wheat genetic coefficients for cv.

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Table 2. The genetic coefficients in the CERES-wheat model (Godwin et al. 1989).

Submodel	Genetic coefficients	Description, process or yield component affected	Range	Unit
Phenological development	PHINT	Phyllochron interval, leaf appearance rate	<100	dd
	P1V	Vernalization	0–9	–
	P1D	Photoperiodism	1–5	–
	P5	Grain filling duration	1–5	–
Yield component	G1	Grains/ear (GPP), Grains/m^2 (GPSM)	1–5	–
	G2	1000-seed weight	1–5	–
	G3	Spike number, affects lateral tiller production (TPSM)	1–5	–

Table 3. Default genetic coefficients for spring (Sw) and winter wheat (Ww) genotypes (Godwin et al. 1989).

Genotype & Location	PHINT	P1V	P1D	P5	G1	G2	G3
Sw/Northern Europe	95.0	0.5	3.5	2.5	4.0	3.0	2.0
Sw/North America	95.0	0.5	3.0	2.5	3.5	3.5	2.0
Ww/ America/N. Plains	95.0	6.0	2.5	2.0	4.0	2.0	1.5
Ww/ West Europe	95.0	6.0	3.5	4.0	4.0	3.0	2.0
Ww/ East Europe	95.0	6.0	3.0	5.0	4.5	3.0	2.0

PHINT = phyllochron interval, leaf appearance rate, P1V = vernalization, P1D = photoperiodism, P5 = grain filling duration, G1 = grains/ear (GPP), grains/m^2 (GPSM), G2 = 1000-seed weight, G3 = spike number, affects lateral tiller production (TPSM).

Polkka governing the phenological development and the yielding capacity were calibrated by using the MTT official variety trial data (Järvi et al. 2000).

The effects of elevated temperature on wheat phenological development

The phenological development of cereals is correlated with the cumulative thermal time (i.e. temperature sum) during growing season. The accumulation of daily thermal time (DTT) is the driving variable in the CERES-wheat phenological submodel (Ritchie and Otter 1985). Model calculates the cumulating DTT units from the base threshold temperature (T_b) (Table 1). In Finland, several previous studies (Kontturi 1979, Kleemola 1991, 1997, Saarikko 1999) have estimated the optimum threshold temperature for different cereals in northern long day growing conditions. According to Kontturi (1979) the spring wheat threshold temperature (T_b) in Finland should be lower in vegetative (T_b = +4.0°C) phase versus generative phase (T_b = +8.0°C). Based on +5°C threshold temperature (generally used in Finland), the thermal time requirement from sowing to yellow ripening stage for spring wheat should be 1050° ± 30° degree-days (dd).

The effects of elevated CO_2 on wheat photosynthesis

In the CERES-wheat crop model (v. 1.9), the effect of elevated CO_2 response on wheat photosynthesis is considered by simulating the performance of the stomata. The atmospheric CO_2 concentration modifies the leaf stomatal conductance, which in turn modifies the rate of plant transpiration. The stomata release concurrently the water vapour into atmosphere as the CO_2 molecules diffuse into stomatal cavity (Ritchie and Otter 1985).

Table 4. MTT experimental sites used in the CERES-wheat genetic coefficient calibration with geographical coordinates, altitude (m), Temp = mean May–September air temperature (°C), Prec = precipitation (mm) 1970–1990, Phot = photoperiod and sunshine hours (h) at the nearest meteorological stations next to each MTT experimental site.

Site	Location	Altitude (m)	Temp (°C)	Prec (mm)	Phot (h)	Soil type
Anttila[1)]	60° 25'N, 24° 50'E	45	13.5	195	18.3	Sandy clay
Anjala	60° 30'N, 26° 50'E	33	13.2	302	18.4	Sandy clay, mould[2)]
Jokioinen	60° 49'N, 23° 30'E	104	12.7	319	18.5	Heavy clay
Kokemäki	61° 16'N, 22° 15'E	38	12.7	297	18.7	Coarse sand, fine sand
Mietoinen	60° 40'N, 21° 50'E	13	13.1	308	18.4	Pure clay, sandy clay
Pälkäne	61° 25'N, 24° 20'E	103	13.1	319	18.7	Silt[2)]
Salo	60° 22'N, 23° 06'E	3	13.6	316	18.3	Sandy clay, silty clay
Tammisto[1)]	60° 16'N, 24° 50'E	45	13.5	295	18.3	Sandy clay

[1)] Hankkija Plant Breeding Institute experimental sites in Tuusula (data for cv. Ruso)
[2)] Few field observations for silt and organic soil (peat and mould) types

Model calibration

The CERES-wheat genetic coefficients governing the phenological development (PHINT, P1V, P1D, P5) and yield potential (G1, G2, G3) for cv. Polkka (Table 2) were calibrated with the RMSD algorithm (Root Mean Square Difference). The genetic coefficients were calibrated for the cv. Polkka by minimizing the RMSD between the simulated and the observed values (Table 4). The RMSD was calculated according to Eq. 1 between the observed and simulated dates (DOY, Day of Year) for phenological development and between the observed and simulated grain yields (t ha^{-1}). The cv. Polkka recorded anthesis and maturity dates and measured grain yield levels from the MTT official variety trials (1985–1990) were used as calibration data (Järvi et al. 2000).

$$RMSD = \sqrt{((\sum_{i=1}^{n} (d^2))/n-1)} \qquad (1)$$

where √ is square-root, d is difference (observed-simulated) in days from sowing to anthesis and from sowing to full maturity in the calibration of phenological coefficients (PHINT, P1V, P1D and P5). Parameter d is also used as the grain yield difference (observed-simulated) (t ha^{-1}, 15% moisture content) in the calibration of yield potential coefficients (G1, G2 and G3). Parameter n is the number of experimental sites* years (35 total) including 4 MTT testing sites: Anjala, Kokemäki, Mietoinen, Pälkäne and Salo (Sugar Beet Research Centre) and Tuusula (Hankkija Plant Breeding Institute) and 6 experiment years (1985–1990, except Tuusula only 5 years) (Table 4). The calibrated coefficients are presented in Tables 5–6.

The CERES-wheat non-potential model was calibrated with the MTT soil data (1985–1990) for clay, sand, silt and organic soils (Table 4). The non-potential model was used to simulate the effects of water and nutrient deficiency (nitrogen) stresses during the growing season. Ritchie (1989) has described the modelling of water stress during growing period in the CERES-wheat soil submodel. Hanks and Ritchie (1991) have presented detailed nitrogen dynamics between soil and plants.

Sensitivity analysis

Sensitivity analysis has been widely applied in optimization theory and operation research (Fiacco 1983, Gal and Greenberg 1996). In crop models the sensitivity analysis has been applied

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Table 5. Phenological coefficients (PHINT, P1V, P1D and P5) for cv. Polkka.

$RMSD_{ANTH}$ (d)	$RMSD_{FMAT}$ (d)	PHINT (dd)	P1V	P1D	P5
2.99	5.86	60.0	0.10	1.00	10.0

$RMSD_{ANTH}$ = RMSD for anthesis (d), the anthesis is reached ca. 5 days after heading
$RMSD_{FMAT}$ = RMSD for full maturity (d)

to study the sensitivity of a response variable (e.g. grain yield) on the changes of independent driving variable (e.g. temperature). According to Thornley and Johnson (1990), a crop model can be classified as sensitive or insensitive based on response variable change. A specific model can be classified as sensitive, if the independent driving variable is deviated for example by 10 per cent causing the response variable to change more than 10 per cent. If the change of response variable is less than 10 per cent, a model can be classified as insensitive. The sensitivity analysis was applied in this study to assess the grain yield sensitivity to temperature and CO_2 changes both with potential and non-potential models.

