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Spring wheat (*Triticum aestivum* L.) ideotype responses to elevated CO_2 and temperature levels - A cereal yield modeling study using satellite information.

DOCTORAL THESIS

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ABSTRACT

The wheat (*Triticum aestivum* L.) ideotype concept is defined as the optimal wheat genotype with a maximum potential for grain yield under optimal growing conditions. The ideotype concept has been widely reviewed in agronomy research for a variety of crops. The wheat ideotype with optimum yielding capacity and with adaptation to elevated atmospheric CO_2 concentrations should have rapid canopy closure at the tillering stage and a long grain-filling period, with high temperature sum requirements from anthesis to maturity.

The CERES-Wheat modeling results using the non-limited Open Top Chamber (OTC) data (1992-1994) indicated, when using the CERES-Wheat potential, non-limiting model, that the simulated grain yield of high-latitude *cv.* Polkka increased under elevated CO_2 conditions (700 ppm) to 142 % and to 161 % for the mid-European *cv.* Nandu, as compared with the reference level (y_{pot}, 100%). The corresponding observed average 1992-1994 increase in OTC experiments was lower (112 % *cv.* Polkka). The elevated temperature (+ 3 °C) accelerated phenological development, especially during the generative phase, according to the CERES-Wheat model estimations. The yield of *cv.* Polkka decreased on average to 80.4 % (59 % *cv.* Nandu, vs. 84 % OTC observed) due to temperature increase from the simulated reference level (y_{pot}, 100%). When modeling the elevated temperature and CO_2 interaction, the increase in grain yield under elevated CO_2 was reduced by the elevated temperature, accelerating phenological development, especially during the generative phase, resulting in a shorter grain-filling period. The combined CO_2 and temperature effect increased *cv.* Polkka grain yield to 106 % (107 % for *cv.* Nandu) under non-limited growing conditions (vs. 102 % OTC observed) as compared with the simulated reference level (y_{pot},100 %).

The modeling results from the CERES-Wheat crop model, ideotype and cultivation value models imply that with new high yielding mid-European ideotypes, the non-potential baseline yield (y_b) would be on average 5150 kg ha^{-1} (+ 108 %) vs. new high-latitude ideotypes (y_b 4770 kg ha^{-1}, 100%) grown under the elevated $CO_{2(700ppm)}$×temperature$_{(+3°C)}$ growing conditions projected for the year 2100 FINSKEN climate change scenario for southern Finland, with elevated CO_2 (733 ppm) and temperature (+4.4 °C) levels.

The Ideotype, Cultivation value, Mixed structural covariance, Path and yield component analysis results emphasized that especially grains/ear, harvest index (HI) and maximum 1000 kernel weight were significant factors defining the highest yield potential for high-latitude and mid-European spring wheat genotypes. In addition, the roles of flag leaf area and dry weight, especially during the generative phase after heading, were important factors defining the final grain yield potential for new high-yielding wheat ideotypes.

The 1989-2004 averaged cereal yield modeling results using optical and microwave satellite data from southern Finland with Vegetation Indices (VGI) and Composite Multispectral (CMM) models, suggest a non-potential baseline yield level (y_b, kg ha^{-1}) of 3950 kg ha^{-1} (R^2 0.630, RMSE 9.1 %) for spring cereals (including spring wheat, barley (*Hordeum vulgare* L.), and oats (*Avena sativa* L.) cultivars), 4330 kg ha^{-1} (R^2 0.630, RMSE 6.7 %) for winter cereals (winter wheat and rye (*Secale cereale* L.) cultivars) and 4240 kg ha^{-1} (R^2 0.764, RMSE 6.6 %) for spring wheat cultivars grown in actual field conditions on farms in southern Finland. The modeled VGI and CMM yield estimates (y_b) were compared with corresponding measured averaged yields in the

experimental areas in the Etelä-Pohjanmaa, Nylands Svenska and Häme Agricultural Advisory and Rural Development Centres (Growing zones I-III) in southern Finland.

The combined modeling results from this study suggest that the 5 t ha^{-1} yield barrier will be surpassed with new high yielding mid-European and high-latitude optimal ideotypes introduced into cultivation after the 1990s, when also taking into account the elevated atmospheric CO_2 and temperature effects, thereby increasing the average spring wheat non-potential yield levels by 1-6 % of high-latitude ideotypes (4-13 % for mid-European ideotypes) by 2100 in southern Finland.

The extrapolation modeling results, combined with earlier sowing and elevated atmospheric CO_2 (700 ppm) and temperature (+3 ºC) effects, suggest an average net increase of 30 million kg annually in spring wheat total production in Finland by 2100 using new high-latitude wheat ideotypes (60 million kg with new mid-European ideotypes) and assuming no changes in wheat cultivated area and land use. Currently the averaged annual spring wheat total production is on the 600 million kg level in Finland, varying significantly between years with changes in wheat total cultivation area in Finland.

LIST OF ORIGINAL PUBLICATIONS

The thesis consists of the following papers, which are referred to by their Roman numerals in the text. The papers are reprinted with the permission of the publisher.

I Laurila H. 2001. Simulation of spring wheat (*cv*. Polkka) responses to elevated CO_2 and temperature by using CERES-Wheat crop model. *Agricultural and Food Science in Finland* 10:175-196.

II Laurila H., Mäkelä P., Kleemola J. and Peltonen. J. 2012. A comparative ideotype, yield component and cultivation value analysis for spring wheat adaptation in Finland. *Agricultural and Food Science* 21: 384-408.

III Laurila, H., Karjalainen, M., Hyyppä, J. & Kleemola, J. 2010. Integrating vegetation indices models and phenological classification with composite SAR and optical data for cereal yield estimation in Finland. Special Issue Microwave Remote Sensing. *Remote Sensing* 2: 76-114.

IV Laurila, H., Karjalainen, M., Kleemola, J. & Hyyppä, J. 2010. Cereal yield modeling in Finland using optical and radar remote sensing. Special Issue Global Croplands. *Remote Sensing* 2: 2185-2239.

CONTRIBUTIONS

	I	II	III	IV
Initial idea	HL	HL, JP	HL, MK	HL, MK. JH
Logic of reasoning	HL	HL	HL	HL
Material	HL	HL, JP	HL, MK, JH	HL, MK, JH
Analyses	HL	HL	HL, MK	HL, JK
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LIST OF DEFINITIONS AND ABBREVIATIONS

The definitions and abbreviations used in the various publications are presented in Table 1. The detailed System Analysis and Design diagram (IIASA 2008) is presented in Figure 1.

Table 1. Definitions and abbreviations used in publications I-IV.

Definition, abbreviation	Unit, [range]	Publi-cation	Explanation
$\overline{x}$		I-IV	Mean of sample
S_d, SD		I-IV	Standard deviation of sample (n)
SEM		I-IV	Standard error of mean = $\frac{SD}{\sqrt{n}}$
R^2	[0.. 1.0]	I-IV	Coefficient of determination, R-square, total variance explained by the statistical model
$r_a, r_b, .. r_x$	[0.. 1.0]	II	Correlation coefficients for independent variables, indirect effects in Path-model
$p_a, p_b, .. p_x$	[0.. 1.0]	II	Path-coefficients for independent variables, direct effects in Path-model
p_v	[0.. 1.0]	II	Vegetation Path-coefficient
p_y	[0.. 1.0]	II	Yield Component Path-coefficient
U		II	Residual factor, the variance not explained by the Path coefficient model
RMSD	kg ha^{-1}, day [d]	I-IV	Root Mean Square Difference $RMSD = \sqrt[2]{\sum_{i=1}^{n} \frac{d^2}{n-1}}$
MSE	%	I-IV	Mean Squared Error $\mathrm{MSE}(\overline{X}) = \mathrm{E}((\overline{X}-\mu)^2) = (\frac{\sigma}{\sqrt{n}})^2$
RMSE	%	I-IV	Root Mean Square Error , square root of MSE
LSE (LSF)		I-IV	Least-Square Estimation-algorithm for linear and non-linear regressions. LSF- Least Square Fit
C_v	%	I-IV	Coefficient of variation (%) = SD/ $\overline{x}$
Ref.		I-IV	Reference genotype/cultivar in field trials or a reference genotype in the statistical analysis or in a dynamic model. As a dependent or response variable it is scaled to relative base value in the corresponding category (1 or 100).
V_p		II	Phenotype variance (Falconer & Mackay 1996)
V_g		II	Genotype variance (Falconer & Mackay 1996)
V_e		II	Environmental variance (Falconer & Mackay 1996)
cov_{ge}		II	Genotype x environmental covariance variation in broad sense (Falconer & Mackay 1996)

HiL **HiL_{New90}**		II	HiL - High-latitude genotype/ideotype (breeding origin and growing latitude > 60° N). HiL_{New90} - a genotype introduced into cultivation in the 1990s or after.
MidE **$MidE_{New90}$**		II	MidE - Mid-European genotype/ideotype (breeding origin and growing latitude < 60° N). $MidE_{New90}$ - a genotype introduced into cultivation in the 1990s or after.
ItPrf(HiL,MidE)		II	Donald's optimal ideotype profiles for high grain yield with generic HiL and MidE genotypes (Donald 1968).
VGI model		III-IV	Vegetation Indices model, see also CMM model. Models I-II in publication III, models I-V in publication IV.
CMM model		III-IV	Composite Multispectral ASAR/SAR & NDVI Model (CMM) – combines both optical and microwave SAR satellite data (Henderson & Lewis 1997). Model III in publication III, model VI in publication IV.
y_{pot} - Potential, non-limited yield for crops (Evans & Fischer 1995) -Yield potential for cultivars (Sinclair 1993)	kg ha^{-1}, 15% moisture content	I-II	Modeled or measured maximum yield capacity for a specific crop (Evans and Fischer 1995) or yield potential for a specific genotype or a cultivar (Sinclair 1993) without limiting environmental stress factors during growing season (vegetation water stress, nutrient deficiencies, pathogen epidemics etc.).
Non-potential, limited yield	kg ha^{-1}, 15% moisture content	I-IV	Modeled or measured yield level (kg ha^{-1}) for a specific genotype or cultivar with limiting environmental stress factors during growing season reducing maximum yield capacity, see potential yield (y_{pot}) and baseline yield (y_b).
Baseline yield (y_b)	kg ha^{-1}, 15% moisture content	I-IV	Modeled baseline yield level (y_b, kg ha^{-1}) for a cereal genotype or a cultivar grown under non-potential field growing conditions. See potential and non-potential yield.
Δyb	%	I-IV	Modeled baseline yield difference (%) between genotypes
y_{pot}(OTC,HiL,MidE)	kg ha^{-1}, 15% moisture content (Figure 1)	I	Modeled potential yield (y_{pot}) level with CERES-Wheat crop model (Jones *et al.* 2003) and using OTC data with elevated CO2 and temperature levels (Laurila 1995, 2001, Publication I, Figure 1).
y_b(OTC,HiL,MidE)	kg ha^{-1}, 15% moisture content (Figure 1)	I	Modeled baseline yield (y_b) level with CERES-Wheat crop model and using OTC data with elevated CO2 and temperature levels (Laurila 1995, 2001, Publication I, Figure 1).
y_b(ItPrf,HiL), y_b(ItPrf,MidE)	kg ha^{-1}, 15% moisture content (Figure 1)	II	Modeled baseline yield (y_b) levels for HiL and MidE ideotype profiles (ItPrf) using Ideotype analysis (Laurila 2012, Publication II, Figure 1).
y_b(Sat,HiL,MidE)	kg ha^{-1}, 15% moisture content (Figure 1)	III-IV	Modeled baseline yield (y_b) level using VGI (Vegetation Indices) and CMM models with optical and microwave satellite data (Publications III, IV, Laurila 2010a,b, Figure 1).
$CVal_{Tot}$	>100 for high yielding ideotypes	II	Cultivation total scoring value of a genotype in growing zones I-III in southern Finland (Figure 7A-C, Appendix 1)
Ca	>20 for high yielding ideotypes	II	Adaptation Value in Cultivation Value model.
Cp	>30 for high yielding ideotypes	II	Cultivation Properties in Cultivation Value model with grain yield accumulation/d and nitrogen (N) amount in grains (g).
C_c	>20 for high yielding ideotypes	II	Cultivation Certainty in Cultivation Value model.
Cb	>20 for high yielding ideotypes	II	Baking Quality in Cultivation Value model.
T, Temp.	degree [C °]	I-IV	Mean temperature as calculated from diurnal minimum and maximum values.
ΔT	degree [C °]	I-IV	Mean diurnal temperature change Kuiper (1993).
T_b	degree [°]	I-IV	Threshold temperature with threshold temperature
ETS(T_b)	dd – degree days	I-IV	Cumulative temperature sum over threshold temperature (T_b = 5 °, Figure 7B, Appendix 1).
dd	[°]	I-IV	degree days
ppm		I-IV	parts per million (CO_2 concentration)
CO_2	Ppm	I-II	Atmospheric CO_2 concentration [ppm]
$\Delta y_{b(CO2,700ppm)}$	%, change range (min. – max.)	II	Change (%) on y_b (baseline yield, kg ha^{-1}) with doubled atmospheric CO_2 concentration (700 ppm , Carter 2004).
$\Delta y_{b(\Delta T,+3°C)}$	%, change range (min. – max.)	II	Change (%) on y_b (baseline yield, kg ha^{-1}) with +3 ºC mean diurnal temperature change (Carter 2004).
$\Delta y_{b(CO2,TempCov)}$	%, change range (min. – max.)	II	Covariance mean change (%) on y_b (baseline yield, kg ha^{-1}) with concurrent doubled atmospheric CO_2 concentration (700 ppm) and with +3 ºC mean diurnal temperature change (Carter 2004).

$\Delta TotProd_{(HiL,MidE,CO2,TempCov)}$	Mkg yr^{-1}	II-IV, Summa ry	Estimated change in annual total national spring wheat production (Mkg yr^{-1}) using new high yielding HiL_{New90} and $MidE_{New90}$ ideotypes with concurrent elevated atmospheric CO_2 concentration (700 ppm) and with +3 ºC mean diurnal temperature change covariant effect and without changes in wheat cultivation area (Carter 2004).
PAR	MJ/d/m^2 [10-20]	I-IV	Photosynthetically Active Radiation (λ=400-700 nm)
RUE	DW g *MJ^{-1}/d [PAR: 1.0-5.0, Global Rad. 0.5-2.5]	I-II	Radiation Use Efficiency: Dry matter (DM) increase / absorbed PAR or global radiation (Goudriaan 1993, Sinclair & Rawlins 1993).
WUE	[mol/m^2/s] / mol/m^2/s]	I-II	Water Use Efficiency: Stomatal CO_2 assimilation rate / water vapor transpiration rate (Goudriaan 1993).
IR NIR -Near IR Mid IR Thermal IR	MJ/d/m^2	III-IV	infrared radiation (IR), λ= 630-690 nm near infra, λ=760-900 nm mid infra, λ=1.55-1.75µm thermal IR, λ=10.4-12.5µm
Rf	[0.0 - 1.0] Optical (λ=400-700nm) and infrared sensors (λ=630-12.5µm) (Table 8, Figure 2).	III-IV	Reflectance - reflected radiation from soil and vegetation canopies and measured by optical satellites (Price 1987, Maas 1991, Maas & Dunlap 1989, Kuittinen 1996, Kuittinen *et al.* 1998).
σ^0 (sigma zero)	[-20 - +10 dB]. Calibrated SAR (Synthetic Aperture radar) backscattering signal with microwave 5.4 GHz (C-band, λ=5.7 cm) and 9.8 GHz (X-band) and polarization levels (HH, VV, VH, HV, Table 8).	III-IV	Backscatter coefficient (sigma zero or nought) for microwave backscattering signal, which is a combined signal reflected from soil and vegetation canopies (Henderson & Lewis 1997, Matikainen *et al.* 1998, Hallikainen *et al*. 1993, Hyyppä *et al.* 1990, Karjalainen *et al.* 2004, 2008, Koskinen 1999. SAR – Synthetic Aperture Radar sensor ASAR – Advanced Synthetic Aperture Radar sensor dB – decibel on logarithmic scale, unit of σ^0 signal
NDVI	%	III-IV	Normalized Difference Vegetation Index
GEMI	%	III-IV	Global Environment Monitoring Index
PAR_{ND}	%	III-IV	PAR_{ND}/FAPAR (Normalized Vegetation Index for Photosynthetically Active Radiation)
OTC		I-II	Open Top Chamber Experiments (Hakala 1998b)
FACE		I-II	Free-air CO_2 Enrichment Experiment (Kimball *et al.* 2002).
SatPhenClass	BBCH (0-8)	III-IV	Satellite data classification algorithm based on spring cereal phenology using BBCH (Lancashire *et al.* 1991) and Zadoks growing scales (Zadoks *et al.* 1984).
a_p,b_p, c_p,d_p	a_p - BBCH 0-12 b_p - BBCH 12-50 c_p - BBCH 50-90 d_p - BBCH > 90	III-IV	Phenological phases based on SatPhenClass phenological classification algorithm for spring cereals in southern Finland. a_p – Vegetative phase, period between sowing and two leaf stage with double ridge formation (May in southern Finland). b_p – Vegetative phase, period between two leaf stage and ear emergence with maximum Leaf Area Index (LAI_{max}) exposure and fully closed canopy structures (June). c_p – Generative phase, period between ear emergence and anthesis with grain filling until full maturity (July). d_p –Harvest, post-harvest and senescence (August).
κ Kappa	Range [0.0 – 1.0]		κ Kappa, accuracy of classification, see SatPhenClass algorithm (McNairn *et al.* 2008).
SSP_{ph} SSP_{phOpt} SSP_{phSAR}		III-IV	Phenological spectral signature profile (optical SSP_{phOpt} and microwave, SSP_{phSAR}) for a genotype or a cultivar in vegetative (a_p,b_p) or in generative (c_p,d_p) growing phase.
Minimum dataset		III-IV	Experimental dataset without ground truth or meteorological data, containing only optical or microwave satellite data.
MAFF, MAFF/TIKE IACS FLPIS CAP		I-IV	Ministry of Agriculture and Forestry in Finland. TIKE Information Centre of the Ministry of Agriculture and Forestry http://www.mmmtike.fi/www/fi/ IACS – Integrated Access Control System FLPI S – Finnish Land Parcel Identification System CAP – Common Agricultural Policy in EU
IIASA		I-IV	The International Institute for Applied Systems Analysis (IIASA 2008)
IPCC		I-IV	Intergovernmental Panel on Climate Change (IPCC 2008)
IGBP/GCTE		I-IV	International Geosphere-Biosphere Programme/ Global Change and Terrestrial Ecosystems (IGBP/GCTE 2008)

Table 1. Cont.

	Publications I-II (Table 6)			
CERES-Wheat Submodel Jones *et al.* (2003)	Genetic coefficients	Description, process or yield component affected	Range	Unit
I Phenological development	PHINT	Phyllochron (plastochron) interval as leaf appearance rate. Measures the age of a plant dependent on morphological traits rather than on chronological age.	<100	dd , °C d $leaf^{-1}$
	P1V	Vernalization	0-9	-
	P1D	Photoperiodism	1-5	-
	P5	Grain filling duration	1-5	-
II 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	-

INTRODUCTION

The wheat ideotype, ideotype profile (ItPrf) and Cultivation value (Cval) concepts

Donald (1968) defined the concept of a spring wheat (*Triticum aestivum* L.) ideotype as the optimal wheat genotype with a maximum potential for grain yield production under optimal growing conditions. A crop ideotype in cereal breeding can be described as a plant model system, that is expected to yield greater quantity or quality of grain, oil or other useful product when developed as a cultivar. According to Badger (1992) the ideotype concept defines an optimal wheat genotype with maximum yield potential under optimal growing conditions.

The ideotype concept has been widely studied and reviewed in a variety of crops, for example, regarding plant canopy and leaf architecture (Carvalho *et al*. 1978, Borojevic *et al*. 1980, 1983), ideotype-based breeding strategies, biotechnology and genetic improvement, quantitative genetics, crop physiology and modeling of crop plant traits (Abelardo *et al*. 2002, Bentota *et al*. 1998, Boote *et al*. 2001), and more specifically for cereals in defining a wheat ideotype (Siddique *et al*. 1990).

In agronomic studies Donald's original ideotype concept has been reviewed by Sedgley (1991) and by Reynolds *et al.* (1994) for yield potential estimations in modern wheat cultivars. According to Sedgley (1991) Donald's ideotype concept explains both the optimal resource allocation and translocation of assimilates maximizing crop yield and the relationships between yield, harvest index (HI) and morphological characters in monoculture and variety mixture growing environments. Later on Donald and Hamblin (1976) expanded Donald's ideotype concept with additional climatic, edaphic, disease, pest and stress ideotype concepts. Sedgley (1991) evaluated the two antagonist components in Donald's ideotype, the optimal communal ideotype for cereals maximizing yield potential with uniculm growth habit without side tillers, short stem and narrow erect leaves and the adversary competitive ideotype with freely tillering and tall stature with large leaves.

Donald's original ideotype concept has been widely studied and reviewed for a variety of crops and traits, e.g. in plant canopy and leaf architecture modeling (Carvalho *et al.* 1978), in ideotype-based breeding strategies for wheat with genotype×environment (G×E) covariances (Sedgley 1991, de la Vega *et al.* 2002), in crop modeling studies

(Boote *et al.* 2001) and in phenotypic plasticity studies for wheat yields (Sadras *et al.* 2009). According to Sadras *et al.* (2009) high yield and low plasticity for yield were coupled with early anthesis, long anthesis duration and low plasticity of post-anthesis development with wheat genotypes grown in Mexico.

According to Badger (1992), wheat ideotypes with optimum yielding capacity and with adaptation for elevated atmospheric CO_2 concentration should have a fast canopy closure at tillering stage and a long grain-filling period with high temperature sum requirements from anthesis to maturity. Wolf *et al*. (1993) emphasized the importance of a long grain-filling period with high temperature sum requirements from anthesis to maturity. In Finland Hakala *et al.* (2005) emphasized the role of Rubisco enzyme on the cell level for Nordic, high-latitude growing conditions. Rubisco controls wheat photosynthesis and respiration, utilizing the gains achieved from the elevated CO_2 concentrations in the plant stomata. Rubisco also enhances the biomass accumulation and thus improves the nitrogen use efficiency (NUE) and the nitrogen index (NI), which has also been taken into account in Finland in organic and ecological production systems (Aula & Talvitie 1995). Moreover, the ability of a genotype to increase sink size is crucial under elevated CO_2 levels (Badger 1992, Aula and Talvitie 1995). Spanakis (1990), Siddique *et al.* (1990) and Aula and Talvitie (1995) in Finland suggested that the spring wheat ideotypes adapted to ecological cultivation systems comprises good quality factors, a high harvest index (HI), extensive resistance to pathogens, maximum horizontal/perpendicular leaf-angle for flag and second leaves, accelerated development after sowing and emergence, extensive symbiosis between the root, mycorrhiza and soil microbe fauna, extensive root biomass growth, and an efficient root system for nutrient intake from the soil.

The benefits of applying both statistical and dynamic, mechanistic crop models for Donald's ideotype evaluation have been reviewed by Boote *et al.* (2001) and de la Vega *et al.* (2002). Crop models used in plant breeding should be both dynamic, varying over edaphic and weather conditions, and mechanistic, simulating physiological processes like phenological development, source-sink relationships and translocation of assimilates. According to Boote *et al.* (2001) crop models simulate genetic improvement and variability within a species by evaluating intracultivar variation and how crop models can be used to hypothesize ideotypes for specific growing environments.

In publication II, the CERES-Wheat/DSSAT dynamic crop model (Ritchie & Otter 1985, Jones *et al.* 2003) was used to define genetic coefficients for MidE (mid-European, growing latitude < 60°N, Laurila 1995, Table 1) and HiL (high-latitude, growing latitude > 60°N, Laurila 2001) high yielding ideotype profiles (ItPrf, Table 1). In Finland Peltonen *et al.* (1993) applied the Cultivation value model ($Cval_{\mathbf{Tot}}$, Table 1, Weizensorten und Backqualität 1990) to estimate the cultivation scoring and ranking values with adaptation plasticity (C_a), cultivation certainty (C_c), cultivation properties (C_p) and baking quality (C_b) components for current high yielding wheat genotypes. In publication II the Cultivation value model was evaluated for high-latitude (HiL) and mid-European (MidE) ideotype profiles (ItPrf) with high yielding capacity. High-latitude and mid-European ideotype profiles with factors estimating the effects of concurrent elevated CO_2 and temperature levels with photoperiodical daylength effects can be utilized when designing future high yielding ideotypes adapted to future growing conditions.

Global trends and adaptation strategies in cereal production under projected climate change

According to demographic projections by the United Nations, the human population is expected to rise to over 9 billion in the 21st century (UN 2000). This increase, combined with the potential changes projected by climate change scenarios (IPCC 2001, 2007) for low latitude and equatorial regions (e.g. severe drought periods and desertification in the Middle-East and sub-Saharan Africa) in the 2050-2100 period could seriously change the demographic balance in Europe, Africa and the Middle-East, causing immigration pressure at northern latitudes. The Stern Review on the Economics of Climate Change (Stern 2006) seriously warned of the global economic consequences, including decreased cereal production, especially at the lower latitude developing countries, if climate change effects are not mitigated by reducing greenhouse gas emissions by 50 % in the developing countries and by 80 % in the developed countries by 2050. In that respect, a projected surplus in cereal total production at high-latitudes due to elevated CO_2 and temperature effects could mitigate the serious consequences anticipated for lower latitude developing countries.

Climate change scenarios 2050-2100

The Intergovernmental Panel On Climate Change (IPCC 2001, 2007, Gore 2007, Pachauri 2007) and the International Geosphere-Biosphere Programme/ Global Change and Terrestrial Ecosystems (IGBP/GCTE 1993, 1994a, 1994b, 1995, 1996) have predicted that in the 21st century the atmospheric CO_2 concentration will double from the Kyoto protocol 1990 reference year level (352 ppm, Kyoto 1997) and the mean diurnal temperature will increase by 3-4 degrees.

It has been estimated that the actual doubled CO_2 level equivalent affecting the *global radiation* budget and warming of the atmosphere should be lower (ca. 555 ppm) since other atmospheric trace gases (CH_4, N_2O, NO_X, SO_2,O_3) with different absorption spectra in the infrared wavelengths, have covariant effect with the atmospheric CO_2 thus increasing the diurnal mean temperature (CDIAC 2012).

According to Houghton (1996) and Machalis & Torrey (1959), the atmospheric CO_2 has absorption maxima bands in the infrared spectrum at 2, 3, 5, and 13-17 µm (Figure 2). However, in developed countries the sulfate aerosol particles in the atmosphere reflect the incoming solar radiation back into space, thus countering the atmospheric warming. Recent up-to-date information on climate change research results can be downloaded from the www.co2science.org and http://cdiac.ornl.gov/ websites (CO_2Science 2012, CDIAC 2012).

High-latitude SILMU climate change scenario for Finland

This study reviews the potential changes caused by climate change in the cultivation of spring wheat genotypes under Finnish long day conditions during the 2000-2100 period. In Finland the 'SILMU central scenario' (Table 2-3, Carter & Posch 1995) and the revised estimates in the FINSKEN (Carter 2004, Carter *et al.* 2004, Finsken 2008a) scenarios estimate that atmospheric CO_2 concentration (with seasonal variation) will increase from the Kyoto protocol reference year (1990) level (352 ppm) to 523 ppm and the mean temperature will increase by 2.4 °C by 2050 and respectively to 733 ppm and by +4.4 °C at the end of 2100. In this scenario the annual CO_2 change in Finland would be 1.8 ppm and the annual temperature change, particularly during winter, would be 0.04 degrees.

The latest climate change scenarios (Carter 2004, Carter *et al.* 2004, Finsken 2008a, IPCC 2007) indicate that the annual precipitation increases in southern Finland would be 0.1 %, particularly during winter (Figure 7C, Appendix 1). However, the northern high-latitude agricultural regions, including southern Finland, might be affected by severe drought periods during the summer growing period.

Table 2. Applied SILMU climate change scenarios in Finland in 2020, 2050 and 2100 compared with the 1990 reference level [1)] (Carter 2004, Carter *et al.* 2004, SILMU 1996).

Year, CO_2 concentration (ppm), mean temperature increase [°C] from the reference year (1990)	SILMU mean scenario	SILMU low scenario	SILMU high scenario
2020			
CO_2	426	400	434
Temperature increase °C	1.2	0.3	1.8
Precipitation increase (%)	3.0	0.75	4.5
Sea level ascend (cm)	8.9	2.1	19.2
2050			
CO_2	523	456	555
Temperature increase °C	2.4	0.6	3.6
Precipitation increase (%)	6.0	1.5	9.0
Sea level ascend (cm)	20.8	4.6	43.3
2100			
CO_2	733	485	848
Temperature increase °C	4.4	1.1	6.6
Precipitation increase (%)	11.0	2.75	16.5
Sea level ascend (cm)	45.4	7.4	95.0

[*1)] According to the Kyoto protocol (1997) Finland agreed to reduce atmospheric CO_2 emissions to the 1990 level between 2008 and 2012.

The potential effects of climate change might impose several changes on crop production at northern latitudes. In most cases increases in cereal yields are relatively low, if the elevated temperature and CO_2 levels together affect current cereal genotypes cultivated at northern latitudes. However, if the growing period in Finland is prolonged as a result of climate change, it might be possible to cultivate new cereal genotypes better adapted to a longer growing period and the photoperiodic and day-length factors (Saarikko & Carter 1996). It has been estimated that in Finland an increase of one degree in mean temperature will extend the growing season by 10 days and also shift the northern limit of cereal cultivation 100-200 km north. In Finland a longer growing season (ca. 1 month) is estimated to occur, resulting in the spring cereal sowing taking place earlier in the southern areas of Finland. Potentially new winter cereals might be introduced for cultivation (e.g. winter barley, *Hordeum vulgare*), and new plant pests and diseases will emerge as new hosts are introduced. Nutrient leaching (nitrogen) in soils might also increase. Adaptation strategies for climate change can include breeding new plant genotypes adapted for conditions of higher CO_2 and temperature (Carter 2001, 2004, Carter *et al.* 2004, Saarikko 1999a, 1999b, Saarikko & Carter 1995, Saarikko *et al.* 1996, Kulmala & Esala 2000).

Table 3. Temperature and precipitation distribution according to SILMU climate change scenarios (Carter 2004, Carter *et al.* 2004, SILMU 1996, Figure 7C, Appendix 1).

	Temperature increase (°C / decade)			Precipitation increase (% / decade)		
Period (months)	Mean $\bar{x}$	Low estimate	High estimate	Mean $\bar{x}$	Low estimate	High estimate
Spring (III-V)	0.4	0.1	0.6	0.5	0.125	0.75
Summer (VI-VIII)	0.3	0.075	0.45	1.0	0.25	1.5
Autumn (IX-XI)	0.4	0.1	0.6	1.0	0.25	1.5
Winter (XII-II)	0.6	0.125	0.75	2.0	0.42	2.5
Year mean $\bar{x}$ (I-XII)	0.4	0.1	0.6	1.0	0.25	1.5

The SILMU climate change scenarios (The Finnish Program for Climate Change 1992-1996, SILMU 1996) suggest that the future climate at high latitudes during the 2050-2100 period will result in growing conditions similar to those that currently exist in Denmark and northern Germany above 50° N (Carter 2004, Carter *et al.* 2004, Saarikko 1999a). The climatic conditions currently prevailing in Jyväskylä (62° 20'N) would occur in Rovaniemi, which is close to the Arctic Circle (66° 50'N) and correspondingly, the conditions in Jokioinen (MTT Agrifood Research Finland, 60° 49'N) would resemble those currently associated with Stockholm (59° 40'N). In the Kyoto protocol (1997) Finland agreed to reduce atmospheric CO_2 emissions to the year 1990 level between 2008 and 2012, and therefore in this study the year 1990, with 352 ppm ambient atmospheric CO_2 level, is used as a *reference year* for SILMU climate change simulations (Tables 2 and 3).

High-latitude FINSKEN climate change scenario for Finland

When compared with the original SILMU policy-oriented climate change scenarios, the new FINSKEN (Finsken 2008c) scenarios for Finland generally project equal or somewhat larger increases in mean temperature and precipitation, and cover a wider range of uncertainty, particularly with changes in precipitation. For up-to-date information on climate change scenarios in Finland, the FINSKEN website and Scenario Gateway provide the latest updated information (Finsken 2008b).

The original SILMU results were shown as linear trends between 1990 and 2100 using 1961-1990 data as a baseline. The SILMU-central scenarios differ from FINSKEN (Finsken 2008c) scenarios by estimating that precipitation, especially in spring and autumn, occur at the lower end of the FINSKEN range. The SILMU-low estimates indicate smaller temperature increases than other simulations analyzed in FINSKEN over all seasons. The new considerably smaller sulfate emission scenarios for the latter half of the 21st century are the main cause of the differences. In winter and spring the SILMU-high scenarios for temperature are lower by several degrees and the precipitation is lower compared with that for the highest FINSKEN scenarios (Stefan Fronzek 2004, pers. comm.).

With respect to temperature and precipitation scenarios, those of SILMU are in the lower range and represent a smaller uncertainty range than the newer FINSKEN scenarios. The SILMU-low scenario is below the range estimated by FINSKEN. For the elevated temperature and precipitation levels, the FINSKEN scenario indicates an increase between +2 °C and +8 °C in mean temperature. The annual precipitation increases between 6 % and 40 % by 2080. The current mean ambient atmospheric CO_2 concentration has increased from the Kyoto protocol year 1990 reference level (352 ppm) and is currently below 390 ppm (Mauna Loa Observatory, Hawaii, CDIAC 2012). According to the Bern-CC model (IPCC 2004, 2007, 2008), the mean atmospheric CO_2 concentration will more than double by the end of 2100 to the 810 ppm level.

CO_2 and temperature effects in crop physiology experiments

According to Carlson (1980) the theoretical net photosynthetic efficiency (i.e. the fraction of light energy converted to assimilates) is ca. 11 %, but the highest actual efficiency occurs with C_4 metabolic pathway plants (e.g. maize, *Zea mays* L.), but still remains below 5 %. The theoretical maximum yield potential occurs at the 30 t ha^{-1} level for cereals with a C_3 metabolism. According to Kivi (1963), the maximum yielding capacity for wheat genotypes occurs above the 10 t ha^{-1} level. According to Kivi (1963) the highest recorded wheat yield level was 14.1 t ha^{-1}. According to Evans (1983), Evans and Wardlaw (1976) and Peltonen-Sainio (1992) the primitive landraces have had mean yields ranging between 400 and 600 kg ha^{-1}.

According to Whatley and Whatley (1980) the annual solar global radiation at the ground surface averages $1*10^6$ kJ (PAR)/m^2. Of this, ca. $20*10^3$ kJ (PAR)/m^2 is used in plant metabolism (e.g. canopy gross photosynthesis and respiration) and the maintenance and growth respiration consume ca. $5*10^3$ kJ (PAR)/m^2. According to Gifford *et al.* (1993), the efficiency of a plant to convert solar radiation into biomass is expressed by the term RUE (*Radiation Use Efficiency*), which is given as daily increment in plant dry weight [DW g/d] / absorbed radiation [MJ/d]). Under current field conditions global radiation (RUE) values range from 0.5-2.5 DM g/MJ and for PAR-radiation, 1-5 DM g/MJ (PAR-radiation λ=380-760 nm). According to Sinclair & Rawlins (1993), at doubled CO_2 levels the RUE of C_3 metabolic pathway plants (e.g. spring wheat) will increase by 40 %, whereas Gifford *et al.* (1993) suggested a value of about 20 %.

Based on previous plant physiology field trials and crop modeling results, C_3 metabolic pathway plants will increase their yield potential by 20-50 % when current ambient CO_2 levels double (600-700 ppm) (Cure & Acock 1986, Goudriaan & Unsworth 1990, Kimball 1983, van de Geijn 1993). Goudriaan (1992) and Goudriaan *et al*. (1985, 1990, 1993a, 1993b) estimated that the effects of doubled CO_2 (700 ppm) will result in an increase of 45-53 % potential net biomass production *(W)* for C_3 plants, when neither water nor nutrients limit growth. With C_4 plants the biomass increase was lower (ca. 15 %). Dijkstara *et al.* (1993) observed both increasing trends in yields (34 %) and above-ground biomass (35 %) as the CO_2 concentration increased from ambient levels to 750 ppm in spring-wheat field experiments. According to Gifford & Morison (1993), the growth rate of spring wheat increased by 24.6 %, the total biomass by 34 %, the grain yield by 36 % and HI by 3 % with a doubling of the CO_2 concentration. The C_3 plants adapt and acclimate to higher CO_2 concentrations during later development stages and thus reduce the CO_2 fertilization effect. During the beginning of plant growth doubling the CO_2 concentration increased the net assimilation by 52 %, but during later growth stages net assimilation increase dropped by 29 %.

An elevated atmospheric CO_2 concentration decreases the size of stomata thereby decreasing the transpiration of water vapor (E) and reducing stomatal conductance. Under elevated CO_2 conditions the water use efficiency (WUE) of C_3 plants improves, and the biomass/transpiration ratio increases. WUE is expressed as a ratio between CO_2 assimilation rate [$mol/m^2/s$] and transpiration rate [$mol/m^2/s$] (Goudriaan 1993). According to Lawlor (1987), the optimal values for diffusion coefficients for H_2O (water vapor diffusing into air) and CO_2 (diffusing into the stomatal cavity) are 0.257 cm^2/s and 0.160 cm^2/s in the stomata respectively. The H_2O and CO_2 molecules exist in a 1.6/1.0-ratio. This exchange ratio (D_{H2O}/D_{CO2}) is derived from diffusion coefficients. The D_{H2O}/D_{CO2} ratio affects stomatal conductance of water vapor and CO_2 inside the stomata.

According to Lawlor (1987) and Lawlor *et al.* (1989), photosynthetic activity is dependent on temperature and PAR-radiation. Kuiper (1993) stated that plant biomass and yield potential are dependent on genotype-specific *minimum, optimum and maximum* temperature regions. The genotype biomass and yield production increases between minimum and optimum temperature regions, whereas between optimum and maximum temperatures the catabolic enzymatic reactions reduce accumulating biomass and yield potential. With C_3 plants the optimum temperature region for net photosynthesis is 15-25 °C and with C_4 plants 25-35 °C. If the diurnal mean temperature is increased by 2-4°C, both the yield level and HI are reduced for wheat genotypes because of a shortened grain-filling period, especially in the generative phase (Lawlor 1987, Lawlor *et al.* 1989). With C_3 plants the affinity of Rubisco is decreased as the temperature level increases. On the other hand, the elevated CO_2 concentration can increase the photosynthetic temperature optimum, thus reducing the decline in enzyme affinity. The elevated temperature increases transpiration through the stomata and decreases the plant water-use efficiency (WUE) (Kuiper 1993, Cure & Acock 1986).

With C_3 plants the affinity of Rubisco is decreased as the temperature level increases. In contrast, the elevated CO_2 concentration can favor binding of CO_2 at the cost of O_2, and thus elevate the photosynthetic temperature optimum.

Modeling CO_2 and temperature effects

Crop modeling results frequently report the so called *potential, non-limited yield level,* i.e. during the growing season the plants develop without limiting factors like water and nutrients. For definitions refer to Table 1. However, under normal field conditions the actual yield level remains below the potential yield level (*non-potential, limited yield,* Table 1) because of stress factors during the growing period that reduce the accumulating yield (Evans 1983, Lawlor 1987, Fangmeieri *et al.* 2002). During stress conditions plants adapt to water and nutrient deficiencies by modifying the glucose translocation mechanism, which allocates assimilates from source (e.g. leaves, assimilating chlorophyll cells) to sink (e.g. grains in the ear).

The results from plant physiology studies can be used as input data for crop growth models to simulate growth. Crop growth models have been used to estimate the effects of climate change on phenological development and biomass and potential for various crops (IGBP/GCTE 1993). IGBP/GCTE Wheat Network (1994a, 1995) and (Jamieson *et al.* 1998) validated several wheat models for climate change research: SUCROS2 (Spitters *et al.*. 1989), AFRCWHEAT2 (Porter 1993, Porter *et al.* 1993, Weir *et al.*

1984, Ewert *et al.* 1999, 2002) and CERES-Wheat (Crop Estimation through Resource and Environment Synthesis, Ritchie & Otter 1985, Ritchie *et al.* 1990, Jones *et al.* 2003, ICASA 2008). The AFRCWHEAT2 model is the successor to the previous AFRC-Wheat model applied in publication I (Porter 1993, Porter *et al.* 1993, Weir *et al.* 1984, Ewert *et al.* 1999, 2002, Jamieson *et al.* 1998).

The IGBP/GCTE Wheat Network validated SUCROS2, AFRCWHEAT2 and CERES-Wheat models (Jamieson *et al.* 1998) in *potential non-limiting mode* (i.e. without limiting environmental factors) using two weather and genotype datasets for current ambient diurnal temperature and CO_2 growing conditions for spring wheat *cv.* Katepwa grown in Minnesota and for winter wheat *cv.* Talent grown in The Netherlands. With the same weather and genotype data, the estimated yield levels differed significantly between the models. With spring wheat (*cv.* Katepwa) the SUCROS grain yield estimate was 4.4 t ha^{-1}, AFRCWHEAT2 4.6 t $ha^{-1}$and CERES-Wheat 3.5 t ha^{-1}. With winter wheat (*cv.* Talent) the SUCROS grain yield estimate was 9.6 t ha^{-1}, AFRCWHEAT2 yield 7.6 t ha^{-1} and for CERES-Wheat, 7.1 t ha^{-1}. When phenological submodels for each crop model were forced to follow predefined LAI (Leaf Area Index) development during growing season, simulated grain yields were 7.8 t ha^{-1} for *cv. Katepwa* (SUCROS), 6.7 t ha^{-1} (AFRCWHEAT2) and 4.0 t ha^{-1} (CERES-Wheat) and correspondingly for *cv. Talent*, 12.1, t ha^{-1}, 9.1 t ha^{-1} and 7.7 t ha^{-1} respectively. By forcing all the phenological submodels to apply constant LAI development data, a reduction in yield variation between models was recorded. The results for the AFRCWHEAT2 model indicated a general increase of 25-30 % on winter wheat yield and biomass levels under doubled CO_2 concentrations (700 ppm) and with different nitrogen application levels and for different weather datasets. The elevated mean diurnal temperature (+2 °C - +4 °C) decreased wheat yields because of accelerated phenological development in the generative phase and a shorter grain-filling period. When the interactive effect of both elevated temperature and elevated CO_2 concentration was modeled, the yield levels decreased. With doubled CO_2 concentration and with +4 °C elevated mean diurnal temperature, the wheat yields remained similar to those associated with current ambient conditions. The total above-ground biomass increased ca. 3 t ha^{-1} at all elevated temperature levels ranging between +2 °C and +4 °C. On the other hand, the HI decreased because the grain number in the head was reduced. When the combined effect of different nitrogen application levels together with elevated CO_2 concentrations and temperature levels was simulated, a potential problem of nitrogen leaching to groundwater was detected (Porter *et al.* 1993).

Jamieson *et al.* (2000) modeled different atmospheric CO_2 effects on wheat and different nitrogen levels with AFRC-WHEAT2, FASSET and Sirius crop models, respectively. Martre *et al.* (2006) modeled wheat protein and nitrogen dynamics, reviewing *management*genotype*environment* interactions with the SiriusQuality1 model.

The APSIM-Wheat crop model (Agricultural Production Systems Simulator, Keating *et al.* 200, APSIM 2008), which has many similar features to CERES-Wheat, has been used to simulate wheat production in southern Australia. The results suggest that increased CO_2 concentrations may have at least three effects on wheat crop production: stimulation of photosynthesis, improved water use efficiency (WUE), and responses to climate change induced by changes in CO_2 and other greenhouse gas emissions. Ludwig & Assenga (2006) applied the APSIM derivative, APSIM NWheat model to climate change impacts on wheat production in Australia and Mediterranean environments. Both Assenga *et al.* (2008) and Milroy *et al.* (2008) applied the APSIM NWheat model in conjunction with system analysis to study wheat yield potential and quality, and drainage and nitrate leaching in Mediterranean-type environments. For up-to-date information and references for the CERES-Wheat, AFRCWHEAT2 and ASPIM crop models reference should be made to the appropriate websites (ICASA 2008, APSIM 2008, Ewert *et al.* 2002, Jones *et al.* 2003).

Implications from previous remote sensing experiments

Remote sensing techniques using satellite-based data have been extensively applied in world crop production estimations by the European Union, the United States of America and the Food and Agriculture Organization (FAO) of the United Nations. The benefits of applying satellite-based remote-sensing data are that satellite sensors provide global coverage and the data are equally calibrated, enabling temporal and spatial comparison over years in monitoring areas (Kondratyev *et al.* 1986).

At northern latitudes cloudiness during the growing season seriously reduces the applicability of optical spectrum satellite data (Kuittinen and Parmes 1985, Kuittinen 1996, Karvonen *et al.* 1991). However, new microwave-based satellite systems (e.g. ERS, ENVISAT/EU, JERS/Japan and Radarsat/Canada) can map images through cloud cover and during the night (Henderson & Lewis 1997). Future generation remote-sensing satellites with even greater ground resolution accuracy and capacity for monitoring in the microwave spectrum will provide more accurate estimates of changes in agricultural production as climate change progresses.

New *precision farming* techniques, combined with *hyperspectral* remote-sensing methods using spectrometers, operating over a wide range of wavelengths (λ=400-2400 nm), can be used to assess crop and soil conditions, and estimate plant canopy water status, nitrogen and chlorophyll content, leaf area and gross cereal photosynthesis (CCRS 2008, Staenz 1996, Strachan *et al.* 2008). In USA the Lanworth Co. of Reuters with USDA (U.S. Department of Agriculture) is applying advanced crop modeling techniques combined with high resolution satellite imagery to estimate the total annual wheat production and inventory (Paynter 2008). In Finland Yara Co. (Kemira GrowHow, Yara 2012) established a commercial Kemira Loris™ (LOcal Resource Information System) integrated *expert system* for farmers using precision-farming techniques for optimum fertilization (the ground based N-sensor system for precision nitrogen fertilization, Yara 2012) and cultivation practices, combined with infrared aerial photographs using one meter ground resolution and precise GPS systems.

Vegetation Indices (VGI) and dynamic crop models have been extensively used together with remote-sensing data for potential cereal yield estimations. Recently Dente *et al.* (2008) modeled durum wheat (*Triticum turgidum* L. subsp. *durum*) yield potential and LAI assimilation in southern Italy with the CERES-Wheat crop model. The enhanced spectral resolution capacity of new generation remote-sensing satellites will enable monitoring of major climatic events, such as global droughts and heat waves during the coming period of climate change (IPCC 2007). The Joint Research Centre of the European Union has applied the FAPAR index with Radiative Transfer models for monitoring global vegetation phenology development, biomass productivity and stress states during Pan-European drought periods (Gobron *et al*. 2006, 2007). Recently Harrison *et al.* (2000) used the AFRCWHEAT2 crop model for scaling-up wheat phenological development to the European scale, and Moulin *et al.* (1996) applied SPOT satellite data to validate the AFRCWHEAT2 and SAIL reflectance models for estimating wheat yield and biomass NPP (*Net Primary Production*).

OBJECTIVES OF THE STUDY

In this study an interdisciplinary approach was used to assess the effects of elevated atmospheric CO_2 and temperature growing conditions on high-latitude (HiL, growing latitude > 60° N) and mid-European (MidE, < 60° N) spring wheat genotypes with adaptation for both current and future growing conditions in southern Finland in the 2000-2100 period.

The general objectives of this study were:

i. To estimate non-potential baseline yield estimates (y_b, kg ha^{-1}, Figure 1) for HiL and MidE spring wheat genotypes grown in current non-potential growing conditions in southern Finland (Figure 1).

ii. To assess and estimate changes both in non-potential baseline yield levels (y_b, kg ha^{-1}) and in national total spring wheat production ($\Delta TotProd_{(HiL,MidE,CO2,TempCov)}$, Mkg yr^{-1}) with new high yielding HiL and MidE spring wheat ideotypes (Donald 1968) and cultivars adapted for future elevated CO_2 and temperature growing conditions in southern Finland projected by the year 2100 FINSKEN climate change scenario (Carter 2004, Figure 1, Table 1).