Results

Calibration of phenological coefficients

The optimum phenological coefficients for cv. Polkka with RMSD values for anthesis ($RMSD_{ANTH}$) and for full maturity ($RMSD_{FMAT}$) under ambient temperature and CO_2 conditions for PHINT, P1V, P1D and P5 were 60.0, 0.1, 1.0, 10.0 respectively (Table 5).

Calibration of yield component coefficients

The yield component coefficients (G1, G2 and G3) for cv. Polkka with the RMSD values for grain yield ($RMSD_{YLD}$) (Table 6) were calibrated with the Anjala, Mietoinen, Kokemäki, Pälkäne and Salo research stations soil data (Table 4). In addition, Hankkija (Anttila and Tammisto sites) cultivar trial data with long time-series (1968–1972) for spring wheat (cv. Ruso) were used. Cv. Ruso resembles cv. Polkka in phenological development, yield potential and with yield quality (Peltonen et al. 1990). Both cv. Ruso and cv. Polkka are late cultivars: 102 (cv. Ruso) versus 102 (cv. Polkka) growing days from sowing to yellow ripening stage. The average grain yield is 3770 and 4030 kg/ha, 1000-seed weight 37.2 and 33.0 g and protein content 14.0 and 14.7 per cent on cv. Ruso and cv. Polkka, respectively (Järvi et al. 2000). The optimum yield coefficients for G1, G2 and G3 were 5.0, 1.0 and 1.5 respectively with all MTT soil data pooled together (Table 6).

The optimum genetic coefficients for cv. Polkka under ambient CO_2 and temperature conditions were for PHINT, P1V, P1D, P5, G1, G2, G3 60.0, 0.1, 1.0, 10.0, 5.0, 1.0, 1.5 respectively.

Model validation and evaluation results

Evaluating phenological development

The cv. Polkka growing days simulated with the phenological submodel (PHENOL) between sowing and anthesis dates (Table 7) were on average 61 days after sowing in ambient versus 63 observed and 51 days in elevated temperature (+3°C) versus 59 observed average (1992–1994) (Hakala 1998a). The observed mean anthesis (1992–1994) occurred on 194 DOY in ambient conditions. Respectively the simulated anthesis (sowing 15 May) occurred on 192 DOY with mean difference of 2 days between observed and simulated.

Table 6. Yield component coefficients (G1, G2 and G3) for spring wheat (cv. Polkka, Svalöf and cv. Ruso, Jo).

Soil type	$RMSD_{YLD}$ (t/ha)	G1	G2	G3
Sand (coarse and fine)[1, 3]	1.7478	0.50	5.00	5.00
Heavy clay[1, 4]	1.8323	1.00	8.50	1.00
Mixed clays[5]	1.7245	1.00	8.50	1.00
Silt, Silt loam[2]	1.4080	1.00	6.00	1.00
Organic soil (Peat, Mould)[2]	0.2892	2.00	2.30	2.00
All soil data pooled	1.7980	5.00	1.00	1.50

$RMSD_{YLD}$ = RMSD for grain yield (t ha^{-1}).
[1] Contains coarse sand, fine sand and loamy sand soil types
[2] Few observations in MTT official variety trial database, the optimized coefficients are only estimates
[3] Data from Kokemäki (coarse sand, 1986–1990), Kokemäki (fine sand, 1985), Tuusula (fine sand, 1988) MTT experimental stations
[4] Data from Mietoinen (heavy clay, 1986–1988,1990) MTT experimental station
[5] Data from Anjala (sandy clay, silty clay, 1988–1990), Salo (sandy clay, silty clay, 1985–1989), Tuusula (sandy clay, silty clay, 1985–1987) MTT experimental stations, Hankkija Plant Breeding Institute Anttila and Tammisto experimental sites (cv. Ruso, 1968–1988)

Table 7. Simulated (cv. Polkka, potential model) anthesis and full maturity estimates (d) from sowing vs. observed mean values (SILMU 1992–1994) (Hakala 1998a).

		Sowing – anthesis					Sowing – full maturity				
		Observed		Simulated			Observed		Simulated		
CO_2 (ppm)	D_{TEMP} (°C)	(SE) (d)	O_{ANTH} (%)	(SE) (d)	S_{ANTH} (%)	D_{ANTH} (d)	(SE) (d)	O_{FMT} (%)	(SE) (d)[*1]	S_{FMT} (%)	D_{FMT} (d)
350	0	62.6[2] (1.9)	–	60.7[3] (3.0)	–	1.90	105.6[4] (3.1)	–	113.3[5] (6.0)	–	–7.70
350	3	59.0 (5.8)	–5.75	51.0 (3.0)	–15.98	8.00	99.3 (3.0)	–5.97	91.7 (1.0)	–19.06	7.60
700	0	62.3 (1.8)	–0.48	60.7 (3.0)	0.00	1.60	109.7 (2.0)	3.88	113.3 (6.0)	0.00	–3.60
700	3	62.3 (5.4)	–0.48	51.0 (3.0)	–15.98	11.30	96.3 (3.0)	–8.81	91.7 (1.0)	–19.06	4.60

CO2 = CO2 concentration (ppm), D_{TEMP} = temperature change (°C), SE = standard error of the mean in observed and simulated values (1992–1994), O_{ANTH} = anthesis change (%) from the observed mean reference (350 ppm/0°C), S_{ANTH} = anthesis change (%) from the simulated mean reference, O_{FMT} = full maturity change (%) from the observed mean reference, S_{FMT} = full maturity change (%) from simulated mean reference, D_{ANTH} = difference between observed and simulated anthesis (d), D_{FMT} = difference between observed and full maturity (d)
[1] Full maturity occurs ca. five days after the yellow ripening stage (Järvi et al. 2000).
[2] Reference value for O_{ANTH}
[3] Reference value for S_{ANTH}
[4] Reference value for O_{FMT}
[5] Reference value for S_{FMT}

The simulated growing days between sowing and full maturity dates were on average 113 days under ambient growing conditions versus 106 observed. Respectively the simulated growing days were 92 days under elevated temperature (+3°C) versus 99 days observed. According to MTT official variety trials, the average growing day number with cv. Polkka under ambient

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Table 8. Simulated (cv. Polkka, potential and non-potential models) mean grain yield (t ha^{-1}) vs. observed mean values (SILMU 1992–1994) (Hakala 1998a).

		Grain yield [1]									
		Observed		Potential model				Non-potential model			
CO_2 (ppm)	D_{TEMP} (°C)	(t ha^{-1}) (SE)	O_{YIELD} (%)	(t ha^{-1}) (SE)	SP_{YIELD} (%)	DP_{YIELD} (t ha^{-1})	PP_{YIELD} (%)	(t ha^{-1})	SN_{YIELD} (%)	DN_{YIELD} (t ha^{-1})	NP_{YIELD} (%)
350	0	5.47 (0.6)[2]	–	6.16 (1.0)[3]	–	0.69	12.61	4.49[4]	–	–0.98	–17.92
350	3	4.62 (0.4)	–17.09	4.05 (0.4)	–19.64	–0.57	–12.34	3.49	–22.27	–1.13	–24.50
700	0	6.15 (0.9)	12.43	8.77 (1.5)	42.37	2.62	42.60	7.52	67.48	1.37	22.28
700	3	5.54 (0.2)	1.28	6.56 (0.8)	6.49	1.02	18.41	5.52	22.94	–0.02	–0.36

CO_2 = CO_2 concentration (ppm), D_{TEMP} = temperature change (°C), SE = standard error of the mean in observed and simulated values (1992–1994), O_{YIELD} = grain yield change (%) from the observed mean reference (350 ppm/0°C), SP_{YIELD} = grain yield change (%) from the simulated mean reference (potential), DP_{YIELD} = difference (t ha^{-1}) between observed and simulated grain yield (potential), PP_{YIELD} = simulated grain yield difference (%) from the observed (potential), SN_{YIELD} = grain yield change (%) from the simulated mean reference (non-potential), DN_{YIELD} = difference (t ha^{-1}) between observed and simulated grain yield (non-potential), NP_{YIELD} = simulated grain yield difference (%) from the observed (non-potential).
[1] 15% moisture grain yield content
[2] Reference value for $O_{YIELD,}$
[3] Reference value for $SP_{YIELD,}$
[4] Reference value for SN_{YIELD}

conditions is ca. 102 days from sowing to yellow maturity stage. The phase from yellow ripening stage to full maturity is ca. five days (Järvi et al. 2000, Kangas et al. 2001). The growing period (d) between sowing and full maturity was 104 /1992, 113/1993 and 100/1994 days in ambient CO_2 and temperature.