The specific objectives of this study were:

i. To evaluate and compare the potential, non-limited ($y_{pot(OTC,HiL,MidE)}$, kg ha^{-1}, Table 1, Figure 1) and non-potential, limited yielding capacity ($y_{b(OTC,HiL,MidE)}$, kg ha^{-1}, Figure 1) and phenological development of a high-latitude spring wheat genotype (*cv.* Polkka, HiL) vs. a mid-European genotype (*cv.* Nandu, MidE) grown under elevated atmospheric CO_2 and temperature growing conditions at high latitudes (Publication I, Laurila 1995).

ii. The identification and evaluation of high-latitude (HiL, growing latitude > 60° N) and mid-European (MidE, < 60° N) optimal ideotype profiles for high grain yield ($ItPrf_{HiL,MidE}$, Figure 1, Table 1) with adaptation for future growing conditions with elevated CO_2 and temperature levels in southern Finland by deriving generic HiL and MidE spring wheat genotypes (Publication II).

iii. To evaluate factors affecting non-potential baseline grain yield levels ($y_{b(ItPrf,HiL,MidE)}$, kg ha^{-1}, Figure 1, Table 1) between HiL and MidE springs wheat genotypes in soil type, cultivation practices and decade of introduction to cultivation categories (Publication II).

iv. To identify the most important vegetation parameters and yield components affecting the yield capacity of new optimal high yielding HiL and MidE wheat ideotypes (Publication II).

v. To evaluate possibilities for estimating spring and winter cereal non-potential baseline yield levels ($y_{b(Sat,HiL,MidE)}$ kg ha^{-1}, Figure 1, Table 1) in large area non-potential field conditions in southern Finland with VGI (Vegetation Indices) and CMM (Composite Multispectral) models and minimum datasets (Figure 1, Table 1) containing solely optical reflectance and microwave backscattering satellite data (Publications III, IV).

vi. To evaluate the use of Phenological Spectral Profiles (SSP_{ph}, Figure 1, Table 1) for the identification of cereals from the satellite images in different phenological phases with optical and microwave satellite data (Publications III, IV).

vii. To assess cultivation adaptation strategies with new high yielding HiL and MidE spring wheat ideotypes grown under elevated CO_2 (700 ppm) and temperature (+3 °C) growing conditions projected by the year 2100 FINSKEN climate change scenario in southern Finland (Publications II-IV, Summary, Carter 2004).

MATERIAL AND METHODS

System analysis and modeling process

Table 4. Data sources for publications (I-IV).

Publication	Dataset	Dataset name	Experiment Years	Reference
I-IV	I	Spring wheat official variety trial data (MTT Agrifood Research Finland)	1978-2005	Kangas *et al.* (2006)
II	II	The European Wheat Database (European Cooperative Programme for Crop Genetic Resources Networks ECP/GR	1978-2005	http://genbank.vurv.cz/ewdb/
II	III	The field experiments of rye and spring wheat varieties for ecological cultivation, MTT Agrifood Research Finland, Satakunta Res. Station	1989-1993	Aula & Talvitie (1995)
I,II	IV	SILMU I Experimental data from Open Top Chamber experiments with elevated CO_2 and temperature levels[1)]	1992-1994	Hakala (1998a,b), Hakala *et al.* (1999), Laurila (2001)
I,II	V	SILMU II Experimental data with field, greenhouse and pot experiments.	1994-1996	Saarikko & Carter (1995), Saarikko *et al.* (1996), Saarikko (1999a, 1999b). Data provided by Dr. Riitta Saarikko
II	VI	Spring wheat yield component and quality factor data.	1996-1998	Rajala (2003), data provided by Dr. Ari Rajala (MTT Agrifood Research Finland)
II	VII	Spring wheat data containing yield component and morphological characteristics for 20 spring wheat genotypes (Helsinki Univ., Dept of Crop Husbandry)	1988	Unpublished data provided by Dr. Reijo Karjalainen and MSc. Tapani Kangasmäki (MTT Agrifood Research Finland).
III,IV	VIII Calibration of optical and microwave VGI models. Minimum dataset	Mellilä and Porvoo Experimental sites Landsat & SPOT, HUTSCAT optical and Microwave Calibration data	1989-1990	Kuittinen *et al.* 1998, Matikainen *et al.* 1998 Hyyppä *et al.* 1999, MAFF 2007, MAFF/TIKE 2008
III,IV	IX Calibration of optical VGI models. Minimum dataset.	Kirkkonummi, Jokioinen, Lapua Experimental sites, Landsat & SPOT Optical Validation data	1993-1997	Kuittinen *et al.* 1998, Gobron *et al.* 2006, Pinty and Verstraete 1998 Price, 1987
III,IV	X Calibration of microwave VGI models. Minimum dataset.	Kirkkonummi, Jokioinen, Lapua Experimental sites, ERS1, Radarsat1, Envisat Microwave Validation data	1998-2004	Matikainen *et al.* 1998, Hallikainen *et al*. 1993, Hyyppä *et al.* 1990, Karjalainen *et al.* 2004, 2008
I - IV	XI Model validation dataset I.	MTT Official variety trial results for spring cereals. VGI model validation dataset I (Public. IV).	1978-2007	Kangas *et al.* 2002, 2006.
II-IV	XII Model validation dataset II.	MAFF averaged inventory sampling results in growing zones I-III (Figure 7A, Appendix 1). VGI model validation dataset II (Public. IV).	1978-2006	MAFF 2007, MAFF/TIKE 2008

[1)] The Finnish Program for Climate Change (SILMU 1992-1996)

In this study an interdisciplinary approach was used for estimating the effects of climate change on spring wheat yield production using different crop modeling techniques combined with satellite-based remote sensing data (Figure 1). The results provide techniques for estimating the trends in cereal yield potential for both high-latitude (HiL) and mid-European (MidE) generic wheat ideotypes with high yielding capacity. The data sources for publications I-IV are presented in Table 4. The modeling process and System Analysis diagram used in Publications I-IV (Ritchey 1996, IIASA 2008) are presented in Figure 1.

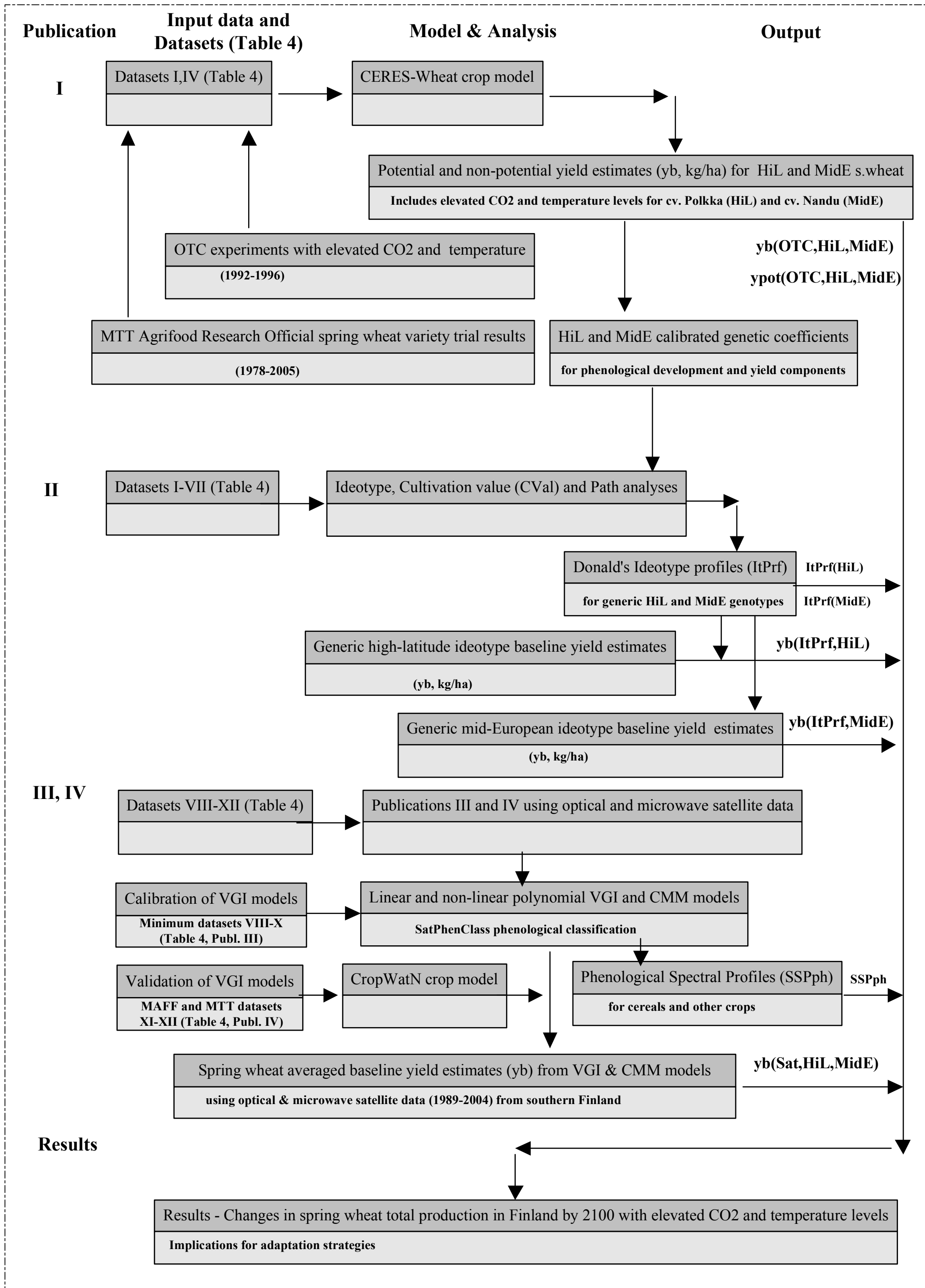

Figure 1. Modeling process and System Analysis diagram for publications I-IV with output parameters for potential ($y_{pot,}$ kg ha^{-1}) and non-potential baseline yield estimations ($y_{b,}$ kg ha^{-1}) (Ritchey 1996, IIASA 2008, ItPrf – Donald's Ideotype profile (Donald 1968), SSPph – Phenological spectral profile, Tables 1,4,11,12).

In publications I-IV two hexaploid spring wheat genotypes *cv.* Polkka (Svalöf-Weibull, Sweden) and *cv.* Nandu (Saatzuchtwirtschaft F. von Lochow-Petkus GmbH, Bergen, Germany) were used to characterize high-latitude (HiL) and mid-European

(MidE) generic high yielding spring wheat ideotypes (ECP/GR 2008, Dataset II, Table 4).

In Table 5 the applied methodology, estimation of error sources and data variation with modeling aggregation levels are presented from the genotype×environment covariance level in publications I - II up to the field parcel level in publications III - IV and finally up to the Finnish national level with implications for changes in total spring wheat production by 2100:

I. In publication I the high-latitude Swedish *cv.* Polkka genotype was modeled with the CERES-Wheat crop model (Weir *et al.* 1984, Ritchie and Otter 1985, Godwing *et al.* 1989, Ritchie *et al.* 1990, Hanks and Ritchie 1991, Hodges 1991, Jones *et al.* 2003) to evaluate the effects of concurrent elevated atmospheric CO_2 concentrations and temperature levels on phenological development and yield potential. In publication I the calibrated phenological development and yield component genetic coefficients for a generic high-latitude spring wheat genotype (Ref. *cv.* Polkka) are depicted. The CERES-Wheat genetic coefficients were calibrated using the RMSD (Root Mean Square Difference) algorithm (Table 1) with the MTT Agrifood Research Finland official variety trial data for spring wheat genotypes (1978-2005, dataset I, Table 4). Elevated CO_2 and temperature modeling results were based on the SILMU Open Top Chamber (OTC) crop physiological experimental results (1992-1993) with ambient and elevated levels of CO_2 and temperature (Hakala 1998a, 1998b, datasets IV-V, Table 4). A previous modeling publication (Laurila 1995) using the CERES-Wheat crop model presents corresponding calibrated genetic coefficients for a mid-European genotype (Ref. *cv.* Nandu). Calibrated genetic coefficients were used with the CERES-Wheat crop model (Publications I, II) to estimate the yield levels of a generic HiL and MidE genotypes grown both under potential, non-limited (y_{pot}(OTC,HiL,MidE), kg ha^{-1}, Table 1, Figure 1) and non-potential, limited growing conditions (y_b(OTC,HiL,MidE), kg ha^{-1}, Figure 1) interacting with elevated CO_2 and temperature levels.

II. Publication II comprises the optimal Ideotype profile (ItPrf($_{\text{HiL, MidE}}$), Donald 1968, Table 1, Figure 1) modeling results derived from the Ideotype, Cultivation value, Mixed covariance, Path and Yield component analyses. In addition, the CERES-Wheat genetic coefficients calibrated in publication I for the generic high-latitude (HiL, growing latitude > 60° N, Table 1) and mid-European (MidE, < 60° N) genotypes are used when constructing the ideotype profiles.

    In the modeling results the most significant yield and morphological components affecting yield potential for high-latitude and mid-European ideotypes with high yielding capacity are evaluated using statistical structural Mixed covariance analysis (Little *et al.* 1991, 1996, 1998), Path coefficient analysis (Wright 1923, 1934, 1960, Li 1974a, 1974b, Dewey and Lu 1959) and Cultivation value analysis (Weizensorten und Backqualität 1990, Peltonen *et al.* 1993). The non-potential baseline yield estimates for high latitude ($y_{b(ItPrf,HiL)}$, kg ha^{-1}, Figure 1) and MidE ($y_{b(ItPrf,MidE)}$, kg ha^{-1}, Figure 1) high yielding ideotypes are presented in the results (Figure 1).

III. Publications III and IV contain results from a study estimating spring non-potential baseline yield levels ($y_{b(Sat,HiL,MidE)}$ kg ha^{-1}, Table 1, Figure 1) with VGI (Vegetation Indices) and CMM (Composite Multispectral) models under non-potential large area field conditions in southern Finland using phenologically classified (SatPhenClass algorithm, Lancashire *et al.* 1991, Zadoks *et al.* 1984) optical and microwave satellite data. Averaged non-potential baseline ($y_{b(Sat,HiL,MidE)}$ kg ha^{-1}) yield estimates (1989-2004) are presented for spring cereals (spring wheat, barley and oats) in southern Finland. The VGI and CMM models were calibrated using the Minimum datasets XIII-X (1989-2004, Tables 1,4, Figure 1) and validated using the MTT official variety trial results dataset (Dataset XI, 1978-2007, Table 4) and MAFF (Ministry of Agriculture and Forestry in Finland) averaged inventory sampling statistics in growing zones I-III (Dataset XII, 1978-2006, Table 4, Figure 1, Figure 7A, Appendix 1). In the results, the calibrated optical and microwave SAR Phenological Spectral Profiles (SSP_{phOpt}, SSP_{phSAR} Table 1, Figure 1) using the optical and microwave satellite data are presented for the identification of cereals.

IV. In summary of this publication, the results from publications I-IV are analyzed to estimate changes in spring wheat total yield production ($\Delta TotProd_{(HiL,MidE,CO2,TempCov),}$ Mkg yr^{-1}) in Finland by 2100 using generic high-latitude and mid-European high yielding ideotypes grown under elevated CO_2 and temperatures growing conditions. SAS/ETS (Economical Time Series Analysis with FORECAST and TIMESERIES modules, SAS 1990) and SAS/GLM (General Linear Models, SAS 1990) statistical models were used for time series trend analysis both in analyzing historical spring wheat yield data (MAFF spring wheat yield inventory data 1979-2010) and in extrapolating future spring wheat yield level trends until 2100. Adaptation strategies for future growing conditions and advances in cultivation methods and plant breeding techniques are also addressed.

Table 5. System analysis with aggregation levels, error estimation and applied methodology.[1)]

Publi-cation	Aggregation level and sources for error variation	Methodology class	Simulation Model Class[1)]	Output
I	- Genotype, cultivar and environmental variation on experimental plot and Open Top Chamber (OTC) level.	- Crop simulation model (Laurila 1995,2001). - Sensitivity analysis for dynamic crop model error evaluation (France & Thornley 1984, Thornley & Johnson 1989).	-II (Mechanistic model) -III(Dynamic model) - CERES-Wheat crop model[2)]	-Calibrated genetic coefficients for high-latitude and mid-European spring wheat genotypes. -Non-potential yield estimates for generic high yielding spring wheat ideotypes grown under elevated CO_2 and temperature growing conditions.
II	- Genotype × Environmental variation on field plot level - Genotype, inter and intra-cultivar variation	-Ideotype, Yield component, Cultivation value, Mixed Structural Covariance and Path analyses.	-I (Statistical empirical model) - Linear (LIN) -Non-linear (NLIN) statistical models	-Ideotype profiles (ItPrf) for high yielding generic HiL and MidE genotypes -Significant yield components and vegetation parameters for high yielding generic spring wheat ideotypes.
III, IV	- Cereal spatial variation between species and cultivars on large area farm field parcel level with non-potential growing conditions	-Remote sensing optical and microwave data, VGI models. -Phenological classification model (*SatPhenClass*) for satellite data.[4)]	-I (Statistical empirical model)- Linear and non-linear (NLIN) statistical models[3)] -II (Mechanistic model) -III(Dynamic model) – CropWatN crop model (Kuittinen *et al.* 1998)	-Non-potential field parcel level baseline yield (y_b, kg ha^{-1}) estimates for spring wheat and other cereal crops. -Phenological Spectral Signature profiles (SSPph) for cereals (Laurila *et al.* 2010a,b).
Sum mary	-Finnish national level with adaptation strategies for future growing conditions by the year 2100.	-Aggregated modeling results from publications I-IV on national level.	-I (Statistical empirical model) SAS/ETS (Economical Time Series Analysis), SAS/GLM (General Linear Models), SAS (1990). -II (Mechanistic model) -III(Dynamic model)	-Changes in national total spring wheat production ($\Delta TotProd_{(HiL,MidE,CO2,TempCov)}$ Mkg yr^{-1}) by the year 2100 using new high yielding HiL_{New90} and $MidE_{New90}$ ideotypes with elevated CO_2 and temperature growing conditions and without changes in wheat cultivation area (Carter 2004).

[1)] Simulation model classification after France & Thornley (1984) and Thornley & Johnson (1989), see Theoretical background for crop modeling section.
[2)] Submodels: Phenological development with genetic coefficients, grain yield and dry-matter accumulation, CO_2 and temperature submodels (Porter 1984, Hanks and Ritchie 1991).
[3)] Submodels: Normalized Difference Vegetation Index (NDVI, Price, 1987), Global Environment Monitoring Index (GEMI, Pinty and Verstraete 1998), Normalized Vegetation Index for PAR Radiation (PAR_{ND}/FAPAR, Gobron *et al.* 2006).
[4)]SatPhenClass phenology submodel for satellite data classification using BBCH (Lancashire *et al.* 1991), Zadoks growth scales (Zadoks *et al.* 1984).

Soil types and growing zones in the experimental locations

The detailed soil classifications in experimental areas in southern Finland (experimental datasets I-XII, Table 4, Figure 3) with corresponding growing zones (I-IV, Table 7A, Appendix 1) is reviewed by Laurila *et al.* (2010a,b) in publications III and IV. The Ylistaro, Lapua, Ilmajoki and Seinäjoki experimental sites were located near the Gulf of Bothnia on sandy clay type soils. Respectively Helsinki, Porvoo and Kirkkonummi experimental sites were located close to the Baltic Sea. Jokioinen and Mellilä sites were located mainly on clay type soils.

Currently a growing zone classification of four growing zones (I-IV, Figure 7A, Appendix 1) is applied for the high-latitude spring wheat genotypes (HiL) currently cultivated in southern Finland and in the Gulf of Bothnia: Zone I - Southern and SW-Finland (Lat. < 61° N), Zone II - Southern Finland (Lat: 61° N - 62° N), Zone III - Southern Finland (Lat: 62° N - 63° N), Zone IV - Gulf of Bothnia and Eastern Finland (Lat: 63° N - 65° N). The zonal classification is based on Effective Temperature Sum (ETS, Table 7B, Appendix 1) expressed as cumulative degree-days [dd] with a threshold temperature (T_b) of 5 °C (Kontturi 1979, Saarikko 1999).

The electromagnetic spectrum

The electromagnetic action spectrum, including *optical* and *microwave* wavelengths, applied in this study (publications I-IV) is shown in Figure 2. In publications I-II the PAR and global radiation (λ=400-700 nm, Table 1) are used as input data for crop models simulating photosynthesis, plant respiration and synthesis of glucose and other assimilates. In publications III-IV the *(i)* optical (λ=400-700 nm), *(ii)* infrared (λ=630-12.5μm) and *(iii)* microwave (C-band, f=5.4 GHz, λ=5.7 cm) spectra, with horizontal and vertical polarization levels, (HH, VV, VH, HV) are used in a *composite* model with optical NDVI and microwave input data for VGI yield response models (Figure 1).

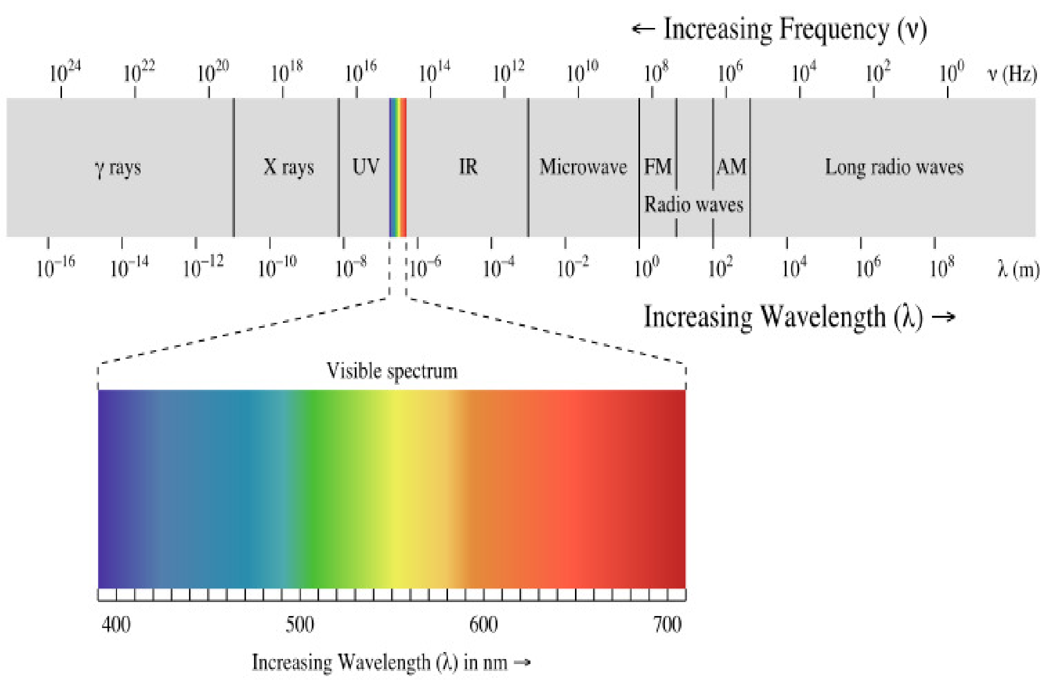

Figure 2. Electromagnetic action spectrum at visible, infrared (IR, publications II-IV) and microwave wavelengths (publications III, IV), adapted from Machlis & Torrey (1959).

Theoretical background for crop modeling

An interdisciplinary approach was used in this study, combining mathematical equations and results of crop physiology experiments, to assess the changes that climate change will cause to agricultural ecosystems in the 21st century at high latitudes. The theoretical background for crop modeling applied in this study is based on theorems developed by the English mathematician Thomas Bayes (Bayes, 1763) and the Austrian philosopher Karl Popper (Popper 1935, 1966, Tennekes 1994).

According to Milthorpe and Moorby (1974) and Thornley and Johnson (1989) several *non-linear* growth functions (logistic sigmoidal functions, *i-iv*) can be applied to crop growth and biomass simulations. The *(i) logistic* growth function describes the three stages of population growth: the slow start, the exponential, accelerating growth with a point of inflexion ($y=1/2*Y_{max}$) and in the final stage, decreasing growth when a limiting factor exercises influence, such as nutrients required by the population or substrate for enzyme-catalyzed reactions. Several growth functions, based on an improved fit for experimental data, have been developed from the logistic growth function: *(ii)* the *Gompertz growth function* (e.g. substrate in enzyme catalyzed-reactions, like *Rubisco* with CO_2 and O_2 competition in chlorophyll), *(iii) monomolecular (negative exponential)* and *(iv) Richard's* growth function. *Richard's* growth function combines *monomolecular, logistic* and *Gompertz* functions (France & Thornley 1984, Karvonen & Varis 1992). The Richard's growth function is applied in the SUCROS growth model (Spitters *et al.* 1989, Goudriaan *et al.* 1985, 1993a, 1993b), where it is used to calculate the plant leaf net photosynthesis and its dependence on PAR (λ=380-760 nm) radiation. The Richard's growth function has been applied as an exponential light response curve limited by the asymptotic maximum net CO_2 assimilation rate. Gifford *et al.* (1993) adjusted with Richard's growth function spring wheat (*cv.* Highbury) biomass data (W) in relation to time (t) both in ambient and elevated CO_2 concentrations. When simulated on elevated CO_2 concentration (660 ppm) the biomass was determined by the equation $(W/1660)^{(0.15)}=1.673*e^{(-0.0432*t)}$ and correspondingly at an ambient concentration (350 ppm) by the equation $(W/1290)^{(-0.15)}=1+1.844*e^{(-0.0437*t)}$.

According to France & Thornley (1984) and Thornley & Johnson (1989), crop growth models can be classified into various *theoretical models* depending on their complexity and the level for which they describe actual plant physiological processes (e.g. plant respiration, photosynthesis, translocation of assimilates, soil processes, Figure 1, Table 5):

I. *Statistical empirical models*: Statistical models without a feedback mechanism (i.e. the results are solely controlled and modified by the driving variables).
II. *Mechanistic models*: Description of internal mechanism processes (e.g. photosynthesis, respiration, translocation of assimilates, soil processes).
III. *Dynamic models*: Simulated process is time-dependent varying in time-space (i.e. the driving variables modify the result through a feedback mechanism).
IV. *Deterministic models*: Models output only one solution, the temporal and spatial variance of phenomena is omitted.
V. *Stochastic models*: Model internal algorithms and generate stochastic random processes; the model output is the *Bayesian* probability distribution with confidence limits.

This *theoretical model* classification is applied in publications I-IV with statistical empirical models (class I, VGI and CMM models, publication III, IV) and with mechanistic and dynamic crop models (classes II-III, CERES-Wheat, Jones *et al.* 2003 and CropWatN, Kuittinen *et al.* 1998). The *system analysis* is presented in Figure 1 and in Table 5. Statistical empirical models (model class I in Table 5, Thornley & Johnson 1989) are generalizations from a historical experiment forced to a statistical linear or non-linear model with different algorithms (e.g. Least Square Fit, LSF or Root Mean Square Difference, RMSD). Compared with dynamic models (model class III in Table

5), statistical models have poor adaptability to sudden environmental phenomena and stress factors such as drought, frost, nutrient deficiencies and pathogen epidemics. The data sources for statistical and dynamic crop models are presented in Table 4.

Potential (y_{pot}) and non-potential (y_b) yield modeling using the CERES-Wheat crop model

In publications I-II, the CERES-Wheat crop model (Ritchie and Otter 1985, Hanks and Ritchie 1991, Jones *et al.* 2003) was evaluated for high-latitude long-day growing conditions. The CERES-Wheat model belongs to model category classes II-III (Table 5, mechanistic, dynamic and deterministic).

According to Hanks & Ritchie (1991) and Jones *et al.* (2003), the CERES-Wheat crop model can be applied for both potential (y_{pot}(OTC,HiL,MidE),kg ha^{-1}, Table 1, Figure 1, Evans and Fischer 1995, Sinclair 1993) and non-potential baseline (y_b(OTC,HiL,MidE),kg ha^{-1}, Table 1) grain yield simulations. In addition, the CERES-Wheat (v. 1.9) can be applied for concurrent atmospheric CO_2 and diurnal temperature change simulations.

In CERES-Wheat, a positive and negative feedback mechanism is included over the growing period (e.g. through weather data, including temperature, radiation and precipitation data). The major *driving variables* in CERES-Wheat model are global and PAR (Photosynthetically Active Radiation, λ=400-700nm) radiation, minimum and maximum temperature and cumulative temperature sum. The driving variables control plant phenological development, photosynthesis, plant respiration and the translocation of assimilates to storage organs. The CERES-Wheat model was calibrated with data from OTC experiments conducted in 1992-1994 (Hakala 1998a, 1998b) and with MTT Agrifood Research Official spring wheat variety trial data (1978-2005, Dataset I, Table 4, Kangas *et al.* (2006) using the using the RMSD algorithm (Table 1). *Cv. Polkka* was grown both under ambient and elevated CO_2 and temperature conditions. After recalibration, the CERES-Wheat model was used to simulate the phenological development and biomass and yield responses of *cv*. Polkka under different CO_2 and temperature growing conditions.

Genetic coefficients for spring wheat genotypes

The CERES-Wheat crop model (Publications I and II, model classes II-III in Table 5) contains submodels for simulating spring wheat phenological development, photosynthesis, plant respiration, translocation of assimilates, soil processes with major soil type profiles and for estimating grain yield and above ground dry-matter accumulation during growing season. Processes in the submodels are controlled by the calibrated genetic coefficients (Godwin *et al*. 1989, Hanks and Ritchie 1991).

The CERES-Wheat genetic coefficients controlling the phenological development and yield components are given in Table 6. The default genetic coefficients for spring (Sw) and winter wheat (Ww) genotypes are shown in Table 7 (Godwin *et al*. 1989). The calibrated and optimized genetic coefficients using the RMSD algorithm (i.e. minimizing the *Root Mean Square Difference* between observed and simulated values) for a high-latitude (*cv.* Polkka, HiL_{Old80}) and for a mid-European (*cv.* Nandu, $MidE_{New90}$) genotypes are presented in Table 9 (phenological development coefficients) and in Table 10 (yield component coefficients).

Table 6. The genetic coefficients in the CERES-Wheat model (Godwin *et al*. 1989, Jones *et al* 2003).

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 7. Default genetic coefficients for spring (Sw) and winter wheat (Ww) genotypes (Godwin *et al*. 1989).[1)]

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

[1)] Variables explained in Table 6.

Crop model internal error estimation with the sensitivity analysis

According to France & Thornley (1984) and Thornley & Johnson (1989) dynamic crop models (e.g. CERES-Wheat crop model) can be evaluated by their sensitiveness to internal error sources (model classes II-III in Table 5, e.g. photosynthesis, plant respiration, soil processes and translocation of assimilates) by estimating the sensitivity of the crop model on specific driving variables affecting the model internally (e.g. diurnal mean temperature, cumulative Effective Temperature Sum (ETS), atmospheric CO_2 concentration). In the sensitivity analysis, the independent driving variable is deviated with constant steps (±10,20,50 and 100 %) from the average value and the effect of deviation on response variable (e.g. potential (y_{pot}) and non-potential grain yield (y_b)) is estimated. Based on sensitivity analysis results, a dichotomy classification (sensitive/insensitive) is applied for the response variable. If the deviation (%) set on driving variable causes the response variable to increase or decrease more (%) than the deviation applied on the driving variable, the dynamic crop model is considered as sensitive on that specific response variable otherwise the model is classified as insensitive.

Theoretical background for satellite measurements

The *reflectance* (rf, Table 1, Figure 2) measured by optical satellites is the reflected radiation from soil and vegetation canopies and the microwave *backscatter coefficient* ($\sigma^{0,}$ sigma zero) is a combined signal reflected from soil and vegetation canopies in the microwave spectrum (Figure 2). Details for reflectance calibration are given by Price (1987), Maas (1991), and Maas & Dunlap, (1989), and for calibration of microwave satellite data using SAR (Synthetic Aperture Radar) and ASAR (Advanced Synthetic

Aperture Radar) sensory data (Table 8) are given by Henderson & Lewis, (1997) and for Finnish growing conditions by Hallikainen *et al.* (1993) and Hyyppä *et al.* (1990). Kuittinen (1996), Kuittinen *et al.* (1998), Matikainen *et al.* (1998), Karjalainen (2010) and Karjalainen *et al.* (2004, 2008, 2012) provide detailed information on using reflectance and microwave data for high-latitude Finnish agricultural growing conditions, and Koskinen *et al.* (1999) for Finnish forestry applications.

Satellite measurement locations and technical configuration of sensors

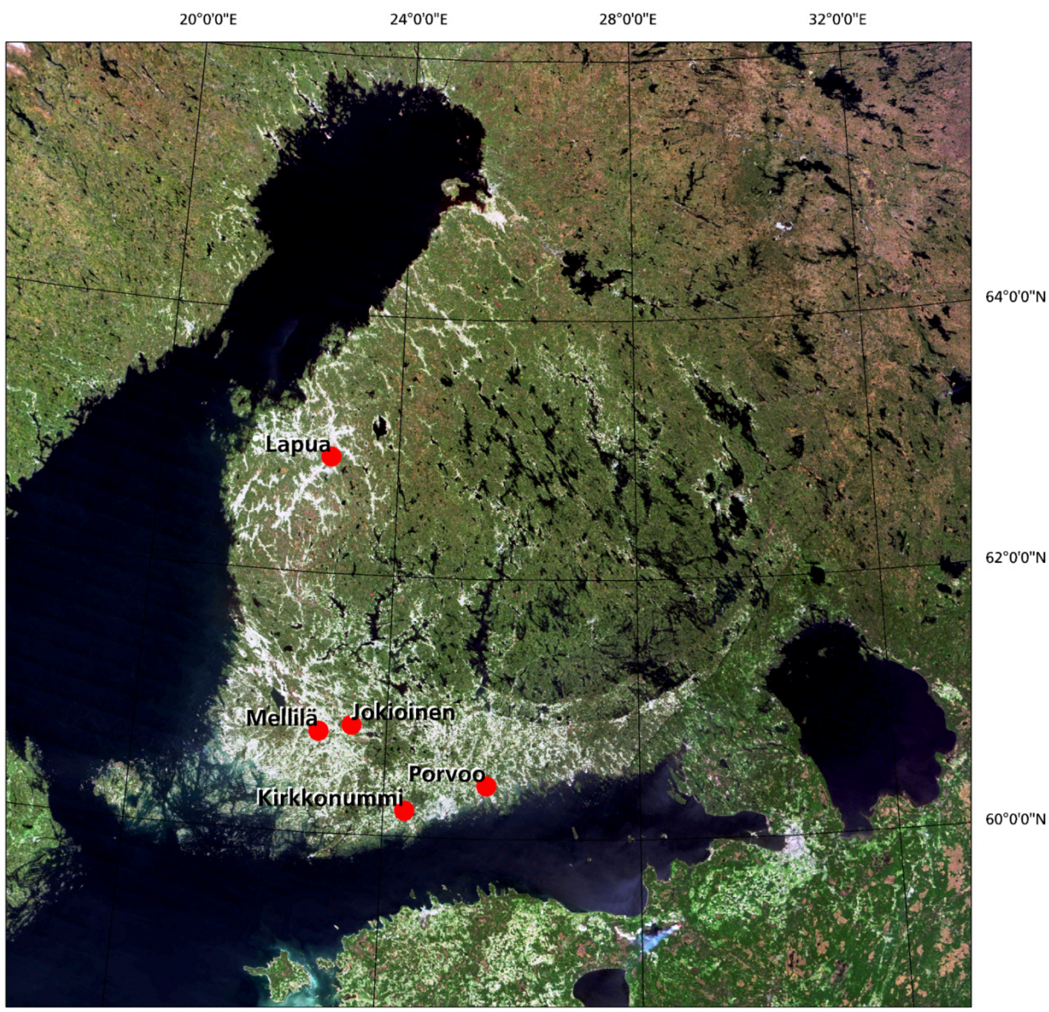

Figure 3. Satellite and ground truth measurement locations (red points) in Finland 1989-2006 (Original Data (©) NASA, visibleearth.nasa.gov/).

Publications III and IV present detailed calibration and validation methodologies applied in both optical and microwave remote sensing satellite systems.

The satellite measurement locations with concurrent ground truth measurements (publications III and IV) in southern Finland (> 60° N lat.) and in Lapua (> 62° N lat.), near the Gulf of Bothnia (1989-2006) are depicted in Figure 3. Satellite systems with *(i)* optical (Landsat, SPOT), *(ii)* microwave (HUTSCAT, ERS1, Radarsat1, ENVISAT) and *(iii)* multispectral sensors (ADEOS1) and applied in remote sensing campaigns are depicted in Table 8.

Table 8.Satellite systems used in remote sensing campaigns (1989-2006).

Satellite type	**Name**	**Sensor**	**Experimental locations & years**	**Reference**
Optical	Landsat 5	Thematic Mapper (TM) (λ=450 nm-2.35μm)	Porvoo, Mellilä, Kirkkonummi, Jokioinen, Lapua (1989-1997, dataset VIII-IX, Table 4).	LANDSAT 2008, www.landsat.org, Kuittinen 1996, Kuittinen *et al.* 1998
Optical	SPOT 2	HRV2/XS (λ=450 nm-890 nm)	Porvoo, Mellilä, Kirkkonummi, Jokioinen, Lapua (1989-1997, dataset VIII, Table 4).	SPOT Image (CNES) 1986. www.spot.com, www.spotimage.fr, Kuittinen 1996, Kuittinen *et al.* 1998
Microwave	HUTSCAT [1)]	Scatterometer (f=5.4 GHz, C-band, 9.8 GHz, X-band), VV, HH, VH, HV polarizations	Porvoo, calibration data (1990, dataset X, Table 4).	www.space.hut.fi/research/equipment/ hutscat.html. Hallikainen *et al.* 1993, Hyyppä *et al.* 1999, Koskinen *et al.* 1999
Microwave	ERS1[2)]	SAR[5)], f=5.3 GHz, C band, (λ=5.7 cm), VV polarization	Seinäjoki, Lapua (1995-1996 , dataset X Table 4).	http://earth.esa.int/ers, earth.esa.int/ers/sar, Matikainen *et al* 1998, Koskinen *et al.* 1999
Microwave	ENVISAT [3)]	ASAR[6)] , f=5.3 GHz, C-band), VV, HH, VV/HH, HV/HH, or VH/VV polarizations	Seinäjoki, Lapua (2002-2004, dataset X Table 4).	http://earth.esa.int, http://envisat.esa.int/object/index.cfm? fobjectid=3772, Karjalainen *et al.* 2004, 2008
Microwave	Radarsat1	SAR[5)], f=5.3 GHz, C band, HH polarization	Seinäjoki, Lapua (2001 , dataset X Table 4).	Karjalainen *et al.* 2004, Canadian Space Agency (CSA). ccrs.nrcan.gc.ca/ , radar/spaceborne/ radarsat1/index_e.php
Multi-sensor	ADEOS1 Advanced Earth Observing Satellite[4)]	AVNIR, ILAS, RIS, IMG, TOMS: atmospheric greenhouse gas (CO_2, O_3, CH_4) columns [4)]	(1996-1997, non-operational) Collaboration with Prof. Hiroshi Koizumi, NIAES/ Tsukuba, Japan	Kuittinen & Laurila 1997, NASDA/ JAXA, http//home.gna.org/adeos/ http://kuroshio.eorc.jaxa.jp/ADEOS ,http://msl.jpl.nasa.gov/QuickLooks / adeosQL.html

[1)] HUTSCAT is helicopter mounted, see space.hut.fi/research/equipment/hutscat.html (Hyyppä *et al.* 1999)
[2)] European Remote Sensing satellite (ESA, European Space Agency)
[3)] ENVISAT (Environmental satellite, ESA) AOS (Announce of Opportunity) contract: AOE-488 for ENVISAT
[4)] ADEOS1 AOS contract: NASDA Contract 1062/Vegetation and Biology, MAFF, 5118/416/94
[5)] SAR, Synthetic Aperture Radar [6)] Advanced Synthetic Aperture Radar

The helicopter-mounted HUTSCAT scatterometer (Table 8) was developed by the Helsinki University of Technology (Laboratory of Space Technology, Hyyppä *et al.* 1999). HUTSCAT data from Porvoo experimental site (1990) were used for spring cereal VGI model calibrations using all four polarization levels (Table 4, Dataset I/IV). HUTSCAT operates both in C- and X- microwave bands with all four linear polarization levels (HH- horizontal, VV-vertical and cross-polarizations VH, HV). The HUTSCAT spectrometer technical configuration using the C-band is similar to SAR (Synthetic Aperture Radar) radars currently on board ERS Radarsat satellites and also similar to ASAR (Advanced Synthetic Aperture Radar) on board the Envisat satellite (Table 8, AOE-488 contract). The ERS1, Radarsat1 and Envisat microwave data (1995-2004) from the Seinäjoki and Lapua experimental sites (Figure 3) were used in evaluation of VGI models (Table 8, 4, Dataset III/IV).

The Japanese ADEOS1 environmental satellite was intended to be used in parallel with other satellite systems in Finnish experimental areas (Figure 3), but unfortunately the structural damage caused by space debris to its solar array paddle in 1997 rendered the satellite non-operational. ADEOS 1 satellite (NASDA contract 1062, Kuittinen &

Laurila 1997, NASDA/ADEOS 2008) measured vertical atmospheric greenhouse gas (CO_2, O_3, CH_4) profile columns globally with AVNIR, ILAS, RIS, IMG and TOMS sensors. In publications III and IV, the ADEOS satellite data were intended to be connected with GCM (General Circulation Models) and BAHC SVAT (Soil-Vegetation-Atmosphere-Transfer) models using Eddy Covariance algorithms (BAHC 2008, IGBP/GCTE 1993, 2008) and finally to be used as input data for dynamic crop models by down-scaling the atmospheric CO_2 estimates from ADEOS sensors at the field parcel level in Finnish experimental areas (Figure 3, Harrison *et al.* 2000, Dente *et al.* 2008). The *eddy covariance* technique is an atmospheric flux measurement technique to measure and calculate vertical turbulent fluxes within atmospheric boundary layers (Stoya *et al.* 2006). The ADEOS program was performed in collaboration with the National Institute of Agro-Environmental Sciences, Tsukuba/Japan (Prof. Hiroshi Koizumi).

SatPhenClass phenological classification algorithm for satellite data

In publications III and IV, the calibrated optical reflectance and microwave backscattering data measured by different satellite systems (1989-2004, Table 8, Figure 3) were classified using a *phenological classifying algorithm* (*SatPhenClass*) developed in this project and using the BBCH growth scale (Lancashire *et al.* 1991, Witzenberger *et al.* 1989, Peltonen-Sainio *et al.* 2005). In addition, Zadoks (Zadoks *et al.* 1984), Feeke's (Large 1954) and Haun's (Cabeza *et al.* 1996) growth scales were used as scaling references. By using the *SatPhenClass* algorithm, the satellite data in the experimental areas (1989-2004, Figure 3) were classified into four major phenological categories (a_p , b_p , c_p and d_p) with corresponding months (May, June, July and August) during the growing season.

The *SatPhenClass* algorithm uses BBCH growth scales (Table 1, Figure 1) with four phenological classes for spring cereals (a_p: BBCH 0–12, b_p: BBCH 12–50, c_p: BBCH 50–90, d_p: BBCH > 90). Class a_p corresponds to the vegetative development period between sowing and two leaf stage with double ridge formation, usually in May in southern Finland. Class b_p corresponds to the vegetative period between two leaf stage and ear emergence with maximum Leaf Area Index (LAI_{max}) exposure with fully closed canopy in June. Class c_p corresponds to the generative period between ear emergence and anthesis with grain filling until full maturity in July. Finally, class d_p corresponds to senescence and post-harvest phases in August.

The cumulative ETS (Effective Temperature Sum, Figure 7B, Appendix 1) and measured LAI (Leaf Area Index) development were used as classifiers for measured satellite data on a specific Julian day. This phenological classification algorithm enabled the temporal synchronization of satellite data with cereal phenological development. The classified optical and microwave data can in turn be used as input for cereal VGI (Vegetation Indices) or dynamic crops models like the CERES-Wheat model.

Cereal identification using the Phenological Spectral Signature Profiles (SSP_{ph})

In publications III and IV the measured optical reflectance and microwave SAR data for different spring cereals were classified into *phenological classes* (a_p,b_p,c_p,d_p, Table 1) with the *SatPhenClass* classification algorithm. The phenologically classified optical and microwave data were used in constructing the Phenological Spectral Signature Profiles (SSP_{ph}) used for the identification of different spring cereals from the satellite images during growing season in different phenological phases (a_p,b_p,c_p,d_p).

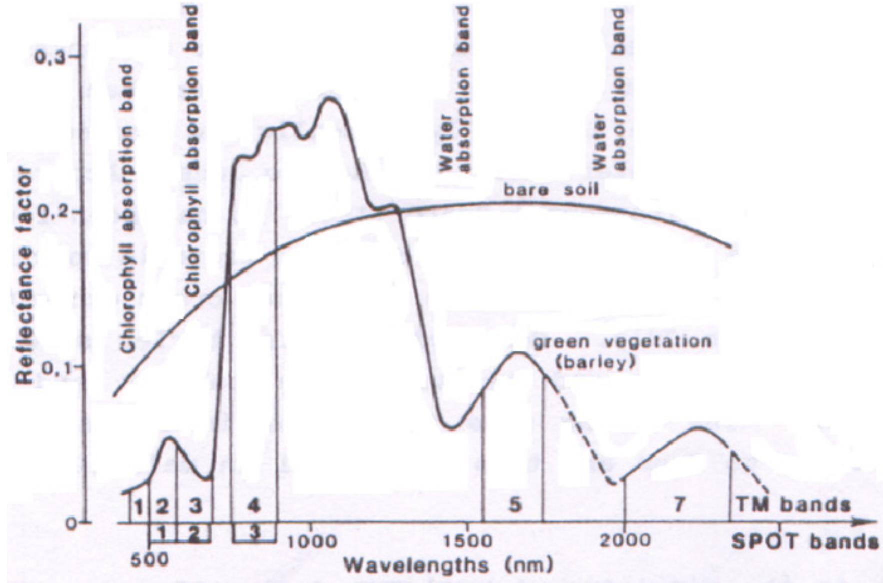

Figure 4. Spectral Signature Curves with scaled Reflectance Factor (Rf) for barley and bare soil, Chlorophyll A, B in PAR spectrum, water absorption maximums and corresponding Landsat/TM and SPOT/HRV2 sensory bandwidths (Table 8, © Original data Swedish National Environmental Board).

Figure 4 depicts typical optical *Spectral Signature Curve* functions (SSC) for barley (green vegetation) and bare soil in Nordic high latitude growing conditions. In addition, Chlorophyll A (λ 460, 680 nm), B (λ 480, 650 nm) and water (λ 1500, 2000 nm) absorption maximums and sensory bandwidths for Landsat and Spot are depicted. SSC functions were utilized when constructing the phenological optical and microwave SAR Phenological Spectral Profiles (SSP_{phOpt}, SSP_{phSAR} Table 1, Figure 1) for spring cereals (Tables 11, 12).

Vegetation Indices (VGI) and Composite Multispectral (CMM) models using minimum datasets

Publications III and IV describe the possibilities for setting up calibrated *yield baselines* for monitoring the trends or changes in spring cereal baseline yield levels (y_b) over a decade of measurement data (1989-2004) using five *Vegetation Indices* (VGI, models I-IV) models and *Composite Multispectral Models* (CMM, model V) incorporating optical and microwave satellite data (Table 1): *(i)* infrared polynomial, *(ii)* Normalized Difference Vegetation Index (NDVI, Price 1987, Scurlock & Prince 1993), *(iii)* Global Environment Monitoring Index (GEMI, Pinty and Verstraete 1998), *(iv)* Normalized Vegetation Index for PAR (PARND/FAPAR, Gobron *et al.* 2006) and *(v)* composite optical (NDVI) and microwave polynomial model (CMM, Henderson & Lewis 1997). Models were calibrated and validated by using 1989-2004 optical (Landsat/TM, SPOT/HRV) and microwave (HUTSCAT, ERS1, Radarsat1 and ENVISAT) satellite data (*Minimum Datasets* VIII-X, Table 4) measured at the experimental sites in Mellilä, Porvoo, Jokioinen and Lapua, characterized by clay, coarse and organic soils respectively (Table 8, Figure 3, Figure 7A, Appendix 1).

Calibration and description of VGI and CMM models

In publication III the polynomial infrared model (I) was calibrated as a polynomial linear regression (SAS 1990), estimating yield production (kg ha^{-1}) with infrared (rf_3) and near infrared (rf_4) channels with categorized satellite data using the *SatPhenClass* phenological classification algorithm. The model II, the Normalized Difference Vegetation Index (NDVI, Jackson & Gaston 1994, Moriondo *et al.* 2007) and model III, the Global Environment Monitoring Index (GEMI, Pinty and Verstraete 1998), were evaluated using infrared and near infrared channels respectively. In publications III and IV, a new model (IV), Normalized Vegetation Index for Photosynthetically Active Radiation (PAR_{ND}/FAPAR), resembling the FAPAR Index (Gobron *et al.* 1999, 2004, 2006, 2007), was applied for yield estimations by explicitly using the PAR-region (λ=400-700 nm). This new PAR_{ND}/FAPAR model emphasizes the vegetation photosynthesis spectral absorption maxima with Photosystem I and II (Ph I: $\lambda < 700$ nm, Ph II:$\lambda < 680$ nm) and chlorophyll A (λ=460, 680 nm) and B (λ=480, 650 nm). The overlapping satellite channels for Ph I and Ph II are Landsat/TM3 and SPOT HRV_2/S_2 and for chlorophyll A and B Landsat TM1 and TM3 and SPOT HRV_2/S_2 (Table 4, Lawlor 1987, Scurlock and Prince 1993, Tucker 1979, Serrano *et al.* 2000). The FAPAR Index is an indicator of the state and productivity of vegetation, representing the fraction of the solar energy that is absorbed by vegetation during the photosynthetic process. The FAPAR algorithm (FAPAR/JRC 2008) minimizes the effects of atmospheric particle scattering, the variation of different soil covers and the changing geometry of illumination.

The *Composite Multispectral Polynomial* model (CMM, model V) evaluates both the cereal vegetative phase before anthesis (a_p,b_p), by using the optical NDVI submodel, and also the generative (c_p) and canopy senescence phase in autumn (d_p), by using microwave canopy and soil backscattering data. Model V was calibrated with HUTSCAT 1990 scatterometer data (Henderson & Lewis 1997, Matikainen *et al.* 1998, Hyyppä *et al.* 1990, Karjalainen *et al.* 2004, 2008, Dente *et al.* 2008).