Validation of yield components

During the validation of the potential and non-potential models, the simulated grain yield, above ground biomass and harvest index (HI) estimates were compared with the mean OTC experiment values (1992–1994) (Hakala 1998a). The simulated grain yield estimates (potential and non-potential models) versus observed mean values are presented in Table 8. Both the absolute and percentage differences between observed and simulated estimates are tabulated. Respectively the simulated estimates and observed mean values for biomass and HI are presented in Table 9. In addition, other significant yield components (1000 seed-weight, grains/ear and tillers/m^2) were taken into account (Table 10).

The observed mean grain yield (1992–1994) was 5.47 t ha^{-1} under ambient conditions (Hakala 1998a). The potential model (sowing 15 May) overestimated the grain yield (6.16 t ha^{-1}) with mean difference of 0.69 t ha^{-1} (DP_{YIELD}) (12.6%, PP_{YIELD}) between observed and simulated. Respectively the non-potential model (sowing 15 May) underestimated the grain yield (4.49 t ha^{-1}) with mean difference of 0.98 t ha^{-1} (DN_{YIELD}) (17.9%, NP_{YIELD}) (Table 8).

The observed mean grain yield (1992–1994) was 4.62 t ha^{-1} under elevated temperature conditions (3°C). The observed grain yield with elevated temperature was 17% (O_{YIELD}) lower compared to the ambient grain yield. Respectively the simulated grain yield with the potential model was 4.05 t ha^{-1}. The simulated grain yield with potential model under elevated temperature was 19% (SP_{YIELD}) lower compared to the simulated ambient grain yield. The potential model underestimated under elevated temperature the grain yield by 570 kg ha^{-1} (DP_{YIELD}) (12.3%, PP_{YIELD}) compared with the observed. Respectively the simulated grain yield with non-potential model was 23% (SN_{YIELD}) lower compared to the simulated ambient grain yield. The non-potential model underestimated with elevated temperature the grain yield by 1.13 t ha^{-1} (DN_{YIELD}) (24.5%, NP_{YIELD}) compared with the observed.

The observed mean grain yield (1992–1994) was 6.15 t ha^{-1} under elevated CO_2 conditions (CO_2 700 ppm, +0°C). The observed grain yield with elevated CO_2 was 12% (O_{YIELD}) higher compared to the ambient grain yield. The simulated grain yield with potential model with elevated CO_2 was 8.77 t ha^{-1}. Respectively the simulated grain yield with elevated CO_2 was 42% (SP_{YIELD}) higher compared to the ambient simulated yield. The potential model overestimated under elevated CO_2 conditions the grain yield by 2.6 t ha^{-1} (DP_{YIELD}) (42%, PP_{YIELD}) compared with the observed. Respectively the simulated grain yield with the non-potential model was 7.52 t ha^{-1}. The simulated grain yield with elevated CO_2 was 67% (SN_{YIELD}) higher compared to the ambient simulated yield. The non-potential model overestimated under elevated CO_2 conditions the grain yield by 1.37 t ha^{-1} (DN_{YIELD}) (22%, NP_{YIELD}) compared with the observed (Table 8).

The observed mean grain yield (1992–1994) was 5.54 t ha^{-1} under elevated CO_2 and temperature conditions (CO_2 700 ppm, +3°C). The observed grain yield with elevated CO_2 and temperature was only 1.3 per cent (O_{YIELD}) higher compared to the ambient grain yield. The simulated grain yield with the potential model was 6.56 t ha^{-1}. Respectively the simulated grain yield with elevated CO_2 and temperature was 6.49% (SP_{YIELD}) higher compared to the ambient simulated yield (sowing 15 May). The potential model clearly overestimated under elevated CO_2 and temperature conditions the grain yield by 1.02 t ha^{-1} (DP_{YIELD}) (18.4%, PP_{YIELD}) compared with the observed. Respectively the simulated grain yield with non-potential model was 5.52 t ha^{-1}. The simulated grain yield (non-potential model) under elevated CO_2 and temperature was 22.9% (SN_{YIELD}) higher compared to the ambient simulated yield (sowing 15 May). The non-potential model predicted accurately under elevated CO_2 and temperature the grain yield (DN_{YIELD} =20 kg ha^{-1}) (0.4%, NP_{YIELD}) compared with the observed (Table 8).

The potential model simulated HI relatively accurately only under ambient temperature and CO_2 conditions. However, the HI difference (D_{HI}) between observed and simulated deviated more than 20% under elevated temperature CO_2 conditions (Table 9). The observed mean HI (1992–1994) was 0.440 (0.503 simulated) in ambient conditions. The observed HI was 0.380 (0.505 simulated) in elevated temperature (+3°C). The observed HI was 0.420 (0.501 simulated) in elevated CO_2 (CO_2 700 ppm). Respectively the observed HI was 0.370 (0.493 simulated) in ele-

Table 9. Simulated (cv. Polkka, potential model) above ground biomass and harvest index (HI) values vs. observed mean values (SILMU 1992–1994) (Hakala 1998a).

CO_2 (ppm)	D_{TEMP} (°C)	Above ground biomass[1)]			Harvest Index (HI)		
		Observed (t ha^{-1})	Simulated (SE) (t ha^{-1})	D_{ABGR} (%)	Observed (%)	Simulated (SE) (%)	D_{HI} (%)
350	0	12.22	12.06 (1.2)	–1.31	0.440	0.503 (0.043)	14.32
350	3	11.96	8.10 (0.7)	–32.27	0.380	0.505 (0.052)	32.89
700	0	14.33	17.22 (1.7)	20.17	0.420	0.501 (0.044)	19.29
700	3	14.75	13.27 (0.6)	–10.03	0.370	0.493 (0.044)	33.24

CO_2 = CO_2 concentration (ppm), D_{TEMP} = temperature change (°C), D_{ABGR} = simulated above ground biomass difference (%) from the observed (potential model), D_{HI} = simulated HI difference (%) from the observed Harvest Index (potential model), SE = standard error of the mean in observed and simulated values (1992–1994).

[1)] 15% moisture content

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Table 10. Simulated (cv. Polkka, potential model mean yield component values vs. observed mean values (SILMU 1992–1994) (Hakala 1998a).