Validation of VGI and CMM models

In publication IV the five calibrated VGI models were validated using two independent datasets with averaged yield levels for different cereals (kg ha^{-1}) (Datasets XI-XII, Table 4) : *(i)* the MAFF Official Yield Statistics (1989-2005), and *(ii)* the MTT Agrifood Official Variety trial data (Table 4, Model validation datasets I-II). The MAFF cereal validation procedure included comparison of the modeled yield estimates (kg ha^{-1}) using VGI models with corresponding averaged yield statistics for 1989-2004 from the Nylands Svenska, Häme and Etelä-Pohjanmaa Agricultural Advisory Centres, from the MAFF official inventory program and calculating percentage differences (MAFF 2007, MAFF/TIKE 2008, Figure 7A, Appendix 1). With the MTT cereal validation, the modeled yield estimates were compared with the MTT Official Variety Trials results for 1989-2004, with cultivars grown in the same cultivation zone and soil profile (Kangas *et al.* 2002, 2006, Figure 7A, Appendix 1). The MAFF validation dataset (Table 4) provided *non-potential* yield inventory estimates for crops grown under *suboptimal* conditions at the farm parcel level. The MTT yield data were close to *optimal* non-limiting growing conditions at experimental sites. By using independent validation datasets, the potential problems with *spatial autocorrelation* (e.g. interdependency between modeled yield estimates from adjacent satellite pixels were avoided (Bailey & Gatrell 1995, Griffith 2003).

RESULTS

Spring wheat crop physiological results from the OTC experiments with elevated CO_2 and temperature growing conditions

In publication I, including the results from a previous modeling study for *cv.* Nandu (Laurila 1995), the 1992-1994 Open Top chamber (OTC) results (Dataset IV, Table 4, Hakala 1998a,b, Laurila 1995, 2001) indicated that the mid-European genotype Nandu yielded ca. 23 % more grain (kg ha^{-1}) under elevated temperature (+3°C) and ambient CO_2 (350 ppm, year 1998 mean ambient atmospheric CO_2 level in high latitudes, Hakala 1998a,b) inside OTC (5580 kg ha^{-1}) in non-limited, optimal growing conditions. The mid-European genotype could thus benefit more from the elevated temperature compared with the high-latitude Swedish *cv.* Polkka (4305 kg ha^{-1}). Both cultivars were harvested on the 18^{th} August. At ambient temperature and CO_2 levels the grain yield was reversed, Nandu grain yield was 20 % lower (3778 kg ha^{-1}) compared with that of Polkka (4751 kg ha^{-1}) and Nandu had an 8 day longer growing period to reach full maturity. Results indicated that both cultivars produced smaller and lighter grains at ambient temperature vs. elevated temperature. This indicates that both genotypes were able to translocate assimilates to the heavier grain fraction despite accelerated developmental rate and shortened development phases under elevated temperature conditions between emergence and full maturity. These results also indicate that the temperature effect was relatively stronger on translocation rate than on development rate, expressed by shortening the grain-filling phase (Hakala *et al.* 2005, Laurila 2001).

The crop physiological results for MidE *cv.* Nandu consisted of a single year only (1992) in the SILMU OTC experiments and can be considered as indicative in conjunction with photoperiodism and day length effects (Saarikko & Carter 1996, Saarikko *et al*. 1996, Hakala *et al.* 2004). On average the day length in mid-summer (June 22^{nd}) at high latitudes (60° N) is 18 h 27 minutes and at mid-latitudes (50 ° N - 40° N) 14 h 52 minutes. Kontturi (1979) and Saarikko (1999a) reported a photoperiodical threshold daylength of 18 hours for high-latitude genotypes adapted to Finnish long day growing conditions. Daylengths below the threshold delay the vegetative phase from sowing to heading. OTC results also indicated that both varieties, at ambient temperatures, produced smaller and lighter grains vs. elevated temperatures. In that respect both genotypes were able to translocate assimilates to heavier grain size fractions despite an accelerated and shorter development phase at elevated temperatures between emergence and full maturity.

Yield component and vegetation parameter modeling results for high yielding HiL and MidE ideotypes

In publication II the modeling results from statistical mixed structural covariance and path analysis provided the most significant yield components and vegetation parameters for high yielding mid-European and high-latitude ideotypes. Results indicated a consistent higher yielding capacity (108 %) for mid-European ideotypes compared with high-latitude ideotypes (100 %). Significant *yield component factors* for high yielding ideotypes were maximum number of grains/ear, maximum spikelets/ear, maximum value for the calculated ratio ear bearing stems (stems/m^2) in August / emerged seedlings after sowing (seedlings/m^2), maximum 1000 grain weight and maximum harvest index (HI). Significant *vegetation parameters* were maximum values for sowing seed density, emerged seedlings, side tillers/plant in June, number of leaves/plant in July, flag leaf and second highest leaf areas in July, flag leaf and second highest leaf dry weights in July and maximum plant whole dry weight in August.

Modeling results seemed to be in accordance with the *a priori* hypothesis emphasizing the important role of the flag leaf in defining the final grain yield. The role of the second highest leaf was less significant for final high yield determination in wheat ideotypes. More specifically, results indicate that especially the flag leaf area and dry-weight in the generative phase after heading might be potential indicators for detecting and evaluating potentially high-yielding ideotypes. High-latitude and mid-European ideotypes introduced into cultivation after the 1990s (HiL_{New90}, $MidE_{New90}$, Table 1) have a significantly higher yielding capacity compared with cultivars introduced earlier. In addition, a general trend of breaking the mean 5 t ha^{-1} baseline barrier (the German cultivar Trappe exceeded 6 t ha^{-1}) over the years with genotypes introduced into cultivation after the 1990s is noticeable in MTT Agrifood Research Finland (1978-2005) official variety trial data (Dataset I, Table 4) with mid-European cultivars like Amaretto, Azurite, Bombona, Jondolar, Marina, Monsun, Picolo, Sella and Zebra. In several years similar results were also recorded with high-latitude cultivars like Tjalve, Kadrilj, Mahti, Vinjet and Anniina.

CERES-Wheat calibration results for genetic coefficients with generic HiL and MidE genotypes

In publications I and II the CERES-Wheat calibrated genetic coefficients for generic high-latitude (Ref. *cv.* Polkka, Laurila 2001) and generic mid-European genotypes (Ref. *cv.* Nandu, Laurila 1995) are presented and used in the CERES-Wheat crop model (Jones *et al.* 2003). The parameters for the CERES-Wheat genetic coefficients are explained in Table 6. The calibrated CERES-Wheat phenological coefficients are shown in Table 9 and yield component coefficients in Table 10. The calibrated coefficients (PHINT, P1V, P5, G1, G2, G3,) were for a generic high-latitude genotype (60.0, 0.10, 1.0, 10.0, 5.0, 1.0, 1.5) and for a generic mid-European genotype (60.0, 0.10, 1.0, 9.0, 4.0, 3.0, 2.0).

Table 9. CERES-Wheat phenological coefficients (PHINT, P1V, P1D and P5, Table 6) for *cv.* Polkka (Kangas *et al.* 2006, Laurila 2001, Table 4, Dataset I) and for *cv.* Nandu (Laurila 1995) [1)].

Genotype	$RMSD_{ANTH}$ (d)	$RMSD_{FMAT}$ (d)	PHINT (dd)	P1V	P1D	P5
High-latitude (*cv.* Polkka)	2.99	5.86	60.0	0.10	1.00	10.0
Mid-European (*cv.* Nandu)	-	-	60.0	0.10	1.00	9.0

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

Table 10. CERES-Wheat yield component coefficients (G1, G2 and G3, Table 6) for spring wheat *cv.* Polkka (Kangas *et al.* 2006, Laurila 2001, Table 4, Dataset I) and for *cv.* Nandu (Laurila 1995) [1)].

Genotype	Soil type	$RMSD_{YLD}$ ($t\ ha^{-1}$)	G1	G2	G3
Mid-European (*cv.* Nandu)	All soil data pooled	-	4.0	3.0	2.0
High-latitude (*cv.* Polkka)	Sand (coarse and fine)	1.747	0.50	5.00	5.00
	Heavy clay	1.832	1.00	8.50	1.00
	Mixed clays	1.725	1.00	8.50	1.00
	Silt, Silt loam	1.408	1.00	6.00	1.00
	Organic soil(peat, mold)	0.289	2.00	2.30	2.00
	All soil data pooled	1.798	5.00	1.00	1.50

[1)] RMSDYLD = RMSD for grain yield ($t\ ha^{-1}$).

The CERES-Wheat crop potential (y_{pot}) and non-potential (y_b) yield modeling results for HiL and MidE genotypes

In publication I the simulated *cv.* Polkka mean potential grain yield (y_{pot}(OTC,HiL), Table1, Figure 1) with the CERES-Wheat potential non-limited model, under ambient mean diurnal temperature (15 ºC) and CO_2 (350 ppm) growing conditions, was 6.16 t ha^{-1} and the non-potential, limited baseline yield (y_b(OTC,HiL), Table 1, Figure 1) was 4.49 t ha^{-1}. The observed SILMU average yield for *cv.* Polkka (1992-1994) was 5.47 t ha^{-1} in ambient OTC chamber experiments (Hakala 1998b). The simulated non-potential baseline yield level (y_b) of *cv.* Polkka increased under elevated CO_2 conditions (700 ppm) to 142 % as compared with the non-limited yield level (y_{pot} 167 %). The corresponding measured average 1992-1994 increase from OTC experiments was 112 % (Hakala 1998b). Simulation results indicated that by maintaining the current sowing date, the elevated temperature (+ 3 °C) accelerated phenological development between sowing and anthesis and between anthesis and full maturity. According to the model estimations, the yield of cv. Polkka decreased on average to 80.4 % with the potential model (76.8 % non-potential) due to temperature increase and the measured average 1992-1994 decrease from OTC experiments was 84 % (Hakala 1998b).

When modeling the effects of both elevated temperature and CO_2, the increase in grain yield due to elevated CO_2 was reduced by the elevated temperature due to accelerated phenological development, especially during the generative phase, and a shorter grain-filling period. The combined CO_2 and temperature effect increased the *cv.* Polkka grain yield (y_b) to 106 % for non-potential growing conditions (y_{pot} 122 % non-limited growing conditions) as compared with the simulated reference (100 %). The measured averaged 1992-1994 increase from OTC experiments was 102 % (Hakala 1998b).

When simulating the effects of earlier sowing of two weeks on final grain yield, the non-potential grain yield (y_b) increased under elevated temperature and CO_2 conditions to 178 % (15 days earlier sowing from 15th May, 700 ppm CO_2, +3 °C) compared with the simulated reference (100 %). Simulation results with the CERES-Wheat model suggested that without any increase in CO_2 level, earlier sowing would only increase the grain yield of spring wheat to any significant extent. Sowing 15 days or more earlier than the 15th May reference date under ambient CO_2 (350 ppm) and temperature conditions would produce an almost equal increase in grain yield as doubling CO_2 (700 ppm) at the reference sowing date and ambient temperature (Hakala *et al.* 2005).

The CERES-Wheat internal error estimation with the sensitivity analysis

In publication I, both the CERES-Wheat potential and non-potential submodels estimating the final grain yield were analyzed with the sensitivity analysis (model classes II-III in Table 5, France & Thornley 1984, Thornley & Johnson 1989) to estimate both the internal error in the submodels and the sensitivity of the final grain yield of *cv.* Polkka on deviations of concurrent atmospheric CO_2 and mean diurnal temperature changes.

Both the simulated potential (y_{pot}) and non-potential (y_b) final grain yields were used as response variables in the sensitivity analysis when the concurrent atmospheric CO_2 concentrations and mean diurnal temperatures, acting as driving variables, were deviated (increased/decreased) with average steps of ±10, ±20, ±50, ±100 % from the current ambient mean diurnal temperature (+ 15 ºC) during growing season and from the ambient atmospheric CO_2 (350 ppm) concentration.

The sensitivity results indicated that in general both the potential submodel estimating the potential grain yield (y_{pot}(OTC,HiL,MidE), kg ha^{-1}, Table 1, Figure 1) and the non-potential submodel estimating the non-potential baseline grain yield (y_b(OTC,HiL,MidE), kg ha^{-1}) were sensitive to small increases or decreases (±10 - ±20 %, Kuiper 1993) in mean diurnal temperature changes, equal to a ± 3 ºC deviation in mean temperature. When higher deviations were used (> ± 20 %) both submodels were insensitive, i.e. deviating less than the corresponding driving variables in final grain yield responses.

When analyzing the atmospheric CO_2 sensitivity results, only the potential grain yield (y_{pot}(OTC,HiL,MidE),kg ha^{-1}) of the potential model was sensitive to atmospheric CO_2 deviations below 20 per cent equaling to 450 ppm in atmospheric CO_2 concentration, in higher CO_2 concentrations both the potential and non-potential models were insensitive.

Respectively the potential model was sensitive to concurrent CO_2 and temperature changes below 20 % equal to concurrent atmospheric CO_2 concentration of 400 ppm and +2 ºC diurnal temperature increase. In higher concurrent atmospheric CO_2 concentrations (> 400 ppm) and temperature change levels (> +2 ºC) both the potential and non-potential submodels were insensitive.

Ideotype profile (ItPrf) modeling results for generic HiL and MidE genotypes

In publication II the optimal Ideotype profile (ItPrf, Figure 1, Donald 1968) modeling results, derived from the Ideotype, Cultivation value, Mixed Structural Covariance, Path and Yield component analyses, are presented. In the results the optimal, high yielding ideotype profiles ($ItPrf_{(HiL,MidE)}$, Figure 1, Table 1) for generic HiL_{New90} and $MidE_{New90}$ genotypes introduced into cultivation in the 1990s or after are presented using the New_{90} Mixed contrast category (Little *et al.* 1996). The $\Delta y_{b(CO2,700ppm)}$, $\Delta y_b(\Delta T_{,+3ºC})$ and the covariant $\Delta y_{b(CO2,TempCov)}$ factors (Table 1) in the ideotype profiles were excluded from the non-potential baseline yield estimates ($y_{b(ItPrf,HiL,MidE)}$, kg ha^{-1}, Figure 1).

The optimal high yielding ideotype profile (Table 1, Figure 1) for a generic HiL_{New90} ideotype ($ItPrf_{HiL,New90}$) with parameters (y_b±S_d [kg ha^{-1}], $\Delta y_{b(CO2,700ppm)}$ [min.-max.,%], $\Delta y_b(\Delta T_{,+3ºC})$ [min.-max.,%], $\Delta y_{b(CO2,TempCov)}$ [min.-max., %], PHINT [dd], P1V, P5, G1, G2, G3, C_a ,C_p ,C_b ,C_{ValTot}) was (4616±564, 1.12-1.42 , 0.72-0.83, 1.01-1.06, 60.0, 0.10, 1.0, 10.0, 5.0, 1.0, 1.5, 24.4, 24.2, 31, 23, 112.8). The optimal high yielding ideotype profile ($ItPrf_{MidE,New90}$) for a generic MidE $_{New90}$ ideotype was (4755±282, 1.49-1.72, 0.59-0.62, 1.04-1.13, 60.0, 0.10, 1.0, 9.0, 4.0, 3.0, 2.0, 23, 29, 34.2, 31.2, 117.4).

When taking into account also the projected concurrent CO_2×temperature covariance effect $\Delta y_b(CO_{2,700ppm},\Delta T_{,+3°C})$ projected by the year 2100 climate change scenario for southern Finland (Carter 2004), the non-potential average baseline yield change (Δy_b, %) would be 1.035 % (range 1.01-1.06 %) for the generic high yielding $ItPrf_{HiL(New90)}$ ideotype. Correspondingly the average Δy_b change for the generic high yielding $ItPrf_{MidE(New90)}$ ideotype would be 1.085 % (range 1.04-1.13 %). These results indicate that the high yielding $ItPrf_{MidE(New90)}$ non-potential baseline yield (y_b) would be on average at the 5150 kg ha^{-1} level (Δy_b +108 %) vs. $ItPrf_{HiL(New90)}$ ideotype profile (y_b 4770 kg ha^{-1}, 100%) and assuming the photoperiodical day length remains constant.

The Mixed Structural Covariance error variance in non-potential yield (y_b) estimations

In Publication II, the Mixed Structural Covariance model was used to estimate the genotype×environmental error variance (Table 5) with HiL and MidE spring wheat non-potential baseline yield estimates ($y_{b(ItPrf,HiL,MidE)}$ kg ha^{-1}, Figure 1) vs. observed MTT Agrifood Research Finland official variety trial yield data results (Table 4, Kangas *et al.* 2002, 2006). The observed HiL and MidE spring wheat grain yield measurements (kg ha^{-1}) were extracted from the MTT Agrifood Research Finland (1970-2005) official variety trial data with growing conditions varying between non-potential, limited and nearly optimal, non-limited growing conditions.

The overall ($y_{b(ItPrf,HiL,MidE)}$ kg ha^{-1}, Figure 1) mean estimation error over all contrast categories (latitude type, decade of introduction into cultivation, cultivation type and soil type) was 94.8 kg ha^{-1} with the Mixed Structural Covariance model vs. observed MTT Agrifood Research Finland official variety trial data results. The overall mean non-potential baseline yield estimate ($y_{b(ItPrf,HiL,MidE)}$ kg ha^{-1}) for a generic ideotype profile ($ItPrf_{(HiL,MidE)}$) was 4014 kg ha^{-1} (SD 245 kg ha^{-1}). All the Mixed contrast categories varied significantly from the mean error estimate when the non-potential baseline yield level ($y_{b(ItPrf,HiL,MidE)}$) was estimated.

In the Mixed decade of introduction to cultivation contrast category, the Mixed mean estimation error was 19.2 kg ha^{-1} ($y_{b(ItPrf,HiLOld70)}$ 3880 kg ha^{-1}) for the HiL_{Old70} contrast category, 35.4 kg ha^{-1} for HiL_{Old80} generic genotypes ($y_{b(ItPrf,HiLOld80)}$ 4010 kg ha^{-1}), 28.2 kg ha^{-1} for the $MidE_{Old80}$ category ($y_{b(ItPrf,MidEOld80)}$ 4340 kg ha^{-1}).

Especially with new MidE genotypes, introduced into cultivation in the 1990s or after (New90), the mean estimation error was higher for MidE genotypes (108.5 kg ha^{-1}, $y_{b(ItPrf,MidENew90)}$ 5060 kg ha^{-1}) vs. the average Mixed model estimate. With new HiL genotypes (New90 category) the estimation error was significantly lower (59.6 kg ha^{-1}, HiL ($y_{b(ItPrf,HiLNew90)}$ 4650 kg ha^{-1}).

In the Mixed soil type contrast category, the Mixed model mean estimation error was highest with loam type soils (120.5 kg ha^{-1}, $y_{b(ItPrf,HiL,MidE)}$ 3702 kg ha^{-1}). With clay type soils (41.0 kg ha^{-1}, $y_{b(ItPrf,HiL,MidE)}$ 4100 kg ha^{-1}) and with coarse type soils (27.5 kg ha^{-1}, $y_{b(ItPrf,HiL,MidE)}$ 3850 kg ha^{-1}) the estimation error was significantly lower.

In the Mixed conventional vs. organic cultivation practices contrast category, the mean estimation error was smaller 17.9 kg ha^{-1} ($y_{b(ItPrf,HiL,MidE)}$ 4269 kg ha^{-1}) with genotypes cultivated with conventional practices vs. 52.5 kg ha^{-1} ($y_{b(ItPrf,HiL,MidE)}$ 3640 kg ha^{-1}) with genotypes cultivated with organic cultivation practices.

Non-potential baseline yield ($y_{b(Sat)}$) modeling results for large cultivation area estimations with VGI and CMM models

In publications III and IV, the 1989-2005 optical and microwave satellite measurement campaign results in southern Finland combined with Vegetation Indices (VGI) and CMM (Composite Multispectral) models suggest a non-potential *baseline* yield (y_b(Sat), kg ha^{-1}, Figure 1) level of 3950 kg ha^{-1} (RMSE 9.1 %, 360 kg ha^{-1}) for spring cereals, 4330 kg ha^{-1} (RMSE 6.7 %, 290 kg ha^{-1}) for winter cereals and more specifically 4240 kg ha^{-1} (R^2 0.764, RMSE 6.65 %) for the averaged spring wheat cultivars in large cultivation area non-potential field conditions in southern Finland (Table 5, large area, field parcel aggregation level). The average non-potential *baseline yield levels* ($y_{b(Sat)}$) were 4390 kg ha^{-1} for barley, 3480 kg ha^{-1} for oats, 3750 kg ha^{-1} for rye and 4920 kg ha^{-1} for winter wheat.

The VGI and CMM *validation results* indicate that in general the average VGI baseline cereal yield estimates tend to stabilize between the observed *non-potential* (i.e. including water and nutrient deficiencies and pathogen epidemics during growing season) yield levels and potential maximum *yielding capacity* levels without effects of limiting environmental factors (e.g. vegetation water stress, nutrient deficiencies). Results suggest that VGI models tend to overestimate the baseline spring cereal yield levels by 1-25 % vs. annual MAFF *non-potential* yield inventory estimates for suboptimal growing conditions at the farm parcel level. When compared with MTT Official Variety trial data with more favorable growing conditions at experimental fields, the *yield difference ratio* (%) between the VGI estimate vs. MTT measured yield varied between 71 % (oats, underestimation) and 112 % (spring wheat, overestimation) from the *baseline reference* yield level (100 %).

Optical Phenological Spectral Signature Profile (SSP_{phOpt}) and Vegetation Indices variation

Table 11 from publications III and IV presents the optical *Phenological Spectral Signature Profile* (SSP_{phOpt}, Table 1) variation during phenological development and crop calendar using optical ρRED and ρNIR reflectance values and optical VGI indices (PAR_{ND}/FAPAR,NDVI and GEMI, Table 1). In Table 11, the VGI indices are tabulated in corresponding phenological classes (a_p,b_p,c_p) during the growing season using the SatPhenClass classification algorithm. In addition, Table 11 presents observed averaged grain yield variation for spring wheat, barley and oats (1996–2006) in growing zones I–IV (Figure 7A, Appendix 1). The observed cereal yield, optical reflectance and Vegetation Indices varied significantly between different spring cereals, cultivars and soil types in the experimental areas in southern Finland (Figure 3).

The averaged grain yield and SSP_{phOpt} variation is depicted between *(i)* species, *(ii)* cultivars and *(iii)* soil types with corresponding categories I–III. Category I depicts *crop species* variation with generic spring cereal cultivars. Category II depicts *intracultivar variance* with identified cultivars from field parcels in experimental areas, and category III *species*soil* covariance variation. Table 11 depicts averaged spring wheat, barley and oats observed grain yield levels (kg ha^{-1}), infrared (*ρ*RED/Rf3) and near infrared (*ρ*NIR/Rf4) reflectance, NDVI, GEMI and PARND/FAPAR variation (Table 1) during germination and emergence after sowing (a_p, BBCH 0–12), ear emergence and maximum LAI exposure with fully closed canopy structure (b_p, BBCH 12–50) and finally during anthesis in the generative phase (c_p, BBCH 50–90).

In Table 11, the observed spring cereal yields (kg ha^{-1}) in satellite measurement locations (Figure 3) were measured by the farmers in the experimental areas in the autumn after the harvest. The observed grain yield levels were 4219 kg ha^{-1} for spring wheat, 4395 kg $ha^{-1}$for barley and 3740 kg ha^{-1} for oats when averaged over years (1996–2006) and locations (growing zones I–IV, Table 7). The spring cereal infrared (ρRED/Rf3) and near infrared (ρNIR/Rf4) reflectance values were higher in June (b_p) and July (c_p) when compared with May values (a_p, Rf3 mean 0.0133, Rf4 mean 0.0195).

The infrared Rf3 signal obtained low reflectance values (b_p, Rf3 mean 0.0265) with spring cereal cultivars in June with high PAR-radiation absorbance in fully closed canopies (LAI > 1).
Correspondingly maximum Rf_3 reflectance values peaked in July (cp, 0.057). Rf_3 values were below average for wheat cultivars (0.048), but had high values with barley cultivars (0.065) in July. The near-infrared Rf_4 signal peaked with maximum reflected mean value of 0.221 in June (b_p) with lower mean reflectance in July (c_p, 0.186).

The VGI indices (NDVI, GEMI, PARND) for spring cereals in June (b_p) and July (c_p) were generally higher than the corresponding May values (a_p). With vegetation indices (NDVI, GEMI, PARND), a significant peak was observed between May and June values (Table 11, Category I). The NDVI ranged between 0.013 (May, a_p), 0.7207 (June b_p) and 0.4093 (July c_p), corresponding values were 0.2603, 0.5883 and 0.4457 for GEMI and 0.0623, and 0.121 and 0.4960 for PARND.

Table 11. Optical phenological Spectral Signature Profiles (SSP_{phOpt}) and averaged observed yields for spring cereals with Reflectance (Rf_3 / ρ_{RED}, Rf_4 / ρ_{NIR}) and PAR_{ND}/FAPAR,NDVI and GEMI indices values between categories (I: crops, II: identified cultivars and III: soil types) with all data (1990–2006, Table 1, Laurila *et al.* 2010a,b) pooled together[1), 2), 3), 7), 8)].

Category	**Yield (obs, X ± S_x)[7)]**		**Area**	**SSP_{ph} : NDVI, GEMI, PAR_{ND} (X ± S_x) [1), 6)]**								
I	**kg ha^{-1}**	**Cv%**	**Ha**	**a_p (May)**			**b_p (June)**			**c_p (July)**		
Crop Species [1)]				NDVI	GEMI	PAR_{ND}	NDVI	GEMI	PAR_{ND}	NDVI	GEMI	PAR_{ND}
Swh	4219 ± 290	14.5	415	0.0012 ± 004	0.257 ± 0.002	0.076 ±0.001	0.498 ± 0.007	0.411 ±0.004	0.039±0.002	0.332 ± 0.007	0.312±003	0.515±0.01
Barley	4395 ± 229	33.8	235	0.0014 ± 002	0.193 ± 0.003	0.062 ±0.001	0.898 ± 0.003	0.660 ±0.002	0.093 ±0.003	0.256 ± 0.01	0.347 ± 0.006	0.443± 0.01
Oats	3740 ± 345	27.6	47	0.0012 ± 005	0.331 ± 0.008	0.049 ± 0.002	0.766 ± 0.01	0.694 ±0.005	0.231 ± 0.01	0.640 ± 0.02	0.678 ± 0.001	0.535±0.02
Mean (Area sum.)	4118 ± 338	25.3	697	0.0013 ± 001	0.2603±0.690	0.0623 ±0.0135	0.7207 ± 0.204	0.5883±0.154	0.1210±0.099	0.4093 ± 0.203	0.4457 ± 0.201	0.4960±0.047

II		Yield (obs.)		Mean $\rho_{RED} - \rho_{NIR}$ for May. June and July [1), 2), 6)]						NDVI (mean) [1), 2)]		
Identified		Mean	C_v%	ρ_{RED}	ρ_{NIR}	ρ_{RED}	ρ_{NIR}	ρ_{RED}	ρ_{NIR}	a_p (May)	b_p(June)	c_p(July)
Cultivars [1)]		**kg ha^{-1}**		a_p May	a_p May	b_p June	b_p June	c_p July	c_p July			
Swh	Kadett	3541	20.0	0.0820	0.1180	0.0012	0.2320	0.0014	0.203	0.0780	0.798	0,562
	Manu	4016	30.9	0.0011	0.0012	0.0560	0.2180	0.0940	0.259	0.0010	0.587	0.592
	Ruso	3900	11.0	0.0730	0.1040	0.0014	0.2420	0.0012	0.169	0.0730	0.887	0.679
	Satu	3181	31.9	0.0011	0.0014	0.0550	0.2550	0.0970	0.242	0.0014	0.557	0.646
	Mean swh	3659 ± 377	20.9	0.0393 ± 0.044	0.0562 ± 0.064	0.0284 ± 0.0312	0.236 ± 0.01156	0.0484 ± 0.054	0.2182 ± 0.0403	0.0383 ± 0.1001	0.707 ± 0.2474	0.619 ± 0.2211
Brl	Artturi[10)]	4656	18.5	0.0012	0.0011	0.0550	0.2020	0.0990	0.199	0.0012	0.601	0.569
MBrl	Arve[10)]	4785	34.2	~ 0.0	0.0012	0.0011	0.2011	0.0390	0.106	0.0014	0.856	0.425
FBrl	Inari[10)]	4750	25.7	0.0014	0.0011	0.0490	0.1920	0.0910	0.158	0.0015	0.595	0.411
9), 10)	Kymppi[10)]	3458	40.5	0.0012	0.0011	0.0012	0.2014	0.0410	0.102	0.0018	0.815	0.343
	Pokko[9)]	5473max	19.6	~ 0.0	0.0014	0.0013	0.2011	0.0560	0.219	0.0014	0.549	0.321
	Mean brl.	4624 ± 729	37.4	0.0007 ± 0.01	0.0011 ± 0.001	0.02152 ±0.0279	0.19952 ± 0.0042	0.0652 ± 0.028	0.1568 ± 0.0529	0.0015 ± 0.0002	0.6832 ±0.1412	0.4138 ± 0.318

Table 11. *Cont.*

II Identified Cultivars [1]		Yield (obs.) Mean kg ha^{-1}	C_v%	Mean $\rho_{RED} - \rho_{NIR}$ for May. June and July [1), 2), 6)] ρ_{RED} a_p May	ρ_{NIR} a_p May	ρ_{RED} b_p June	ρ_{NIR} b_p June	ρ_{RED} c_p July	ρ_{NIR} c_p July	NDVI (mean) [1), 2)] a_p (May)	b_p(June)	c_p(July)
Oats	Puhti	4565	45.4	0.0014	0.0011	0.0350	0.2310	0.0840	0.285	~ 0.0	0.547	0.437
	Salo	4680	14.7	~ 0.0	0.0013	0.0012	0.2011	0.0370	0.181	0.0012	0.822	0.428
	Veli	4129	25.7	0.0011	0.0011	0.0580	0.2802	0.0360	0.108	~ 0.0	0.867	0.655
	Mean oats	4458 ± 290	28.6	0.0008	0.0011	0.0314	0.23743	0.0523	0.1913	0.0004	0.745	0.464
Cereal	Mean Tot.	4261 ± 641.9	27.9	0.0133 ± 0.028	0.0195 ± 0.041	0.0265 ± 0.0257	0.2214 ± 0.0259	0.0566 ± 0.034	0.1859 ± 0.0581	0.0302 ± 0.065	0.7327 ± 0.1701	0.4830 ± 0.367

III Soil type		Yield (observed) (kg ha^{-1}) $X \pm S_x$	Cv%	NDVI (mean) [5) 6)] b_p (June)	c_p (July)	Mean ρ_{RED} /Rf3 and ρ_{NIR} Rf4 for b_p.June and c_p.July [4) 6) 10)] ρ_{RED} / ρ_{NIR} (June)	ρ_{RED} / ρ_{NIR} (July)
Clay[1)]	Swh	4224 ± 8.9	14.3	0.497	0.330	0.006 / 0.131	0.023 / 0.088
	Brl	4363 ± 30.8	34.5	0.910	0.224	0.016 / 0.256	0.023 / 0.104
	Oat	3485 ± 33.8	18.3	0.786	0.569	0.037 / 0.297	0.043 / 0.255
Coarse[2)]	Swh	4224 ± 8.9	14.3	0.482	0.112	0.004 / 0.214	0.029 / 0.065
	Brl	4363 ± 30.8	34.5	0.720	0.356	0.024 / 0.256	0.045 / 0.121
	Oat	3485 ± 33.8	18.3	0.686	0.487	0.052 / 0.316	0.064 / 0.197
Organic[3)]	Swh Erl.	3972 ± 483	19.7	0.596	0.429	0.056 / 0.218	0.107 / 0.348
	Swh Lt.	4984 ± 641	22.8	0.642	0.541	0.055 / 0.255	0.097 / 0.342
	Brl Erl.	4656 ± 862	26.9	0.569	0.401	0.055 / 0.202	0.099 / 0.399
	Brl Lt.	4741 ± 659	21.1	0.603	0.596	0.049 / 0.192	0.091 / 0.358
	Oat Erl.	3932 ± 824	29.9	0.655	0.557	0.058 / 0.280	0.114 / 0.401
	Oat Lt.	3257 ± 629	28.7	0.737	0.547	0.035 / 0.231	0.084 / 0.285

[1)] Includes sandy and gyttja clay soil-classes (Lapua, Mellilä, Porvoo, Kirkkonummi Exp. Areas) [2)] Includes fine and coarse sand soil-classes (Porvoo and Kirkkonummi Exp. Areas) [3)] Early (Erl.; SwH: *cv.* Manu, Brl: *cv.* Artturi, Oat: *cv.* Veli) and Late (Lt. SwH: *cv.* Satu, Brl: *cv.* Inari, Oat: *cv.* Puhti) cereal cultivars measured in the Kuuma/Jokioinen (3 x 3 randomized lattice) and Porvoo Exp. (2 x 2 randomized lattice) areas with organic mold and peat top soil profiles [4)] R_f for May excluded from the table. [5)] R_f and NVDI values for May close to ~0.0 [6)] Rf_3 , Rf_4, NDVI data categorized for a_p (May, BBCH 0-12), b_p (June, BBCH 12-50) and c_p (July, BBCH 50-90) phenological classes during the growing season. [7)] Cereal averaged yields (kg ha^{-1} corrected as 15% moisture content) were measured by the farmers in the experimental areas in the autumn after the harvest, yield samples were measured from the granary silos. [8)] Averaged over years (1996-2006) and locations in growing zones I-IV (Figure 7A, Appendix 1). [9)] Enzyme malting barley cultivar (MBrl) [10)] Fodder barley cultivar(FBrl).

SAR Spectral Signature profiles (SSP_{phSAR}) and canopy×soil backscattering covariance

Table 12 from publications III and IV presents microwave based SAR phenological Spectral Signature Profiles (SSP_{phSAR}, Table 1) depicting both SAR (Synthetic Aperture Radar, Table 1) backscattering horizontal and vertical polarization levels (HH, VV) and the cross-polarization levels (VH/HV) of the monostatic HUTSCAT scatterometer. In addition, Table 12 depicts the SAR (Radarsat, ERS, Tables 1,8), ASAR (Advanced Synthetic Aperture Radar, Envisat) and HUTSCAT backscattering variance (σ_0) between different spring cereals in Lapua, Seinäjoki and Porvoo experimental sites.

The Radarsat horizontal (HH) backscattering (σ_0) variation between malt (MBrl) and fodder barley (FBrl) is presented in Radarsat sensor column. Table 12 depicts cereal *canopy*soil* backscattering covariance during generative phenological phases c_p and d_p (anthesis, grain full maturity and canopy senescence, Table 1) grown on clay, coarse and fine sand type soils.

Both the soil type and soil×cereal canopy covariances in Table 12 expressed extensive variation with SAR backscattering signal (σ^0) on clay type soils, which were dominant in experimental areas in zones I–IV (Figure 3, Figure 7A, Appendix 1). When analyzing the variation between different SAR sensors the HUTSCAT backscattering signal (f = 5.4 GHz, Table 12) varied with wheat, barley and oat between –29 dB (oats*c_p*VH*coarse sandy clay) and –6 dB (wheat*c_p*VV*coarse and fine sand clay, barley*c_p*VV*fine sand and gyttja clay). The ERS signal (f = 5.3 GHz) varied between –8 dB (barley*d_p*VH*fine and coarse sandy clay) and -10 dB (barley*c_p*VV* sandy clay, oats*c_p*VV*sandy clay). The Radarsat signal (f = 5.3 GHz) varied between –13 dB (malt barley*c_p*HH* fine and coarse sandy clay) and -10 dB (wheat*d_p*HH*sandy clay). The Envisat signal (f = 5.3 GHz) varied between -16 dB (oats*d_p*VH* fine and coarse sandy clay) and –9 dB (barley*d_p*VV* sandy clay). The helicopter mounted HUTSCAT signal amplitude varied more significantly when compared with other backscattering signals (Envisat, ERS, Radarsat) measured on clay and sandy soils. In addition, the HUTSCAT C-band measurement frequency was slightly higher (f=5.4 GHz) than with Envisat, ERS and Radarsat (f = 5.3 GHz).

Table 12. SAR/microwave phenological Spectral Signature Profiles (SSP_{phSAR}) and backscattering variation (σ^0, f=5.3-5.4 GHz) on sand and clay type soils with different horizontal, vertical and cross polarization levels during anthesis (c_p), full grain maturity and canopy senescence (d_p, Table 1, Laurila *et al.* 2010a,b) [1) 2)]

SAR Sensor	**Main soil Type**	**S.wheat [dB] ($X \pm S_d$)**				**Barley** [1)] **[dB] ($X \pm S_d$)**				**Oats [dB] ($X \pm S_d$)**			
DVS[3)]		**c_p (July)**		**d_p (Aug.)**		**c_p (July)**		**d_p (Aug.)**		**c_p (July)**		**d_p (Aug.)**	
HUT SCAT Scattero Meter	Sandy Clay	VV/ HH	VH/ HV [3)]	VV/ HH	VH/ HV [3)]	VV/ HH	VH/ HV [3)]	VV/ HH	VH/ HV [3)]	VV/ HH	VH/ HV [3)]	VV/ HH	VH/ HV [3)]
		–6.40 (±0.84)/ –16.21 (±0.32)	–20.26 (±0.35)/ –20.16 (±0.14)	–10.53 (±0.24)/ –10.09 (±0.23)	–20.71 (±0.15)/ –20.05 (±0.13)	–5.78 (±1.79)/ –12.27 (±1.72)	–22.85 (±0.90)/ –22.97 (±0.87)	–11.26 (±1.79)/ –10.21 (±1.72)	–22.54 (±0.67)/ –22.48 (±0.49)	–9.75 (±1.58)/ –18.52 (±1.87)	–21.09 (±0.90)/ –21.31 (±0.73)	–13.39 (±1.47)/ –11.62 (±1.97)	–21.54 (±0.76)/ –21.17 (±0.58)
Envisat ASAR	Fine, coarse sand	VV	VH	VV	VH	VV	VH	VV	VH	VV	VH	VV	VH
		–12.47 (±1.17)	–17.52 (±0.95)	–10.09 (±1.41)	–14.81 (±1.18)	–11.45 (±2.17)	–17.16 (±1.59)	–9.45 (±1.38)	–14.59 (±1.51)	–11.08 (±2.51)	–17.22 (±1.47)	–11.37 (±1.37)	–16.25 (±1.87)
Radarsat SAR [(1),(2)]	Fine, coarse sand	HH		HH		MBrl HH [2)]	FBrl HH [2)]	MBrl HH [2)]	FBrl HH [2)]	HH		HH	
		–12.27 (±2.28)		–10.48 (±0.79)		–13.88 (±1.25)	–12.57 (±1.58)	–12.28 (±2.27)	–11.39 (±1.28)	–12.64 (±1.65)		–11.23 (±0.97)	
ERS SAR	Fine, coarse sand					VV		VV		VV		VV	
						–10.24 (±1.17)		–8.12 (±2.11)		–10.24 (±1.28		–9.28 (±1.02)	

(1) MBrl- Malt barley, FBrl—feed barley [(2)] Detailed soil types in publications III, IV. [(3)] HUTSCAT σ^0 VH/HV cross-polarization

Historical trends in spring wheat yield levels, cultivation area and total production in Finland

In order to predict potential future changes in spring wheat non-potential baseline yield levels (y_b, kg ha^{-1}) and in Finnish national total grain yield production ($\Delta TotProd_{(HiL,MidE,CO2,TempCov)}$, Mkg yr^{-1}) in the 2050-2100 era, and outlined in Figure 6 in the discussion section, a preceding historical time series analysis for non-potential yield levels (y_b) of a generic HiL spring wheat genotype was performed and analyzed (SAS/ETS, SAS/GLM, SAS 1990, Figure 5). In the time series analysis the MAFF averaged yield inventory sampling statistics for spring wheat (1979-2010) without the inclusion of elevated CO_2×temperature covariant effect was used (MAFF 2007, MAFF/TIKE 2008, Fingrain 2011).

When analyzing the results of Finnish historical time series analysis with spring wheat yield levels, cultivation area and total national grain yield production (MAFF 2007, Fingrain 2011), there has been a significant variation in spring wheat total cropping area, in grain yield levels as well as in total grain yield production in Finland between 1975 and 2010, partly because of the *Common Agricultural Policy (CAP)* applied in Finland. According to Mela and Suvanto (1987), a general increasing trend in wheat yields between 1952 and 1985 was recorded both with spring sown wheat (+0.34 %/year) and with autumn sown wheat cultivars (+0.16 %/year) due to improved plant breeding and other cultivation techniques during recent decades in Finland. New cultivars have increased average yield levels by 15-20 % in Finland in the time period 1956-1976.

Figure 5 shows the yield levels of a generic high-latitude (HiL) spring wheat genotype with linear and polynomial trend lines in 1979-2010 in Finland without the elevated CO_2 and temperature effects (MAFF 2007, Fingrain 2011). Both the linear and polynomial non-linear trends are increasing, but R^2 is not very significant for linear (R^2 0.168) and polynomial models (R^2 0.123, Figure 5).

The official agricultural statistics for 1989-2011 (MAFF/TIKE 2008, Fingrain 2011) indicate that the average spring wheat grain yields ($\bar{x}$, kg ha^{-1}) were 2760 (1980), 3000 (1985), 3390 (1990), 3710 (1995), 3570 (2000), 3190 (2002), 3610 (2006), 3860 (2007), 3620 (2008), 4120 (2009), 3370 (2010) and 3740 (2011). In 2009 the averaged wheat yield exceeded the 4 t ha^{-1} level (Fingrain 2011). The MAFF statistics indicate an increasing spring wheat yield trend, the yield levels have increased by 29 % in the 20 year period (1980-2000) and by 22 % in the 30 year period (1980-2010). The current (2010) average baseline yield (y_b) is steadily above the 3000 kg ha^{-1} level ($\bar{x}$ 3600 kg ha^{-1} in 2001-2010) when taking into account the temporal variation between years (Fingrain 2011).

In 1990 (the SILMU scenario reference year) spring wheat cultivars occupying most of the spring wheat cultivation area in Finland were Reno (27.8 %), Satu (17.3 %), Runar (11.5 %) and Kadett (11.3 %, Publication I). In 2001 the most important cultivars were Tjalve (20.1 %, Publications I-II), Mahti (14.7 % Publications I-II) and Vinjett (10.5 %).

In 2010 the most important spring wheat cultivars were Anniina (80 %, 43 600 ha, HiL_{New90} Mixed structural contrast category, publication II), Zebra (78 %, 39 700 ha, HiL_{New90} category), Kruunu (17.5% 33 400 ha, HiL_{New90} category), Amaretto (7 %, 13 500 ha, $MidE_{New90}$ category), Quarna (16 %, 11 700 ha, $MidE_{New90}$ category), Bjarne (4 %, 8200 ha, HiL_{New90} category), Tjalve (3.8 %, 7 300 ha, Ref. HiL_{New90} category), Epos (2.9 %, 5 600 ha, $MidE_{New90}$ category), Mahti (2.6 %, 5000 ha), Marble (1.9 %, 3 700 ha, HiL_{New90} category), Picolo (1.7 %, 3 200 ha), Aino (1.5 %, 2 900 ha), Vinjett (1.08 %, 2000 ha), Wellamo (0.7 %, 1 300 ha, HiL_{New90} category), Manu (0.6 %, 1100 ha),Trappe (0,5 %, 1000 ha, $MidE_{New90}$ category), Polkka (0.3 %, 620 ha, Ref. HiL_{Old80} category, Publications I-II), and Nandu (0.2 %, 400 ha, Ref. $MidE_{New90}$ category Publications I-II).

This rapid change in the cultivar pool indicates on the one hand changes and acceleration in breeding methods (including new gene and biotechnology techniques) and on the other hand changes in cultivation technology. Moreover, both industry requirements for wheat baking quality factors and the current Common Agricultural Policy applied by the European Union and Finland have affected cultivar selection in Finland.

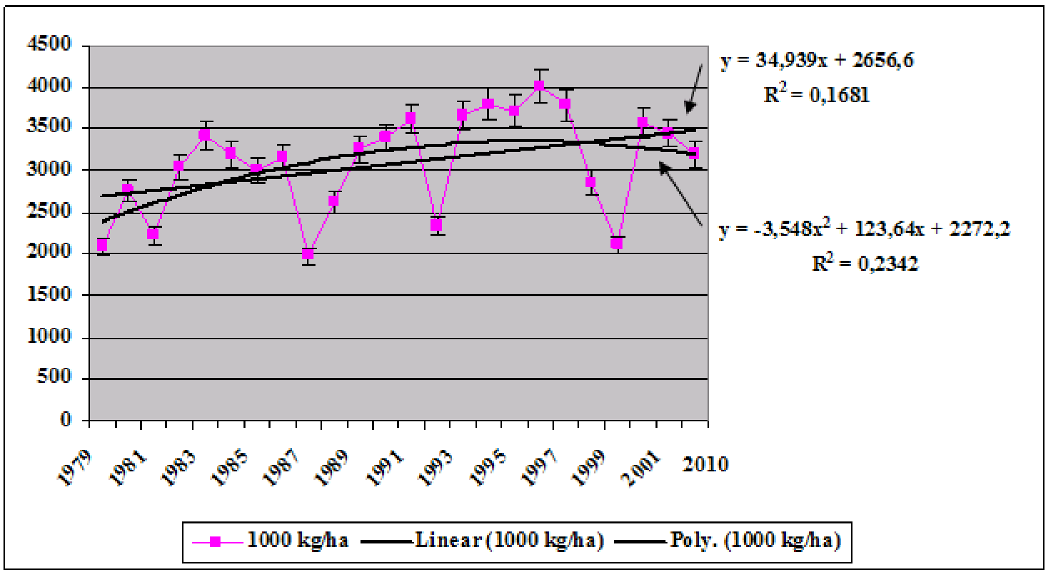

Figure 5. Non-potential yield levels (y_b kg ha^{-1}) for a generic high-latitude spring wheat genotype with linear and polynomial trend lines with 95 % confidence intervals (1979-2010) in Finland without elevated CO_2 and temperature effects (MAFF/TIKE 2008, Fingrain 2011).

Both the national wheat cultivation area (ha) and total grain yield production (million kg yr^{-1}) statistics indicate extensive variation between years in the 30 year period (1980-2010).

The total spring wheat cultivation area (ha) in Finland was 180 700 (1975), 96 900 (1980), 152 500 (1990), 88 100 (1995), 109 500 (2000), 151 900 (2002), 172 100 (2006), 166 600 (2007), 193 400 (2008), 199 800 (2009), 188 900 (2010) and 214 000 (2011). The total spring wheat cultivation area increased by 13 % in the 20 year period (1980-2000, MAFF/TIKE 2008) and by 95 % in the 30 year period (1980-2010). In 2011 the total cultivation area exceeded the 200 000 ha level (Fingrain 2011).

The spring wheat total yield production varied annually between 260 (1980) and 800 million kg (2011) in the 1980-2011 period. In 2011 the total spring wheat production exceeded the 800 million kg level (MAFF/TIKE 2008, Fingrain 2011). The total spring wheat grain yield production (million kg yr^{-1}) was 267.6 (1980), 423.5 (1985), 489.5 (1990), 327.0 (1995), 390.8 (2000), 483.9 (2002), 621.4 (2006), 642.4 (2007), 700.5 (2008), 823.3 (2009), 635.9 (2010) and 801.4 (2011).

The total spring wheat production in Finland increased by 46 % in the 20 year period (1980-2000, MAFF/TIKE 2008) and by 138 % in the 30 year period (1980-2010, Fingrain 2011) mainly because of the increase in total cultivation area. In addition, improved plant breeding and cultivation technologies have increased the total spring wheat production through increased average yield levels. In the 2000-2010 decade, the average national spring wheat total production stabilized above 600 million kg level ($\bar{x}$ 614 million kg, S_d ± 141 Mkg yr^{-1}) with extensive variation between years and Agricultural Advisory Centres in growing zones I-III in southern Finland (Figure 7A, Appendix 1, Fingrain 2011).

DISCUSSION

Implications from the CERES-Wheat modeling results vs. OTC crop physiological results

In Publication I both the simulation results with the CERES-Wheat crop model (Ritchie & Otter 1985, Jones *et al.* 2003) and the spring wheat crop physiological measurements from the Open Top Chamber (OTC, Hakala 1998a,b) experiments with wheat genotypes grown both in current ambient and in elevated temperature×CO_2 growing conditions were compared and evaluated.

The benefit of using the well calibrated CERES-Wheat crop model with the MTT Agrifood Research Finland official variety trial data for HiL and MidE spring wheat genotypes, was its capability to simulate intermediate temperature×CO_2 covariance levels lacking in the OTC measured crop physiological results with only pre-defined combinations of temperature×CO_2 covariances set initially in the OTC experiment design.