CO_2 (ppm)	D_{TEMP} (°C)	1000-seed weight (g)			Grains/ear			Tillers/m^2		
		Obs.	Sim. (SE)	D_{SWG} (%)	Obs.	Sim. (SE)	D_{GRE} (%).	Obs.	Sim (SE)	D_{TLL} (%)
350	0	34.4	37.1 (2.9)	7.85	22.2	23.7 (2.1)	6.76	615.7	584.4 (16.9)	–5.08
350	3	32.7	32.7 (2.8)	0.00	19.2	18.7 (1.1)	–2.60	649.0	565.5 (<1)	–12.87
700	0	33.4	37.8 (3.3)	13.17	23.5	26.9 (1.6)	14.47	643.1	718.4 (36.4)	11.71
700	3	33.9	32.7 (2.8)	–3.54	21.2	28.6 (1.4)	34.91	701.9	592.9 (3.9)	–15.53

CO_2 = CO_2 level (ppm), D_{TEMP} = Temperature change (°C), D_{SWG} = simulated 1000-seed weight difference (%) from the observed, D_{GRE} = simulated grains/ear difference (%) from the observed, D_{TLL} = simulated tillers/m^2 difference (%) from the observed, SE = standard error of the mean in observed and simulated values (1992–1994).

vated CO_2 and temperature (CO_2 700 ppm, +3°C). The potential model simulated above ground biomass accurately only under ambient temperature and CO_2 conditions. However, the above ground biomass difference (D_{ABGR}) between observed and simulated was more than 30 per cent under elevated temperature conditions (Table 9).

The simulated and observed yield components (1000-seed weight (g), grains/ear, grains/m^2 and tillers/m^2) are presented in Table 10. The potential model simulated 1000-seed weight relatively accurately, only with elevated CO_2 the difference (D_{SWG}) between observed versus simulated deviated more than 10%. Respectively the tillers/m^2 difference (D_{TLL}) remained below 15% level. However, the grains/ear difference (D_{GRE}) was significant (35%) under elevated temperature and CO_2 conditions.

Sensitivity analysis results

The grain yield sensitivity for temperature and CO_2 changes was analysed with both potential and non-potential models (Table 11). The applied dichotomy classification (sensitive/insensitive) is after France and Thornley (1984), Thornley and Johnson (1990). According to sensitivity analysis results, both the potential and non-potential models were sensitive to small temperature changes in mean temperature. Only with the non-potential model, the temperature increase of 20 per cent (equal to +3°C increase) decreased the grain yield less than corresponding temperature change. When analysing the CO_2 sensitivity results only the potential model was sensitive to CO_2 deviations below 20 per cent (450 ppm), in higher CO_2 concentrations both potential and non-potential models were insensitive. Respectively the potential model was sensitive to concurrent CO_2 and temperature changes below 20 per cent (400 ppm and +2°C). However, in higher CO_2 and temperature levels both the potential and non-potential models were insensitive.

Elevated CO_2 and temperature effects under potential growing conditions

The sensitivity analysis results for elevated CO_2 effect indicate that the elevated CO_2 concentration increased the biomass and yield potential of cv. Polkka from CO_2 compensation point (ca. 50 ppm) to saturation point (ca. 1000 ppm) (Lawlor 1987, Lawlor et al. 1989, Hakala et al. 1999). According to the sensitivity analysis results for cv. Polkka potential yield, the grain yield increased with potential model to +142% (8.77 t ha^{-1}) under elevated CO_2 conditions (Point D, Fig. 1) from the ambient simulated reference (100%, 6.2 t ha^{-1}) (Point A, Fig. 1). The 100% baseline of yield reference with isoline of equal yield refers to current ambient temperature and

Table 11. The sensitivity analysis results for potential and non-potential models: the grain yield sensitivity (%) of cv. Polkka on different temperature and CO_2 deviations (%).

Driving variable			Response variable (grain yield, t ha^{-1})			
			Potential model[4)]		Non-potential model[4)]	
		Change (%)[5)]	Yield change (%)	Sensitivity class	Yield change (%)	Sensitivity class
Temperature	Temperature change (°C)[1)]					
	1	7	–19.0	Sen	–15.7	Sen
	2	13	–22.9	Sen	–19.3	Sen
	3[2)]	20	–22.7	Sen	–13.3	Ins
CO_2	CO_2-level (ppm)					
	390	11	11.9	Sen	9.6	Ins
	438	21	32.7	Sen	11.4	Ins
	525	50	38.3	Ins	32.8	Ins
	700[3)]	100	63.9	Ins	67.4	Ins
CO_2* temperature	CO_2/ Temp.					
	390/2	11–13	–39.5	Sen	–0.7	Ins
	440/3	20–21	–13.6	Ins	–12.2	Ins

Response variable (grain yield) dichotomy classification: Sen = Sensitive, Ins = Insensitive

1) The mean reference temperature is ca. 10–15°C during the growing season in Southern Finland (Hakala 1998a)
2) Temperature level corresponds to the point B (point A reference) in Fig. 1. and Fig. 2.
3) CO_2 level corresponds to the point D (point A reference) in Fig. 1. and Fig. 2.
4) Negative percentage change denotes decreasing yield
5) Percentage change is calculated from the current ambient temperature and CO_2.

CO_2 level. Respectively the measured mean grain yield (1992–1994) increased to 112% (6.15 t ha^{-1}) from the ambient reference level (5.47 t ha^{-1}) (Hakala 1998a).

The simulation results for elevated temperature effect indicated a clear acceleration of phenological development between anthesis and full maturity and a decrease of grain yield and above ground biomass. Especially after the anthesis, the ripening of the grains was accelerated through the increase of thermal time. Full maturity was thus reached earlier, causing a reduction in the final grain yield. The potential model decreased the grain yield to 80.4% (4.1 t ha^{-1}) (Point B, Fig. 1) under elevated temperature conditions from ambient simulated reference (100%, 6.2 t ha^{-1}). Respectively the measured mean yield (1992–1994) decreased to 84 per cent (4.62 t ha^{-1}) from the ambient reference (Hakala 1998a).

The simulation results for elevated temperature and CO_2 interaction indicate that the increase in biomass and grain yield due to the elevated CO_2 was reduced through the interaction with elevated temperatures. The potential model increased the grain yield to 106% (6.56 t ha^{-1}, Point C, Fig. 1) from the simulated ambient reference (6.2 t ha^{-1}). Respectively the measured mean grain yield (1992–1994) increased to 102% (5.54 t ha^{-1}) from the observed ambient reference (Hakala 1998a).

Non-potential growing conditions

The sensitivity analysis results under non-optimal growing conditions (water and nutrient de-

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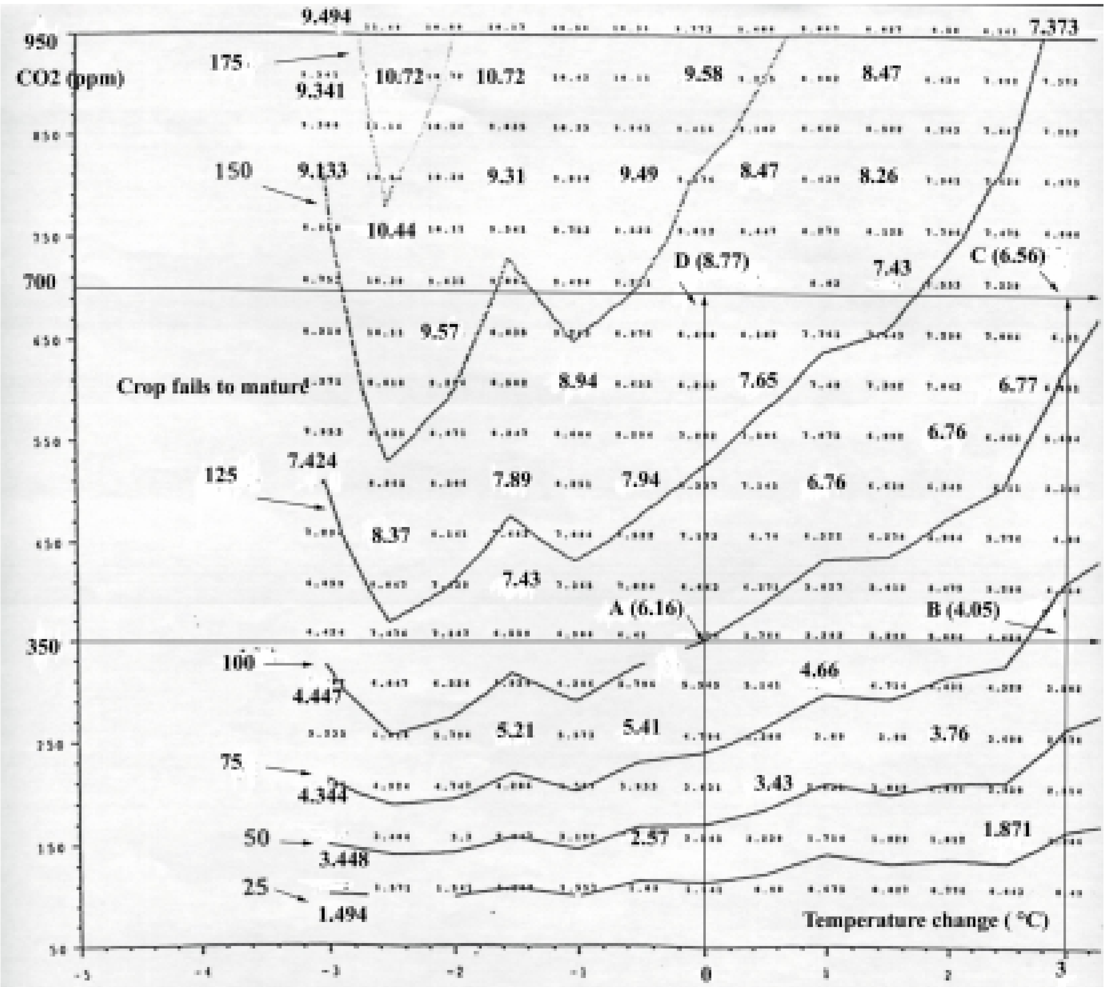

Fig. 1. Results of the sensitivity analysis of the CERES-wheat potential model for grain yield (t ha^{-1}) of spring wheat cv. Polkka in response to CO_2 (ppm) and temperature (°C). Model reference values are 0°C and 350 ppm (point A) indicating change from current mean temperature and CO_2 level. Isolines denote mean grain yield change (%) with steps of ±25% from the reference (100%) going through point A.

ficiencies during growing period) are presented in Fig. 2. The sensitivity analysis results indicate that, under elevated CO_2 and temperature condition (700 ppm CO_2/3°C) the grain yield increased to +122% (5.52 t ha^{-1}, Point C, Fig. 2) from the reference (Point A, Fig. 2) (100%, 4.49 t ha^{-1}). The simulated grain yield level increased to +167 percentage under elevated CO_2 conditions (7.52 t ha^{-1}, Point D, Fig. 2) from the simulated ambient reference. However, the simulated grain yield decreased under elevated temperature to –76.8 percentage (3.49 t ha^{-1}, Point B, Fig. 2).

Impact assessment

Impact assessment of early sowing on wheat phenology and yield potential

According to simulation results, the observed mean anthesis occurred on 167 DOY (Table 12)

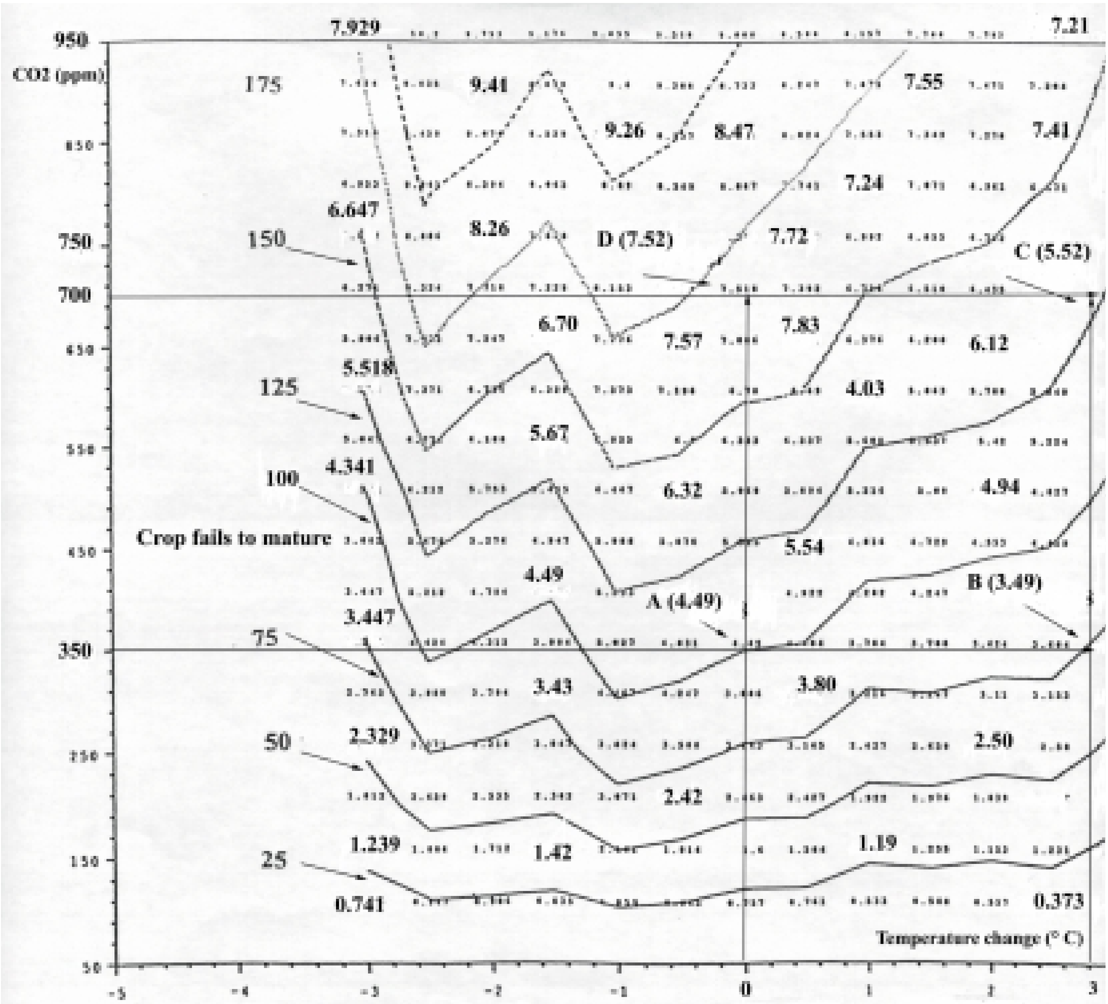

Fig. 2. Results of the sensitivity analysis of the CERES-wheat non-potential-model (with stress factors: water stress, nitrogen deficiency) for grain yield (t ha^{-1}) of spring wheat cv. Polkka in response to CO_2 (ppm) and temperature (°C). Model reference values are 0°C and 350 ppm (point A) indicating change from current mean temperature and CO_2 level. Isolines denote grain yield change (%) with steps of ±25 % from the reference (100%) going through point A.

with earlier sowing (15 d, sowing 29 April 1992) under elevated temperature conditions (Hakala 1998a). Respectively the simulated anthesis occurred on 171 DOY with mean difference of 4 days between observed and simulated (Table 12). The observed anthesis with earlier sowing (15 d) and elevated temperature occurred 27 days earlier compared to the reference anthesis date (15 July). Respectively the simulated anthesis with earlier sowing (15 d) occurred 18 days earlier compared to the simulated reference anthesis date. The potential model estimated the anthesis to occur with earlier sowing on average 9 days later compared with the observed.