Previously Boote *et al.* (2001) and de la Vega *et al.* (2002) emphasized the benefits of applying both statistical and dynamic, mechanistic crop models for Donald's ideotype evaluation (Donald 1968). Dynamic mechanistic crop models (France and Thornley 1984, Thornley and Johnson 1989, Table 5) used in plant breeding should be both dynamic, varying over edaphic and weather conditions and mechanistic simulating physiological processes like phenological development, soil processes, source-sink relationships and translocation of assimilates. According to Boote *et al.* (2001), crop models simulate genetic improvement and variability within a species by evaluating intracultivar variation and how crop models can be used to hypothesize ideotypes for specific growing environments.

In our study (Publication I) simulation results with the CERES-Wheat model indicated that when the diurnal mean temperature increased by +3 °C, the grain yield of *cv*. Polkka (HiL_{Old80}) was reduced to 57 % (59 % *cv*. Nandu, $MidE_{New90}$) when compared with the reference levels (100%). In controlled OTC experiments (1992-1993) yield reduction was only recorded for *cv*. Polkka (to 91 %). Surprisingly with *cv.* Nandu ($MidE_{New90}$) the yield increased to 147 % contrary to modeling expectations, implying the potential 'chamber effect' (Hakala 1998b). However, the OTC crop physiology results for *cv*. Nandu were for a single year only (1992) and can be considered only indicative.

Both the CERES-Wheat *potential* and *non-potential* models underestimated the potential ($y_{pot(OTC,HiL,MidE)}$, kg ha^{-1}) and non-potential ($y_{b(OTC,HiL,MidE)}$, kg ha^{-1}) grain yield under elevated temperature conditions versus observed mean grain yield levels from the OTC experiments (Hakala 1998a, 1998b), implying that the phenological submodel terminated the grain-filling phase too early in the generative phase. 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 sub-optimal, non-limited growing conditions.

When evaluating the error variation in the CERES-Wheat modeling results, the sensitivity analysis results (with genotype×environment aggregation level in Table 5, France & Thornley 1984, Thornley & Johnson 1989) from the publication I indicated, that the CERES-Wheat crop model was sensitive to small (< 20 %, CO_2 400 ppm, +2 ºC) concurrent mean temperature (Kuiper 1993) and atmospheric CO_2 concentration changes (Goudriaan *et al.* 1985, Goudriaan 1993) when simulating both the potential ($y_{pot(OTC,HiL,MidE)}$, kg ha^{-1}) and non-potential ($y_{b(OTC,HiL,MidE)}$) grain yield estimations for high yielding HiL (*cv.* Polkka, HiL_{Old80}, Publication II) and MidE (*cv.* Nandu, $MidE_{New90}$) genotypes.

The CERES-Wheat, using the calibrated genetic coefficients for high yielding HiL and MidE genotypes (Publication I), overestimated both potential and non-potential grain yield levels in conjunction with small CO_2×temperature covariance changes when compared with the corresponding measured yield levels in OTC experiments.

The sensitivity analysis results imply that the CERES-Wheat internal subroutines (Weir *et al.* 1984, Hanks & Ritchie 1991, Hodges 1991) controlling phenological development, photosynthesis, plant respiration, translocation of assimilates and grain yield response functions were unable to response to small non-linear CO_2×temperature covariant changes.

When comparing and analyzing the simulated CERES-Wheat crop modeling results with the measured OTC crop physiological results, several publications have critically reviewed problems with the data from OTC experiments, and also with the validation results of crop simulation models with CO_2 and O_3 (ozone) data from OTC experiments (van Oijen and Ewert 1999 using spring wheat *cv.* Minaret). Van Oijen *et al*. (1999) suggested that OTC experiments might overestimate the effects of rising CO_2 with spring wheat genotypes.

McLeod & Long (1999) reviewed FACE (*Free-air CO_2 Enrichment*) experiments incorporating different crops stating that FACE results indicated significant yield level increases with wheat, cotton (*Gossypium hirsutum* L.) and pasture crops. However, some of these increases are less than suggested by OTC chamber experiments. In general the OTC results are influenced by the '*chamber effect*', caused by differences in energy balance and water relations inside the OTC chambers, potentially modifying the response of vegetation to elevated CO_2 conditions. Kimball *et al.* (2002) reviewed the responses of agricultural crops from the free-air CO_2 FACE experiments grown in more natural growing conditions vs. corresponding OTC experimental results and concluded that elevated CO_2 increased photosynthesis, biomass and yield substantially in C_3 species, but not significantly in C_4 species (e.g. maize). Elevated CO_2 decreased stomatal conductance in both C_3 and C_4 species and improved water-use efficiency (WUE) in all crops. Tubiello *et al*. (1999) and Ewert *et al.* (1999) published revised modeling results (CERES-Wheat) with CO_2 and ozone (O_3) FACE data for spring wheat growth and development at different sites in Europe.

The SatPhenClass classification accuracy results

In publications III and IV, the optical and microwave satellites data (minimum datasets) were phenologically pre-classified with the SatPhenClass classification algorithm (Figure 1). When evaluating the internal error variation with the SatPhenClass phenological classification algorithm in Publications III-IV on large areas, at the farm field parcel aggregation level (Table 5), the SatPhenClass *classification accuracy* for spring cereals varied between 61% and 89% in phenological classes (a_p-d_p, κ Kappa range 0.60 - 0.87) in non-potential growing conditions when using both optical and SAR microwave composite data. Especially the early vegetative phase before *double-ridge* induction (a_p) and post-harvest senescence (d_p) phases were major source for error variation, decreasing the overall classification accuracy. The highest classification accuracies (>80%) were obtained during the anthesis (b_p) near the LAI maximum proximity.

Recently McNairn *et al.* (2008) reported results obtained in Canadian prairie growing conditions that the composite VV-VH SAR combined with the optical data to be the most suitable for red hard wheat, maize and soybean (*Glycine max* L.) classification with over 85% overall accuracy (κ Kappa range 0.47–0.89). McNairn *et al.* (2008) applied three primary classification methodologies *Neural Networks*, *Gaussian Maximum-Likelihood Classifier* and *Decision trees* for crop classification using composite SAR and optical data.

The Optical and SAR Phenological Spectral Signature profile (SSPph) results

In publications III and IV, the optical (SSP_{phOpt})and SAR phenological Spectral Signature profile (SSP_{phSAR}) analysis for spring cereals provide a new promising technique in future remote sensing campaigns for the identification of spring cereals from optical and microwave satellite images during the growing season. In addition, the optical and SAR Spectral Signature Profiles can potentially be applied for the detection of plant stress growing conditions (drought periods, fertilization (N) deficiencies, pests and diseases) in different phenological phases (a_p,b_p,c_p,d_p) by detecting abnormalities and deviations from the standardized Spectral Signature profiles for spring cereals (McNairn *et al.* 2008).

When analyzing the optical Phenological Spectral Signature Profile (SSPphOpt) variation in publications III and IV, the spring cereal infrared (ρRED/Rf_3) and near infrared (ρNIR/Rf_4) reflectance values were higher in June (phenological phase bp) and July (c_p) when compared with May values (a_p).

The infrared Rf_3 signal obtained low reflectance values (b_p) with spring cereal cultivars in June with high PAR-radiation absorbance in fully closed canopies (LAI > 1). Usually in Finnish long day growing conditions the maximum LAI (LAImax) and also the maximum photosynthetic capacity is observed in June (b_p). Correspondingly maximum Rf_3 reflectance values peaked in July (c_p) for spring cereal cultivars. The near-infrared Rf_4 signal peaked in June (b_p) with lower mean reflectance in July.

Cereal *flag leaf* (L_7, Peltonen-Sainio *et al.* 2005) and the 2nd uppermost leaf (L_6) below head contain Chlorophyll A with spectral *absorption maximums* at 460 and 680 nm and Chlorophyll B at 480 and 650 nm overlapping with Landsat/TM and SPOT/HRV2 infrared (Rf_3, λ= 630-690 nm) and near infrared (Rf_4, λ=760-900 nm) sensory bandwidths respectively (Figure 4, Tables 1,8, Scurlock & Prince 1993).

The spring cereal VGI indices derived from reflectance values (NDVI, GEMI, PARND) in June (b_p) and July (c_p) were generally higher than the corresponding May values (a_p). Currently in southern Finland the sowing of spring cereals occurs in May, and May indices values were low, denoting sparse vegetation and canopy cover. A significant reflectance peak was observed in vegetation indices between May and June values.

When analyzing the microwave based SAR phenological Spectral Signature Profiles (SSP_{phSAR}) in publications III and IV, both the soil type and soil×cereal canopy covariances expressed extensive variation with SAR backscattering signal (σ^0) on sand and clay type soils, which were dominant in experimental areas in growing zones I–IV (Figure 3, Figure 7, Appendix 1).

Both the SAR backscattering (σ^0) signal and SAR and NDVI baseline yield (y_{bSat}) levels in Composite Multispectral models (CMM, model III in publication III and model VI in publication IV) models varied significantly both in cereal *soil*species* and *species*canopy* covariance categories. In the *species*soil* covariance category the SAR backscattering signal varied significantly, especially on clay type soils with minor fractions of sand, silt and organic mold in the Porvoo, Mellilä, Kirkkonummi, Jokioinen and Lapua experimental areas.

With spring wheat cultivars, the VH cross-polarization amplitude was higher when compared with VV vertical levels both in anthesis (c_p) and full maturity (d_p) on clay and sandy soils. The wheat horizontal signal (HH) amplitude was higher in c_p phase compared with d_p.

In the *species*canopy* covariance category level there was significant variation both in backscattering amplitude and polarization properties between spring wheat, barley and oats. Especially the canopy structure of oat differs morphologically from other spring cereals. Oat, with a more *planophile* canopy and *panicle* inflorescence structures, differs in polarization properties from wheat and barley, with more *erectophile* head and canopy structures.

The optical VGI modeling results for non-potential baseline yield ($y_{b(Sat)}$) estimations in large area conditions

In publication IV (Kuittinen *et al.* 1998), the optical *VGI Composite modeling* results for spring cereals suggest that the best VGI model for HiL and MidE spring wheat cultivars in large area farm level yield estimations was NDVI based VGI model (Model II in publication IV) using phenologically classified (SatPhenClass) and harmonized Landsat/TM and SPOT/HRV2 data.

When analyzing the accuracy of the optical Model II (Table 5, large area, field parcel aggregation level), the modeling results indicated that with HiL and MidE spring wheat cultivars the Model II overall accuracy was significant (R^2 0.737).

The *Time Series Analysis* results suggest that when using the 1990–1997 optical validation data from growing zones I–IV that the VGI simulated non-potential spring wheat baseline yield levels ($y_{b(Sat)}$, Figure 1) in Zone I were below the MAFF averaged stratum sampling levels in 1990 but above in 1994. In Zone II the VGI simulated spring wheat non-potential baseline yield levels ($y_{b(SAT)}$) were above the MAFF stratum levels in 1994 and 1995. In the averaged Zone III/IV the VGI spring wheat non-potential baseline yield levels ($y_{b(Sat)}$) were below the averaged MAFF stratum sampling levels.

In summary, both the VGI modeling results and Time Series validation analysis results (1990-1997) for spring wheat yields in growing zones I–IV indicated varying non-potential baseline yield levels ($y_{b(Sat)}$, kg ha^{-1}, Figure 1) between years and experimental locations with optimized VGI models when compared with annual MAFF stratum yield sampling estimates. The overall VGI based mean non-potential baseline yield level ($y_{b(Sat)}$ kg ha^{-1}) was 4240 kg ha^{-1}, (RMSE 297 kg ha^{-1}, Figure 1) in large area farm level yield estimations (Table 5, field parcel aggregation level) for HiL and MidE spring wheat cultivars grown on different soil types in growing zones I–IV (Figure 7, Appendix 1).

The Composite Multispectral ASAR/SAR & NDVI (CMM) modeling results for non-potential baseline yield ($y_{b(Sat)}$) estimations in large area conditions

Publication IV presents the optical VGI model *vs.* ASAR/SAR and NDVI Multispectral Composite Model (CMM, Model VI in publication IV) validation results in the Etelä-Pohjanmaa Agricultural Advisory Centre, which indicated varying non-potential baseline yield results ($y_{b(Sat)}$, Figure 1) between the modeled *vs.* observed MAFF inventory sampling statistics in growing zones I-IV (Figure 3, Figure 7, Appendix 1).

When analyzing the accuracy of the CMM model predictions in large area farm level yield estimations (Table 5, field parcel aggregation level), the Composite Multispectral Model (CMM) validation results indicated that the R^2 accuracy tends to stabilize on the 60–70% level similarly to optical VGI models. The *Composite Multispectral models* (CMM) combined with the SatPhenClass phenological classification algorithm for spring cereals provides a promising integrating technique for combining both microwave SAR/ASAR and optical reflectance data. The Composite Multispectral model takes into account with spring cereals both the pre-anthesis phenological phases (a_p, b_p) using the NDVI component and post-anthesis and senescence phases (c_p, d_p) using the SAR component with backscattering polarization levels. In addition, the Composite Multispectral Model can be used in assessing the *soil*canopy* covariances between cereal canopies and soil top layers on different soil types.

With ENVISAT/ASAR sensory data, the CMM model overestimated the MAFF averaged stratum yield estimates for HiL and MidE spring wheat cultivars in growing zones III-IV. Respectively the CMM model overestimated the SAR/Radarsat and SAR/ERS HiL and MidE spring wheat averaged yield levels when compared with the MAFF annual averaged inventory estimates measured at farm level.

The ASAR/SAR and NDVI composite CMM model mean yield accuracy for wheat grain yield was 0.61 (R^2) and RMSE 402 kg ha^{-1} using both phenologically classified reflectance and backscattering data when compared with the MAFF annual averaged inventory statistics. With Envisat and Radarsat composite CMM models, the inclusion of both ASAR/SAR and the NDVI components increased the overall accuracy from the 60% to the 70% level.

The Composite Multispectral Model (CMM) validation results for wheat final grain yield ($y_{b(Sat)}$, kg ha^{-1}) indicated that the use of the Envisat ASAR additional cross-polarization component (VH) did not increase the R^2 level compared to ERS (VV) and Radarsat (HH) with only one polarization level in the 5.3 GHz measurement spectrum.

The NDVI optical model (Model II, publication IV) overall accuracy (R^2) with spring wheat non-potential yield ($yb_{(Sat)}$) was 0.73 (RMSE 297 kg ha^{-1}), when compared with the MAFF averaged inventory sampling estimates. Respectively with the composite

CMM model, the overall accuracy with spring wheat non-potential yield ($yb_{(Sat)}$) was 0.72 (RMSE 302 kg ha^{-1}). With the composite SAR/Radarsat and NDVI CMM model, the overall accuracy with spring wheat non-potential yield ($yb_{(Sat)}$) was 0.73 (RMSE 300 kg ha^{-1}) when compared with the MAFF averaged inventory sampling estimates.

In summary, the Envisat and Radarsat CMM validation results from Publication IV suggest the inclusion of the horizontal polarization component (HH) in the NDVI & SAR/ASAR CMM composite models, thus increasing the overall accuracy of the composite CMM models. The overall mean NDVI & ASAR/SAR CMM model non-potential baseline yield level ($yb_{(Sat)}$, kg ha^{-1}, Figure 1) was 4170 kg ha^{-1} for HiL and MidE spring wheat cultivars in large area farm level yield estimations (Table 5, field parcel aggregation level) in growing zones I–IV (Figure 7, Appendix 1).

Soil×cereal canopy covariances modeling results using optical VGI and multispectral CMM models

In publications III and IV, the spring cereal spatial error variation between cultivars grown in different soil types on farm field parcel aggregation level (Table 5) was evaluated with the optical Vegetation Indices (VGI, models I-II in publication III and models I-V in publication IV) and Composite Multispectral ASAR/SAR & NDVI (CMM, model III in publication III and model VI in publication IV) models. Both the VGI and CMM models indicated an extensive error variation between spring cereals when the non-potential baseline yield levels ($y_{b(Sat,\ HiL,MidE)}$) were estimated for spring cereals cultivars grown in clay, sandy clay, silt and organic soil types in non-potential growing conditions.

The VGI and CMM models suggested the mean RMSE (Root Mean Square Error) error value of 9.1 % for spring cereals (mean $y_{b(Sat,\ HiL,MidE)}$ 3950 kg ha^{-1}, R^2 0.630) and more specifically an estimation error of 6.6 % for spring wheat cultivars (mean $y_{b(Sat,\ HiL,MidE)}$ 4240 kg ha^{-1}, R^2 0.764) grown in actual non-potential field conditions on farm level in southern Finland and in the Gulf of Bothnia region in growing zones I-IV (Figure 3, Figure 7, Appendix 1).

In publication IV the results for the *soil*×*species*, *soil*×*cultivar* and *cultivar*×*canopy* covariances using both the optical and microwave SAR data are reviewed. *Soil*×*canopy* and *soil*×*crop yield* covariances including total evapotranspiration, canopy transpiration through stomatal cavity and evaporation from soil surfaces with remote sensing techniques have been reviewed by Kondratyev *et al.* (1986) and Henderson and Lewis (1997). According to Henderson and Lewis (1997) the vertically oriented components (VV) with cereals, especially the stems, interact effectively with vertically polarized signals resulting in increased backscattering attenuation.

The optical reflectance and microwave backscattering measured by satellite sensors contain combined interacting signals reflected from soil cover and vegetation canopies, varying with spring cereal phenological development (a_p-d_p) during the growing season. In spring time before cereal sowing in May, the bare soil reflectance dominates the reflectance signal. Soil optical *reflectance fraction* is reduced by germinating cereal tillers developing gradually into full canopy coverage and closure (LAI > 1) between heading and anthesis with maximum LAI values (LAI_{max}>4). Currently spring cereal sowing in southern Finland generally occurs at the beginning of May. In May most of the soil for spring cereal cultivations is a mixture of bare soil combined with germinating and emerging spring cereals. Thus the soil component absorbance is high compared with combined reflectance and albedo.

The optical Infrared modeling results in southern Finland were especially affected by the *soil*canopy* interactions in the beginning of the growing season (a_p, May, BBCH 0–12) when the soil is only partly covered by emerging spring cereal canopies. Because of this *infrared*, *near infrared* and also Landsat Thermal Infrared (λ = 10.4–12.5 µm) reflectance values are close to zero ranging between 0.010 and 0.020 at *species* and *cultivar* level.

The optical Infrared VGI calibration results in the soil (clay)*species covariance category indicated that the *non-potential baseline yield* ($y_{b(SAT)}$, Figure 1) response was 4240 kg ha^{-1} for spring wheat with high R^2 (0.764) and 4420 kg ha^{-1} for barley with low R^2 (0.166) on cultivars grown on clay type soils when compared with measured MTT Agrifood Official Variety trial results in growing zones I-IV (Figure 7, Appendix 1).

In general, the results indicated a significantly better polynomial fit for spring wheat cultivars on clay type soils. The more detailed *soil*cultivar* covariance calibration for spring cereals with clay type soils indicated a low R^2, varying between 0.089 and 0.144. The optical *covariance validation* results with non-potential VGI Infrared models indicated an underestimated yield difference between −8.2% and −9.5% in *soil*species* category and between −10.1 and −44.9% in soil*cultivar category. In both categories the Infrared models underestimated the spring wheat and barley yield levels compared with corresponding MTT Agrifood Official Variety trial yield levels grown under more optimal non-limiting growing conditions in growing zones I-IV (Figure 7, Appendix 1).

On more detailed *soil*species* and *soil*cultivar* level the Infrared models underestimated the baseline yield levels compared with the corresponding observed MTT yield levels. Especially the spring wheat *cv.* Satu yield level on clay type soils was clearly underestimated (–44.9%).

The combined *cultivar*canopy* covariance results from both VGI optical modeling results (stages a_p - c_p) from SAR backscattering analysis and *Composite multispectral* (CMM) modeling results (stages c_p - d_p), indicate specific morphological differences in canopy structure between different spring cereal species. Oat cultivars with more *planophile* leaf and canopy structure (*i.e*., leaves aligned perpendicular to the plane of incident light and PAR-radiation) and *panicle* inflorescence differ both in optical PAR spectrum and also with SAR polarization properties from those of wheat and barley with more *erectophile* head and canopy structures. With *planophile* crops, flag leaf (L_7) and upper canopy structure are more perpendicular to incoming PAR-radiation. The *planophile* canopy structure is affected by mutual shading attenuating lower canopy photosynthesis (Henderson & Lewis 1997, Kuittinen *et al.* 1998, Karjalainen *et al.* 2008, Karjalainen 2010).

Modeling results using optical VGI (Vegetation Indices) and CMM (Composite Multispectral) models combined with optical and microwave SAR data in publications III and IV indicated that both the soil type and soil×cereal canopy covariances expressed extensive variation with SAR backscattering signal (σ^0) on clay type soils, which were dominant in experimental areas in zones I–IV (Figure 3, Figure 7, App. 1).

On sandy clay soils the HUTSCAT backscattering signal (σ^0) varied between -6 dB and -29 dB. On fine and coarse sands the Envisat and ERS SAR signal amplitude varied between -17 dB (Envisat in VV, VH dual polarization mode) and -8 dB (ERS) respectively. In the Porvoo experimental area the topsoil (5–10 cm) and the subsoil (<10 cm) consisted of fine and coarse sandy *alluvium deposits* from the Porvoo river and gyttja clays containing minor fractions of organic compounds (mold, peat and mud) and silt. In Lapua and Seinäjoki areas the major soil type was sandy clay with minor fractions of organic mold and humus fractions.

The SAR backscattering signals indicated extensive *topsoil*cereal canopy layer covariance* interaction, especially after the anthesis (phenological stage c_p) and during grain filling, yellow ripening and canopy senescence (d_P).

Implications from the non-limited, potential (y_{pot}) and non-potential baseline (y_b) yield modeling results with HiL and MidE Ideotype profiles

In publication I the averaged (1994-1996) CERES-Wheat non-potential baseline yield estimate $y_{b(OTC, HiL)}$ for a generic HiL genotype (ref. *cv.* Polkka) without the concurrent elevated CO_2×temperature covariant effect was 4490 kg ha^{-1} , the non-limited, potential yield estimate $y_{pot(OTC, HiL)}$ was 6160 kg ha^{-1} (Figure 1, Dataset IV, Tables 1,4). The averaged observed, non-limited HiL yield (Ref. *cv.* Polkka) from OTC experiments was 5470 kg ha^{-1} (Hakala 1998a,b, Laurila 2001). The corresponding averaged (1992-1993) non-potential baseline yield estimate $y_{b(OTC, MidE)}$ for a generic MidE genotype (ref. *cv.* Nandu) was 4370 kg ha^{-1}, the potential yield estimate $y_{pot(OTC, MidE)}$ was 5330 kg ha^{-1}(Laurila 1995).

In publication II the averaged (1978-2005) Ideotype profile ($ItPrf_{HiLNew90}$) non-potential baseline yield estimate $y_{b(ItPrf,HiLNew90)}$ for a generic HiL_{New90} high yielding genotype was 4616 kg ha^{-1} without the concurrent elevated CO_2×temperature covariant effect (Dataset I, Tables 1,4, Figure 1). The corresponding averaged (1978-2005) non-potential baseline yield estimate $y_{b(ItPrf, MidENew90)}$ for a generic $MidE_{New90}$ genotype was 4755 kg ha^{-1}.

In publications III and IV the averaged (1985-2005) VGI-model based non-potential baseline yield estimate $y_{b(Sat, HiL,MidE)}$ for a combined HiL and MidE generic genotype without the concurrent elevated CO_2×temperature covariant effect was 4240 kg ha^{-1} (R^2 0.764, RMSE 6.65 %, Datasets VIII-IX , Tables 1,4, Figure 1).

When summing up the modeling results for new high yielding HiL and MidE generic ideotypes without the concurrent elevated CO_2×temperature covariant effect from publications I-IV (Figure 1), the potential, non-limited $y_{pot(OTC, HiL)}$ was 6160 kg ha^{-1} (Ref. *cv.* Polkka) and the $y_{pot(OTC, MidE)}$ was 5330 kg ha^{-1} (Ref. *cv.* Nandu, Publication I, Laurila 1995, 2001). Respectively the averaged non-potential, limited baseline yield estimate $y_{b(HiL)}$ was 4450 kg ha^{-1} (S_d ±190 kg ha^{-1}) and the averaged $y_{b(MidE)}$ was 4460 kg ha^{-1} (S_d ±270 kg ha^{-1}, Publications I-IV, Laurila 1995, 2001, 2010a,b).

Strategies for future spring wheat breeding programs and cultivation practices

The theoretical spring wheat ideotype concept was defined by Donald (1968) as the optimal wheat genotype with a maximum potential for grain yield production under optimal growing conditions. The modeling results from publication II, using Ideotype, Cultivation value, Mixed and Path analyses suggest that significant yield component factors for high yielding mid-European (MidE) and high-latitude (HiL) ideotypes were maximum number of grains/ear, maximum spikelets/ear, maximum ear-bearing stems in August (m^2)/ emerged seedlings after sowing (m^2), maximum 1000 grain weight and maximum HI. These modeling results seem to be in accordance with the *a priori* hypothesis emphasizing the important role of the flag leaf in defining the final grain yield. The modeling results from publication II indicated that particularly the flag leaf dry-weight and the flag leaf area in the generative phase might be indicators for detecting and evaluating potentially high-yielding cultivars.