The observed mean full maturity (1992–1994) occurred on 236 DOY in ambient conditions. Respectively the simulated full maturity (sowing 15 May) occurred on 244 DOY with

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Table 12. Simulated results (potential model) of earlier sowing for cv. Polkka phenology vs. observed values (SILMU 1992–1994) (Hakala 1998a).

CO_2 (ppm)	D_{TEMP} (°C)	SOW (d)	O_{ANTH} (DOY)	S_{ANTH} (DOY)	D_{ANTH} (d)	O_{FMT} (DOY)	S_{FMT} (DOY)	D_{FMT} (d)
350 Ref.[1)]	0[1)]	0[1)]	194	192	2	236	244	–8
350	3	0	190	182	8	234	226	8
350	3	10		175			216	
350	0	15		182			230	
350	3	15	167[2)]	171	–4	209[2)]	213	–4
350	5	15		165			205	
700	0	0	192	190	2	234	238	–4
700	3	0	170	159	11	207	202	5
700	3	5		178			219	
700	3	10		175			216	
700	0	15		182			230	
700	3	15		171			213	
700	5	15		165			205	

The date of 15 May used as the sowing reference value. SOW = earlier sowing (number of days before 15 May), CO_2 = CO_2 concentration (ppm), D_{TEMP} = temperature change (°C), O_{ANTH} = observed anthesis date (DOY, S_{ANTH} = simulated), D_{ANTH} = difference between observed anthesis vs. simulated (d), O_{FMT} = observed full maturity date (DOY, S_{FMT} = simulated), D_{FMT} = difference between observed full maturity vs. simulated (d).

[1)] Used as the reference value (sowing 15 May, CO_2 350 ppm, ambient temperature)

[2)] Observed 1992 mean value from OTC experiment (sowing 29 April, CO_2 350 ppm, +3°C) (Hakala 1998a)

mean difference of 8 days between observed and simulated. The observed mean full maturity occurred on 209 DOY with earlier sowing (15 d) under elevated temperature condition (sowing 29 April 1992). Respectively the simulated full maturity occurred on 213 DOY with mean difference of 4 days between observed and simulated. The observed full maturity with earlier sowing (15 d) under elevated temperature occurred 32 days earlier compared to the reference full maturity date (22 August) in ambient conditions (Table 12). Respectively the simulated full maturity with earlier sowing (15 d) occurred 31 days earlier compared to the reference full maturity. The potential model estimated the full maturity to occur with earlier sowing on average one day later compared with the observed. According to MTT variety trials, the cv. Polkka full maturity occurs on average 5 days from the yellow ripening stage (Järvi et al. 2000, Kangas et al. 2001).

The observed mean above ground biomass (1992–1994) was 12.22 t ha^{-1} (9.7 t ha^{-1} simulated) in ambient conditions (Table 13). Respectively the observed mean above ground biomass was 12.12 t ha^{-1} (10.5 t ha^{-1} simulated) with earlier sowing (15 d, sowing 29 April) under elevated temperature condition.

The observed mean 1000-seed weight (1992–1994) was 34.4 g (35.4 g simulated) in ambient conditions. Respectively the observed 1000-seed weight was 36.9 g (37.0 g simulated) with earlier sowing (15 d, sowing 29 April) and elevated temperature. The observed mean grains/ear variable (1992–1994) was 22.2 g (18.9 g simulated) in ambient conditions. Respectively the observed grains/ear variable was 24.6 g (22.7 g simulated) with earlier sowing (15 d, sowing 29 April) and elevated temperature (Table 13).

The observed mean grain yield was 4.95 t ha^{-1} with earlier sowing (15 d) under elevated temperature conditions (sowing 29 April 1992,

Table 13. Simulated results (potential model) of earlier sowing for cv. Polkka biomass and yield components vs. observed values (SILMU 1992–1994) (Hakala 1998a).

CO_2 (ppm)	D_{TEMP} (°C)	SOW (d)	O_{BMASS} (t ha^{-1})	S_{BMASS} (t ha^{-1})	O_{KERWT} (g)	S_{KERWT} (g)	O_{GPP} (grains/ear)	S_{GPP} (grains/ear)	S_{TPSM} (tillers/m^2)
350 Ref.[1)]	0[1)]	0[1)]	12.22	9.7	34.4	35.4	22.2	18.9	574.5
350	3	0	11.96	–	32.7	–	19.2	–	–
350	3	5		9.5		36.9		20.8	565.5
350	3	10		10.7		36.6		23.0	565.5
350	0	15		14.0		37.9		28.1	612.0
350	3	15	12.12[2)]	10.5	36.9[2)]	37.0	24.6[2)]	22.7	565.5
700	0	0	14.33	–	33.4	–	23.5	–	–
700	0	5		18.4		39.9		28.1	750.5
700	3	0	14.75	–	33.9	–	21.2	–	–
700	3	5		14.7		37.5		28.5	624.9
700	3	10		15.8		36.9		28.1	669.2
700	0	15		19.6		38.6		30.8	768.3
700	3	15		15.8		37.3		29.0	652.6
700	5	15		13.5		36.9		27.4	580.1

The date of 15 May used as the sowing reference value. SOW = earlier sowing (number of days before 15 May), CO_2 = CO_2 concentration (ppm), D_{TEMP} = temperature change (°C), O_{BMASS} = observed above ground biomass (t/ha, (S_{BMASS} = simulated biomass), O_{KERWT} = observed 1000-seed weight (g, S_{KERWT} = simulated), O_{GPP} = observed grains/ear in main shoot (S_{GPP} = simulated), S_{TPSM} = simulated tillers/m^2.

1) Used as the reference value (sowing 15 May, CO_2 350 ppm, ambient temperature)

2) Observed 1992 mean value from OTC experiment (sowing 29 April, CO_2 350 ppm, +3°C) (Hakala 1998a).

3°C) (Table 14). Respectively the simulated grain yield was 5.6 t ha^{-1}. The observed grain yield with earlier sowing (15 d) and elevated temperature was 9.5% lower compared to the ambient grain yield. Respectively the simulated grain yield with earlier sowing (15 d) was 19 per cent higher compared to the simulated ambient grain yield (sowing 15 May). The potential model overestimated with earlier sowing the grain yield by 650 kg ha^{-1} (13%) compared to the observed (sowing 29 April 1992, +3°C).

The simulated grain yield under elevated CO_2 and temperature conditions was 40% higher compared to the ambient simulated yield (sowing 15 May). The model clearly overestimated with elevated CO_2 and temperature conditions the grain yield by 1.02 t ha^{-1} (18.4%) compared with the observed. Respectively the simulated grain yield was 8.40 t ha^{-1} in earlier sowing (15 d) and elevated CO_2 and temperature (CO_2 700 ppm, +3°C), the yield increase was 78% from the ambient simulated reference (Table 14).

Discussion

Spring wheat phenological development

The simulation results indicate that the phenology submodel estimated relatively accurately the phenological development of cv. Polkka. The anthesis and full maturity estimates for cv. Polkka deviated less than one week versus observed mean values in OTC experiments (1992–1994). Only with elevated temperature and CO_2, the simulated anthesis difference vs. observed was 11 days. Respectively the simulated full maturity difference was less than one week.

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Table 14. The simulated (cv. Polkka, potential model) results of earlier sowing for grain yield (t ha^{-1}, 15% moisture content) vs. observed mean grain yields (SILMU 1992–1994) (Hakala 1998a).

			Observed		Simulated		Difference (obs.-sim.)	
CO2 (ppm)	D_{TEMP} (°C)	SOW (d)	O_{YIELD} (SE) (t ha^{-1})	PO_{YIELD} (%)	S_{YIELD} (t ha^{-1})	PS_{YIELD} (%)	D_{YIELD} (t ha^{-1})	D_{DIF} (%)
350 Ref[1)]	0	0	5.47 (0.6)[3)]	–	4.70[4)]	–	–0.77	–14.08
350	3	0	4.62 (0.4)	–15.54	4.05[5)]	–13.83	–0.57	–12.34
350	3	5			5.10	8.51		
350	3	10			5.60	19.15		
350	0	15			7.70	63.83		
350	3	15	4.95[2)]	–9.51	5.60	19.15	0.65	13.13
350	5	15			4.30	–8.51		
700	0	0	6.15	12.43	8.77[5)]	86.60	2.62	42.60
700	3	0	5.54	1.28	6.56[5)]	39.57	1.02	18.41
700	3	5			7.90	68.09		
700	3	10			8.20	74.47		
700	0	15			10.80	129.79		
700	3	15			8.40	78.72		
700	5	15			6.90	46.81		

The date of 15 May used as the sowing reference value. CO_2 = CO_2 concentration (ppm), D_{TEMP} = temperature change (°C), SOW = earlier sowing (d) before reference sowing date (15 May), O_{YIELD} = observed mean grain yield (t ha^{-1}), PO_{YIELD} = observed grain yield change (%) from the observed mean reference, S_{YIELD} = simulated grain yield estimate (t ha^{-1}), PS_{YIELD} = simulated grain yield change (%) from the simulated mean reference, D_{YIELD} = difference between observed and simulated yield (t ha^{-1}), D_{DIF} = simulated grain yield difference (%) from the observed, SE = standard error of the mean (1992–1994).

1) Ref. used as the reference value (sowing 15 May, CO2 350 ppm, ambient temperature)

2) Observed 1992 mean value from OTC experiment (sowing 29 April, CO2 350 ppm, +3°C) (Hakala 1998a).

3) Reference value for $PO_{YIELD,}$

4) Reference value for $PS_{YIELD,}$

5) Simulated mean grain yield estimate (1992–1994)

Under elevated temperature, the potential model accelerated the phenological development from sowing to anthesis and from sowing to full maturity. Both in vegetative phase before the anthesis and in generative phase from anthesis to full maturity the potential model estimated the phenological phases to occur too early under elevated temperature conditions compared with the observed mean values (1992–1994). This might be explained by low phyllochron value (60 dd) used in simulation for cv. Polkka compared to default value (95 dd) for spring wheat genotypes cultivated in Northern Europe (Table 3). In addition, the grain filling duration variable P5 was high (10.0) compared to default value (2.5) and the threshold temperature (T_b) for different growth stages (Table 1) was low (0–2°C) compared to previous results suggesting 4.0°C for vegetative and 8.0°C for generative phase (Kontturi 1979). However, under ambient and elevated CO_2 conditions, the potential model predicted the anthesis accurately. In addition, the feedback mechanism between the CO_2 and phenological subroutines in the potential model (CERES-wheat v. 1.9) accelerated the phenological development under elevated CO_2 and temperature conditions. The observed yellow ripening dates under elevated temperature and CO_2 conditions confirm this phenomenon (Hakala 1998a).

Grain yield and other yield components under elevated temperature and CO_2

The mean observed grain yield for cv. Polkka under ambient growing conditions versus simulated estimates with potential and non-potential models suggest that the growing conditions might have been sub-optimal under ambient conditions in OTC experiments (1992–1994). The observed mean grain yield remained between the potential and non-potential estimates. Recent studies have critically reviewed problems with the data from OTC experiments. van Oijen et al. (1999) suggested that OTC experiments might overestimate the effects of rising CO_2 with spring wheat genotypes. Moreover, several recent publications have critically reviewed the validation results of crop simulation models with CO_2 and O_3 (ozone) data from OTC (van Oijen and Ewert 1999) and free-air CO_2 enrichment (FACE) experiments. Tubiello et al. (1999) validated the CERES-wheat model with FACE data. Ewert et al. (1999) published revised modelling results with CO_2 and O_3 data for spring wheat growth and development in different sites in Europe. In addition, the CERES-wheat model was originally developed for the simulation of field conditions (Ritchie and Otter 1985, Hanks and Ritchie 1991), which differ from OTC growing conditions.

Both the potential and non-potential models underestimated the grain yield under elevated temperature conditions versus observed mean grain yields. This might imply that the phenological submodel terminated the grain filling phase too early. According to the CERES-wheat model estimations, the yield of cv. Polkka decreased on average to 80.4 % with potential model (76.8% with non-potential simulating water and nitrogen deficiencies) under elevated temperature conditions compared to the simulated reference (100%).

Both the potential and non-potential models overestimated the grain yield under elevated CO_2 conditions versus observed. This might imply that the coefficients for CO_2 response in the CERES-wheat model (version 1.9.) overestimated the CO_2 response on cv. Polkka grain yield. The yield of cv. Polkka increased to 142% under elevated CO_2 condition with potential model (167% with non-potential) from the simulated reference (100%). Respectively the observed grain yield increased only to 112 per cent. Originally the SILMU OTC experiment was established to mimic the potential growing conditions for cv. Polkka under both ambient and elevated temperature and CO_2 conditions (Hakala 1998a). However, several previous studies have suggested that C_3-metabolic pathway plants will increase the grain yield potential between 20 to 53% under doubled CO_2 concentration (Kimball 1983, Goudriaan et al. 1990, van de Geijn et al. 1993). However, the forecasted variation range is very large (Cure and Acock 1986). In that respect, the simulated grain yields under elevated CO_2 in this study accord with the projected range.

The potential model clearly overestimated the grain yield under elevated temperature and CO_2 conditions versus observed mean grain yield. When simulating the interactive effect of increased CO_2 and temperature together, the increase in grain yield due to elevated CO_2 was reduced by the elevated temperature producing a net increase between 6–22%. The grain yield increased with the potential model on average to 106% (122% non-potential) from the simulated reference yield. In addition, the yield component grains per ear difference between observed and simulated was significant (35%) with the potential model under elevated temperature and CO_2 conditions. This might indicate that the potential model is sensitive to wheat translocation changes during grain filling period in yellow ripening stage before full maturity (growth stages 5 and 6, Table 1), since all yield components are interconnected through the plant metabolism and translocation of assimilates.

However, the non-potential model predicted accurately the grain yield compared to the observed (Table 8): This might imply that the average growing conditions under elevated temperature and CO_2 in OTC experiments resembled the sub-optimal conditions simulated with the non-

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potential model. These factors might explain to some extent the difference between the observed and simulated grain yields. In addition, one can speculate how representative the validation data of only three years (1992–1994) actually is.

Early sowing

If the mean temperature will increase during late winter and spring in Finland according to climate change scenarios, it will enable earlier sowing in southern and mid-Finland. In Finland a longer growing season for crops (ca. 1 month) is projected: sowing will occur earlier, thus causing changes in pre-anthesis radiation and daylength conditions especially during vegetative phase. Earlier sowing will potentially entail changes in spring wheat phenological development (Saarikko and Carter 1996, Saarikko 1999).

The simulation results with current Finnish cultivars imply that by using earlier sowing a substantial increase in grain yields can be expected under elevated CO_2 growing conditions. Earlier sowing combined with elevated CO_2 can mitigate the decreasing effect of elevated temperature on yield potential. When simulating the effects of early sowing, the potential model increased the grain yield with earlier sowing dates (varying between 5 to 15 days) compared to ambient conditions with mean sowing date in southern Finland. According to simulation results with the potential model, the grain yield increase with earlier sowing days from the reference (15 May) was +51% (5 d), +57% (10 d), +64% (15 d) under ambient temperature and CO_2 conditions. Respectively under elevated temperature and CO_2 conditions, the simulated grain yield increase with earlier sowing was +68% (5 d), +75% (10 d), +78% (15 d). The simulation results also indicate with earlier sowing that the increasing effect of elevated CO_2 on grain yield is reduced under elevated temperature levels.