In Finland Peltonen-Sainio *et al.* (2005), Peltonen-Sainio & Rajala (2007) and Peltonen-Sainio (2013, personal communication) suggested a detailed cereal leaf development order and nomenclature (L_1-L_7) starting from the emergence of the *cotyledon* leaf (L_1), followed by the first actual growing leaf (L_2), both leaves with initial photosynthetic capacity, until the development of the second highest leaf (L_6) and the *flag leaf* (L_7, highest leaf) below the head. In Finnish long day growing conditions cereals differentiate six or seven leaves in the main stem. Previously Ledent (1979) and Gent & Kiyomoto (1985) reported the crucial roles of wheat flag leaf (L_7) and the second highest leaf (L_6) on yield formation.

Both new high-latitude and mid-European spring wheat genotypes introduced into cultivation after the 1990s have significantly higher yielding capacity compared with cultivars introduced earlier, more specifically a general trend of breaking the average 5 t ha^{-1} baseline barrier was observed in the modeling results.

Finnish plant breeders (Boreal 2008, Peltonen *et al.* 1990) suggest that new high yielding spring wheat cultivars should take account of breeding objectives such as good baking quality with high protein content and quality, high falling number and high yield potential with high 1000 kernel weight and test weight. New cultivars should be lodging resistant and should also serve the starch and fodder industries.

The climate change scenarios for Finland (SILMU 1996, Carter 2004, Carter *et al.* 2004) have indicated the possibility of the emergence of new pathogens because of elevated temperature levels during the growing season. In Finland spring wheat cultivars are susceptible to plant diseases and pathogens like powdery mildew (*Blumerella graminis*). According to MTT Agrifood Research Finland official variety trials (1995-2005) conducted under current ambient temperature and CO_2 growing conditions, the mid-European cultivar Nandu ($MidE_{New90}$) and high-latitude Polkka (HiL_{Old80}) were not significantly susceptible to pathogens in field trials (Kangas *et al.* 2002, 2006). These field experiment results indicate the importance of resistance breeding against pathogens for new cultivars to be introduced for cultivation in the 21st century because climate change scenarios suggest milder winters and earlier sowing dates in the spring for high-latitude growing conditions. New pathogens might immigrate from lower latitudes, overcoming the cold and frost barrier in the winter that currently hinders invasion of new pathogens into northern latitudes. New dihaploid breeding methods reduce breeding time of spring wheat varieties by between 4 and 5 years, and new biotechnology techniques and gene mapping will be important tools for breeding varieties resistant to pests and pathogens (Boreal 2008), such as the *cv.* Mahti (Borealis, Jo.) introduced in 1995 for cultivation, which currently represents ca. 15 % of the total spring wheat cultivation area in Finland (MAFF 2007, MAFF/TIKE 2008) and is very resistant to stripe rust (*Puccinia striiformis*) (Kangas *et al.* 2002, 2006).

In publication II, preliminary considerations were evaluated for optimal high yielding HiL and MidE spring wheat ideotype profiles (ItPrf) with adaptation for elevated CO_2 and temperature growing conditions. In addition, the ecological cultivation cycle without the application of nitrogen or other fertilizers or herbicides was used as a structural contrast factor in the Mixed covariance analysis. The ecological cultivation methods might diminish nitrogen leaching, also reported from the AFRC-wheat modeling results earlier (Jamieson *et al.* 2000, Porter 1993). The Structural Mixed Covariance modeling results (Publication II) with conventional vs. organic cultivation practices contrast and using high-latitude wheat genotypes suggest that traditionally cultivated crops (herbicide application, chemical fertilizers) had on average a 600 kg ha^{-1} higher yielding capacity compared with genotypes cultivated using organic practices.

In the 21st century a significant part of the spring wheat cultivation area might be under organic and ecological cultivation (Finfood 2008, MAFF 2007, MAFF/TIKE 2008). According to the Ministry of Agriculture and Forestry in Finland (MAFF) scenarios, about 15 % of the total agricultural cultivation area in Finland will consist of organic farming systems by the year 2010. On a European scale the total organic cultivation area is below 2 % (Finfood 2008, Organic-Europe 2008).

Future adaptation strategies using high yielding spring wheat ideotypes

Because of forthcoming climate change, the new high yielding wheat genotypes have to adapt to elevated temperatures and atmospheric CO_2 growing conditions in northern latitudes.

In publication I crop simulation results combined with results from a previous modeling study (Laurila 1995) using the CERES-Wheat crop model (Laurila 2001), Open Top Chamber crop physiological results (Hakala *et al.* 2004) for *cv*. Polkka (HiL_{Old80}) and for cv. Nandu ($MidE_{New90}$) indicated that the concurrent elevated atmospheric CO_2 concentration and elevated diurnal temperature will increase the yield potential of HiL wheat genotypes by 1-6 % and by 4-13 % with MidE wheat genotypes. Badger (1992) stated that wheat ideotypes with optimum high yielding capacity and with adaptation for elevated atmospheric CO_2 concentration should have a fast canopy closure at tillering stage and a long grain filling period with high temperature sum requirements from anthesis to maturity. According to Slafer & Savin (1997) the elevated atmospheric CO_2 concentration (720 ppm) below the CO_2 saturation point (ca. 1000 ppm with C_3 metabolic pathway cereals) did not affect significantly the phyllochron leaf appearance rate (PHINT) or the phenological development in vegetative or generative phases with winter and spring wheat genotypes. The CERES-Wheat crop model takes into account the photoperiodism by using the phenological genetic coefficient P1D, which is linked to PHINT coefficient affecting genotype phyllochron interval and leaf appearance rate (Jones *et al.* 2003).

In Publication I, the internal error evaluation results for the CERES-Wheat crop model using dynamic, mechanistic simulation model classification after France & Thornley (1984) and Thornley & Johnson (1989) on genotype×environment aggregation level (Table 5) is reviewed in the previous CERES-Wheat modeling results vs. OTC crop physiological results in conjunction with the previous sensitivity analysis results section.

According to Kontturi (1979) and Saarikko (1999) the Effective Temperature Sum (ETS) requirement of 1050 ± 30° degree-days (dd, T_b +5 °C) from sowing to yellow ripening stage is considered adequate for HiL spring wheat genotypes grown in zones I–IV in Finland. According to Peltonen (2010) the new $MidE_{New90}$ genotypes require higher ETS values, exceeding the 1000 dd for full maturity in cultivation zones I-II, e.g. *cv.* Trappe (1052 dd) and *cv.* Picolo (1092 dd). The average ETS requirements with new HiL_{New90} genotypes are for *cv.* Mahti (985 dd), *cv.* Tjalve (996 dd), *cv.* Anniina (962 dd), *cv.* Aino (968 dd).

In publication II, the Mixed structural covariance and Cultivation value results indicated a significant increase in baseline yield (y_b, kg ha^{-1}) trends between new and old genotypes (HiL/MidE $_{Old70, Old80}$ vs. HiL/MidE $_{New90}$). Results indicated that new HiL and MidE genotypes introduced into cultivation after 1990s (HiL/MidE$_{New90}$) have a significantly higher yielding capacity between 9 % and 13 % vs. HiL/MidE $_{Old70, Old80}$ genotypes. Results from the Cultivation value analysis indicated, that especially MidE cultivars belonging to the MidE$_{New90}$ and Elite classes obtained the highest Cultivation value ratings and produced the highest final grain yield levels.

When evaluating the Mixed Structural Covariance model internal error variation in Publication II on genotype×environment aggregation level (Table 5), all the Mixed model contrast category (latitude type, decade of introduction into cultivation, cultivation type and soil type) error estimates (kg ha^{-1}) varied significantly from the mean error estimate over all contrast categories (94.8 kg ha^{-1}) when the non-potential baseline yield level ($y_{b(ItPrf,HiL,MidE)}$ kg ha^{-1}) for a generic ideotype profile (ItPrf) was estimated. The high amplitude of the error variation indicated extensive spring wheat genotype×environment, inter and intra-cultivar variation on experimental field and plot level with growing conditions varying between non-potential, limited and nearly optimal, non-limited conditions.

According to optimal Ideotype profile analysis results obtained in Publication II, the two high yielding ideotype profiles (ItPrf$_{MidE(New90)}$ and ItPrf$_{HiL(New90)}$) with HiL and MidE genotypes introduced into cultivation after 1990's, have significant adaptive yield potential for the future growing conditions with elevated temperature and atmospheric CO_2 growing conditions. The modeling results for generic high yielding ItPrf$_{MidE(New90)}$ and ItPrf$_{HiL(New90)}$ ideotypes indicated that the non-potential baseline yield (y_b, kg ha^{-1}) comparison without the concurrent CO_2×temperature covariance effect yielded the baseline yield difference (Δyb) 140 kg ha^{-1} (+102 %) for ItPrfMidE$_{(New90)}$ vs. ItPrfHiL$_{(New90)}$ (y_b 4620 kg ha^{-1}, 100 %).

When taking into account also the concurrent CO_2×temperature covariance effect $\Delta y_b(CO_{2,700ppm},\Delta T_{,+3°C})$ projected by the year 2100 climate change scenario for southern Finland (Carter 2004), the non-potential average baseline yield change (Δy_b, %) would be 1.035 % (range 1.01-1.06 %) for the generic high yielding ItPrf$_{HiL(New90)}$ ideotype. Correspondingly the average Δy_b change for the generic high yielding ItPrf$_{MidE(New90)}$ ideotype would be 1.085 % (range 1.04-1.13 %).

The modeling results obtained in Publication II with new high yielding MidE and HiL ideotypes (MidE$_{New90}$, HiL$_{New90}$) imply that the mid-European non-potential baseline yield (y_b) would be on average 5150 kg ha^{-1} (+ 108 %) vs. high-latitude ideotypes (y_b 4770 kg ha^{-1}, 100 %) grown under the elevated $CO_{2(700ppm)}$×temperature$_{(+3°C)}$ growing conditions projected by the year 2100 climate change scenario in southern Finland.

Spring wheat modeling results obtained in the ideotype and cultivation value modeling study in Publication II can be utilized when designing and breeding new adapted wheat genotypes with optimal high yielding ideotype profiles (ItPrf) with factors estimating the effects of concurrent elevated CO_2 and temperature levels and photoperiodical daylength effects for agricultural adaptation strategies. Especially the wheat adaptation plasticity (C_a), cultivation certainty (C_c) and cultivation property (C_p) components are important selection factors and criteria when breeding the future wheat ideotypes with high yielding capacity and adaptation for elevated temperatures and CO_2 growing conditions in northern latitudes.

If the concurrent elevated atmospheric CO_2 concentration (700 ppm) and elevated diurnal temperature (+3 ºC) increase is also taken into account in the adaptation strategies, the MidE$_{New90}$ non-potential baseline yield levels (y_b) will be permanently surpassing the 5 t ha^{-1} barrier by 2100 in southern Finland. This barrier surpassing will confirm the hypothesis of transferring high yielding mid-European genotypes to be cultivated in northern high latitudes with adaptation for long day growing conditions, a phenomenon already observed in Publication II and also in current practical wheat cultivation on farm level in southern Finland.

Potential future changes in spring wheat yield levels and national total production

In Figure 6 a simulated linear non-potential baseline grain yield trajectory with an increasing yield trend (y_b kg ha^{-1}, 1985-2100, R^2 0.168, SAS/ETS, SAS 1990) until the year 2100 is depicted for a generic spring wheat genotype without the inclusion of non-linear concurrent elevated CO_2×temperature covariant effect in southern Finland. This theoretical increasing wheat yield trend until the year 2100, also reported previously by Mela & Suvanto (1987), is based on the Ministry of Agriculture and Forestry annual inventory sampling stratums containing the non-potential baseline yield levels (y_b) for both HiL and MidE genotypes (1979-2002) cultivated in Finland (MAFF 2007, MAFF/TIKE 2008, Fingrain 2011). The preceding time series analysis results for spring wheat non-potential yield levels (y_b kg ha^{-1}) in the 1979-2010 period is depicted in Figure 5.

The hypothetical linear trend outlined in Figure 6 suggests that with HiL and MidE genotypes currently in cultivation the long term average annual wheat yield could permanently settle to a level of above 4000 kg ha^{-1} (y_b 3600 kg ha^{-1} 2001-2010), even surpassing the 5 t ha^{-1} barrier in 2050. The linear trend includes also technological progress factors such as advances in new genetic and biotechnological techniques in plant breeding and advances in cultivation technologies like precision farming (CCRS 2008, Staenz 1996, Strachan *et al.* 2008), using new high accuracy GPS satellites for position control, e.g. the new EU-funded GALILEO system (Galileo 2008).

When evaluating the predictability of the linear trend until the year 2100 (as indicated in Table 5 for national aggregation level estimations) depicted in Figure 6 for a non-potential baseline yield level trajectory (y_b kg ha^{-1}), the linear trend is only indicative and highly hypothetical, containing significant internal error component (R^2 only 0.168). In addition, the trend is lacking the non-linear concurrent elevated CO_2 ×temperature covariant effect.

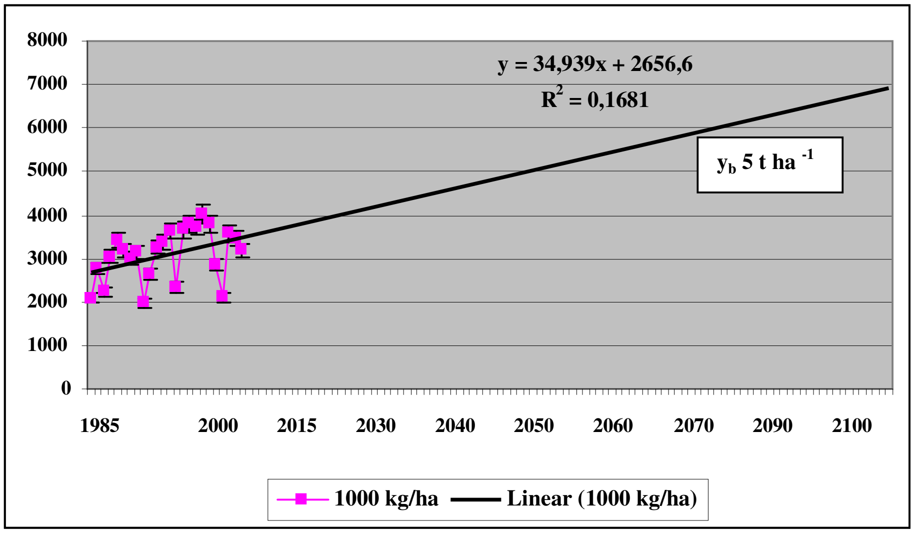

Figure 6. Non-potential baseline yield level trends (y_b, kg ha^{-1}, 1985-2100) for a generic spring wheat genotype in southern Finland as extrapolated with a linear trend line until 2100 (R^2 0.168). The combined non-linear elevated CO_2×temperature covariant effect is excluded from the data. Observed HiL and MidE spring wheat yield data 1979-2006 (MAFF 2007, Fingrain 2011).

The modeling results (publications I, II, Laurila 1995, 2001) and previous OTC crop physiological measurements (Hakala 1998, Saarikko *et al.* 1995, 1996) suggest that the 5 t ha^{-1} non-potential baseline yield (y_b) barrier with new HiL_{new90} and MidE $_{new90}$ cultivars (Table 1) will be surpassed under growing conditions of elevated CO_2 and temperature, which will increase the HiL spring wheat yield potential on average by 1-5 % (9-13 % for MidE high yielding ideotypes) by 2100 in southern Finland.

In publication II the modeling results support the general rising yield trend for HiL and MidE genotypes. The average higher baseline yielding capacity (108 %) with new mid-European ideotypes vs. new high yielding high-latitude ideotypes (100 %) was observed when summing the total net increase between 9 and 13 % with new mid-European cultivars introduced into cultivation after the 1990s (HiL_{New90} and MidE $_{New90}$, Table 1) in southern Finland and providing that the photoperiod effect with new MidE genotypes is not a limiting factor (Saarikko & Carter 1996). However, these simulated yield levels for new generic high yielding mid-European and Nordic high-latitude wheat ideotypes (HiL_{New90}, MidE $_{New90}$) comprise only 50 % of the theoretical maximum yielding capacity level above 10 t ha^{-1} reported by Evans & Wardlaw (1976) and Kivi (1963) for spring wheat genotypes.

In publication II the measured yield results in practical cultivation on farm level in southern Finland (2008-2009) also support the general rising baseline yield (y_b) trend. The average yield levels have been rising steadily from the old 3 t ha^{-1} average level above 5 t ha^{-1} in southern Finland by using new HiL_{New90} and MidE $_{New90}$ genotypes, incorporated with new fertilizer and pesticide practices (Kangas *et al.* 2006, Peltonen 2010). The increase of sowing seed density from 600 seeds m^{-2} to 700 seeds m^{-2} has increased the yield levels by 1 t ha^{-1}. Peltonen (2010) reported promising high yield results in southern Finland using new spring wheat cultivars from the $MidE_{New90}$ category (e.g. *cv.* Quarna ($y_{b(obs.)}$ 4740 kg ha^{-1}), Amaretto ($y_{b(obs.)}$ 5650 kg ha^{-1}), Trappe ($y_{b(obs.)}$ 5980 kg ha^{-1}) and from the HiL_{New90} category from Borealis (*cv.* Marble ($y_{b(obs.)}$ 5120 kg ha^{-1}), Wellamo ($y_{b(obs.)}$ 5120 kg ha^{-1})) and *cv.* Zebra ($y_{b(obs.)}$ 5060 kg ha^{-1}) from Svalöf-Weibull.

When taking into account the simulation and crop physiology experiment results derived from the publications I and IV, an increase in the total wheat production can also be expected providing that the total cultivation area remains at the current national level.

By using the linear extrapolation until the year 2100 (Brezinski and Redivo-Zaglia 1991, Figure 6) and with the inclusion of concurrent CO_2×temperature covariant effect on spring wheat yield potential, it can be projected that by using new high-latitude spring wheat ideotypes with high yielding capacity (HiL_{new90}, publication II), the theoretical total spring wheat production of Finland may increase on average by 5 % (+30 Mkg yr^{-1}, $\Delta TotProd_{(HiLNew90,CO2,TempCov)}$) to 630 million kg annually by 2100 from the current average 600 million kg baseline level as averaged from the 2000-2010 MAFF annual inventory yield levels ($\overline{x}_{(2000\text{-}2010)}$ 614 Mkg, $y_{b(2000\text{-}2010)}$ 3600 kg ha^{-1}, Fingrain 2011). Respectively with the introduction of new high yielding mid-European ideotypes ($MidE_{new90}$, publication II), the annual spring wheat yield production may increase to 660 million kg, i.e. an average 10 per cent increase (+60 Mkg yr^{-1}, $\Delta TotProd_{(MidE90,CO2,TempCov)}$) by the year 2100 and assuming no major changes in current wheat total cultivation area in Finland. However, the national total wheat production varies significantly between years, e.g. in 2011 the total spring wheat production was 800 Mkg, mainly because of the increase in total cultivation area (214 000 ha, $y_{b(2011)}$ 3740 kg $ha^{-1)}$, Fingrain 2011).

CONCLUDING REMARKS

This thesis provides a transect of interdisciplinary tools using crop modeling and satellite-based remote sensing techniques for weighing the negative and positive effects of elevated atmospheric CO_2 and temperature levels for high-latitude cereal production, specifically for spring wheat, during projected climate change in 2050-2100.

In conclusion, the combination of earlier sowing and elevated atmospheric CO_2 (700 ppm) and diurnal temperature (+3 ºC) effects suggests an average net increase of 30 million kg (+ 5 %) annually in total spring wheat yield in Finland by 2100 using new high yielding high-latitude wheat ideotypes and an average increase of 60 million kg (+10 %) with new high yielding mid-European ideotypes, as calculated from the current annual averaged 600 million kg baseline production level, varying significantly between years with changes in wheat total cultivation area in Finland.

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When I consider every thing that grows,
Holds in perfection but a little moment,
That this huge stage presenteth naught but shows,
Whereon the stars in secret influence comment;
When I perceive that men as plants increase,
Cheered and check'd even by the same self sky,
Vaunt in their youthful sap, at height decrease,
And wear their brave state out of memory;
Then the conceit of this inconstant stay,
Sets you most rich in youth before my sight,
Where wasteful Time debateth with Decay,
To change your day of youth to sullied night;
And, all in war with Time, for love of you,
As he takes from you, I engraft you new.

Shall I compare thee to a summer's day?
Thou art more lovely and more temperate;
Rough winds do shake the darling buds of May,
And summer's lease hath too short a date;
Sometimes too hot the eye of heaven shines,
And often is his gold complexion dimm'd;
And every fair from fair sometime declines,
By chance, or nature's changing course, untrimm'd;
But thy eternal summer shall not fade,
Nor loose possession of that fair thou owest;
Nor shall Death brag thou wander'st in his shade,
When in eternal lines to time thou grow'st;
So long as men can breathe, or eyes can see,
So long lives this, and this gives life to thee.

William Shakespeare (1564-1616) - The Midsummer Night's Dream and Sonnets (15, 18) by Burgess & Bowess Ltd., London, 1986

In the beginning, was the Word (Genesis, Book of John).

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APPENDIX 1

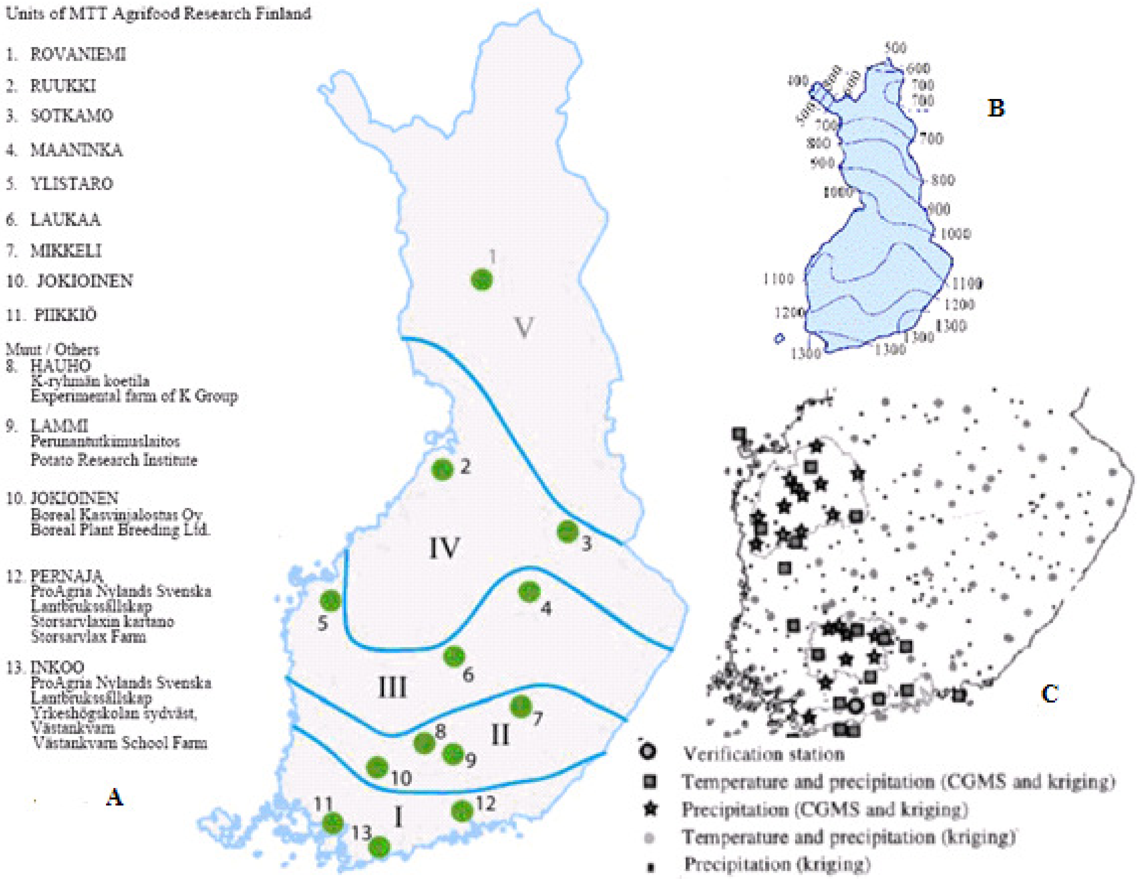

Figure 7. (A) Growing zones (I–V) and MTT Experimental Station locations in Finland, (B) ETS (Tb 5 ºC) cumulative isolines, (C) Meteorological Weather Stations in Finland (© Original Data, MTT Agrifood Research Finland, Finnish Meteorological Institute).

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