There was a large variation in observed grain yields between years (1992–1994) especially in the OTC experiments under elevated CO_2 conditions (Hakala 1998a). In addition, the measured earlier sowing data (15 d, sowing 29 April) with elevated temperature consisted of only 1992 data. The data of only one-year might mitigate the conclusions drawn between the simulated grain yield estimates with earlier sowing versus observed values.

Adaptation strategies for the climate change

According to climate change scenarios, the future climate in Finland (2050–2100) will resemble the growing conditions currently prevailing in southern Sweden and northern Germany. A scheme of transferring mid-European cultivars to Finland to be grown under elevated temperature and CO_2 growing conditions can be hypothesised. A longer growing period would enable cultivation of crops with a longer growing period (Carter 1992), supporting the hypothesis of transferring mid-European spring wheat genotypes to Finland for cultivation. However, current mid-European cultivars are adapted to longer growing period and shorter daylength compared with the cultivars currently cultivated in Finland and adapted to northern long-day growing conditions. Daylength and photoperiodic constraints should be evaluated before introducing mid-European cultivars for cultivation in Finland. Laurila (1995) evaluated with the CERES-wheat model phenological development and yield potential differences between a German cultivar (cv. Nandu) and cv. Polkka currently cultivated in Finland under ambient and elevated temperature and CO_2 growing conditions. Simulation results suggested that the mid-European cv. Nandu would benefit more from the elevated CO_2 and temperature levels. The grain yield of cv. Nandu increased to 161% versus 158% for cv. Polkka under elevated CO_2 condition (700 ppm) from the ambient reference (100%). Respectively the grain yield of cv. Nandu decreased to 59% versus 57% for cv. Polkka under elevated temperature conditions, since the elevated temperature (3°C) accelerated the phenological development with both cultivars. Respectively the concurrent elevated CO_2 and temperature conditions increased the grain yield of cv. Nandu to 107% versus 104% for cv. Polkka compared to the ambient reference.

Conclusions

Previous crop physiological experiments and theoretical calculations suggest, that the yield potential of wheat cultivars can be increased even by 30 per cent from the maximum yielding capacity by using higher radiation levels and providing that the translocation of assimilates and the sink capacity are non-limiting factors. According to theoretical calculations, the maximum yielding capacity arises above 10 tons per hectare for wheat cultivars (Stoy 1966, Evans 1973, Evans and Wardlaw 1976). If the doubled CO_2 increases the yield levels of spring wheat cultivars between 10 and 40 per cent from the current average yield level, as the crop physiological and simulation results suggest, the yield levels with current cultivars still remain below the maximum yielding capacity.

In conclusion, the simulation results suggest that by using earlier sowing a substantial increase in grain yields can be expected under elevated CO_2 growing conditions with cultivars currently cultivated in Finland. Earlier sowing with elevated CO_2 will mitigate the decreasing effect of elevated temperature on grain yields. A longer growing period due to climate change will potentially enable cultivation of new wheat cultivars adapted to a longer growing period: In future it might be possible to cultivate cultivars currently grown in central Europe also in Finland.

Acknowledgments. I wish to express my sincere gratitude to professor Timo Mela, Dr. Kaija Hakala, Ms.Sci. Timo Kaukoranta, Ms.Sci. Markku Kontturi and Dr. Riitta Saarikko (MTT), professor Timothy Carter (The Finnish Environment Institute), professors Eero Varis, Eija Pehu and Pirjo Mäkelä (Helsinki University), professor Risto Kuittinen (The Finnish Geodetic Institute), professor Tuomo Karvonen (Helsinki University of Technology), Dr. Jouko Kleemola (Kemira Agro Oy), professor Jan Goudriaan (Wageningen Agricultural University, Netherlands), professor John T. Ritchie (The Michigan State University, USA), Dr. John H.M. Thornley (Hurley Research Station, Berkshire, UK) and professor John R. Porter (The Royal Veterinary and Agricultural University, Denmark) for their advises during the modelling work and preparation of the manuscript.

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SELOSTUS

Kohotettujen CO_2:n ja lämpötilan vaikutukset kevätvehnän fenologiseen kehitykseen ja sadontuottomahdollisuuksiin

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CERES wheat -kasvumallilla simuloitiin kohotettujen CO_2:n (700 ppm, parts per million) ja lämpötilan (+3 °C) vaikutuksia kevätvehnälajike Polkan (*Triticum aestivum* L., cv. *Polkka*) fenologiseen kehitykseen sekä biomassa- ja sadontuottomahdollisuuksiin optimaalisissa kasvuoloissa (*potentiaalinen kasvumalli)*. Toinen simulointi suoritettiin kasvukauden aikaisten stressitekijöiden (sää, kuivuus, sadanta ja typpilannoitus) vaikuttaessa fenologiseen kehitykseen ja sadontuotantoon (*non-potentiaalinen kasvumalli)*. Suomen ilmastonmuutos -tutkimusohjelman (SILMU 1992–1994) skenaarioiden mukaan Suomen kasvuolosuhteet tulevat muistuttamaan v. 2100 olosuhteita, jotka vallitsevat tällä hetkellä Tanskassa ja Pohjois-Saksassa. Tällöin keskilämpötila on kohonnut 3 °C ja ilmakehän CO_2-taso kaksinkertaistunut nykyisestä 350:stä 700 ppm:ään.

CERES wheat -kasvumallituksen tulokset indikoivat kaksinkertaisen CO_2-tason kohottavan Polkka-lajikkeen satoa 142 % potentiaalisella mallilla (167 % non-potentiaalisella) laskettuna nykyisestä referenssitasosta (100 %, ambientti lämpötila, CO_2 350 ppm). Kohotettu lämpötila (+3 °C) pienensi Polkan satoa 80,4 %:iin referenssitasosta (100 %, 6,16 t ha^{-1}) potentiaalisella mallilla (76,8 % non-potentiaalisella mallilla referenssitasosta 4,49 t ha^{-1}). Kohotettu lämpötila lyhensi kasvin kasvuaikaa kiihdyttämällä kasvua vegetatiivisessa ja generatiivisessa vaiheessa. Kasvuajan lyhentyminen puolestaan alensi Polkkavehnän satoa. Kun simuloitiin kohotettujen CO_2-tason ja lämpötilan yhteisvaikutusta Polkan satoon, kiihdytti kohotettu CO_2-taso vegetatiivisessa vaiheessa biomassan muodostumista ja generatiivisessa vaiheessa sadonmuodostusta. Toisaalta kohotettu lämpötila lyhensi kasvin generatiivista vaihetta ja pienensi CO_2:n satoa kohottavaa vaikutusta. Tällöin kohotettu lämpötila aiheutti tähkän täystuleentumisen aikaisemmin ja sato jäi alhaisemmaksi (106 % potentiaalinen malli, 122 % non-potentiaalinen malli). Tulokset olivat samansuuntaiset Maatalouden tutkimuskeskuksessa v. 1992–1994 Polkka kevätvehnällä tehtyjen open top -kasvukammio kokeiden kanssa (Hakala 1998a). Simuloitaessa aikaisempaa kylvöaikaa (15 päivää aiempi kylvö, referenssi 15.5.) sato kohosi potentiaalisella mallilla 178 %:iin referenssitasosta (100 %) kohotetussa lämpötilassa ja CO_2-tasossa.