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Estimating the development and regional thermal suitability of spring wheat in Finland under climatic warming

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ABSTRACT: Models relating development rate to temperature were used in conjunction with indices of growing season length to evaluate the regional thermal suitability for spring wheat *Triticum aestivum* cultivation in Finland. Thermal suitability was computed using interpolated temperature data for the baseline period 1961–1990 over a regular 10 km grid. Confidence limits of the development model were re-interpreted as spatial uncertainties in modelled suitability. The effects of climatic warming on modelled suitability were investigated by adjusting the baseline temperatures both systematically and according to scenarios of future temperature change. Three main results were obtained: (1) the thermal suitability for spring wheat cultivation could shift northwards by some 160 to 180 km per 1°C increase in mean annual temperature; (2) in regions of present-day suitability, climatic warming shifts the timing of crop development to earlier in the year and shortens the development phases; and (3) the range of predictions of future climate imposes substantially greater uncertainty on estimates of suitability than the uncertainties of the suitability model itself.

KEY WORDS: Crop phenology models · Mapping · Spatial uncertainties · Scenarios

1. INTRODUCTION

Low temperature is a major constraint on the development, growth and yield of cereal crops in high latitude regions such as Finland. Severe winter conditions combined with a short growing season require the use of fast developing cereal cultivars to ensure reliable year-to-year crop maturation. There is a strong dependence of crop development rate on temperature, and this allows zones of thermal suitability to be delimited by matching the temperature requirements for crop maturation to the prevailing thermal climate in different regions. Such zonations are commonly used to advise farmers of the most appropriate regions in which to cultivate different crop cultivars. However, these zonations are only valid if the prevailing climate is assumed to be stationary.

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Climatic warming induced by the enhanced greenhouse effect could lead to substantial changes in growing season length, in crop development rate and, hence, in thermal suitability. One potentially beneficial effect is that crops could complete their life span in regions that are currently unsuitable (e.g. Carter et al. 1991, Kenny et al. 1993, Carter & Saarikko 1995, 1996). Conversely, in zones of current suitability, a temperature increase may truncate important development phases and so reduce yield potential (Nonhebel 1993), or change the timing of developmental events disadvantageously in relation to damaging frosts or drought (Bindi et al. 1993).

Several different models have been proposed to estimate crop development between sowing and fruit maturity and many of them correlate the rate of progress during certain phases to air temperature and daylength (e.g. Robertson 1983, Porter et al. 1987, Roberts et al. 1988, Ritchie 1991). These are statistical-type models, since the physiological processes of crop development are not sufficiently understood for the construction of more mechanistic models. We will demonstrate that statistical models, which are also adopted in this study, can pose problems for interpreting the possible effects of climate change, since they may require the extrapolation of relationships to accommodate the changed conditions.

This paper examines some effects of climatic warming on the regional thermal suitability of spring wheat *Triticum aestivum* L. in Finland. Attention is focused on 3 main aspects: (1) mapping of spring wheat development and thermal suitability in Finland under present-day climate, (2) possible changes in the pattern of thermal suitability under scenarios of future regional climate, and (3) quantification of a number of sources of uncertainty in these projections. Aspects of crop growth and productivity, as distinct from crop development, are outside the scope of the paper. While results with the development model are specific to wheat in Finland, the approach to mapping thermal suitability and issues concerning uncertainty are more generally applicable to other crops and regions.

2. METHODS, MODELS AND SCENARIOS

The thermal suitability of 2 spring wheat cultivars was examined: an early-maturing cultivar (cv.), Ruso (Boreal Plant Breeding, Jokioinen, Finland), and a late-maturing cultivar, Kadett (Svalöf-Weibull, Svalöv, Sweden). Suitability was estimated using a combination of crop development models and growing season indices. These were tested and applied across the whole of Finland and simulations were run for both the present-day (baseline) climate and scenarios of future climate.

2.1. Crop development models. In a previous study, a linear temperature model was found appropriate to explain the development rate of spring cereals during certain phenological phases (sowing to heading, S–H; heading to yellow ripening, H–YR; and sowing to yellow ripening, S–YR). Cultivar-specific models were developed using air temperature and observed phenology data from 14 experimental stations in different parts of Finland during the period 1970–1990 (Saarikko & Carter 1996). The effects of photoperiod and precipitation on development rate were also examined, but found to be negligible. The model relationship can be expressed as follows:

$$r_{ij} = \begin{cases} a + bT_j & \text{if } T_j > T_b \\ 0 & \text{if } T_j \le T_b \end{cases} \quad (1)$$

where r_{ij} is the development rate on day j during phase i (d^{-1}), T_j is the daily mean temperature (°C), T_b is the base temperature (°C) and a and b are parameters. When crop development is predicted, the daily rates are accumulated until the sum exceeds a value of 1 on the last day of the phase:

$$R_i = \sum_{j=1}^{n_i} r_{ij} = 1 \quad (2)$$

where R_i is the development stage at the end of phase i and n_i the number of days taken to complete phase i.

Since daily development cannot be observed in a crop stand, parameter values a and b (Eq. 1) were computed in a linear regression analysis with the mean phasal temperature as the independent variable and the mean development rate of a phase (i.e. the reciprocal of the number of days taken to complete a phase) as the dependent variable (Saarikko & Carter 1996). Fig. 1 illustrates the relationship for the phase S–YR in cv. Ruso.

Also shown in Fig. 1 are the 95% confidence intervals of the regression model (e.g. Zar 1984). The 2 curves closest to the regression line express the 95% confidence limits of the predicted mean phase duration at each temperature, while the 2 outer curves denote the 95% confidence limits of the individual predictions. The confidence intervals are applicable only to the temperature range within which the model was constructed.

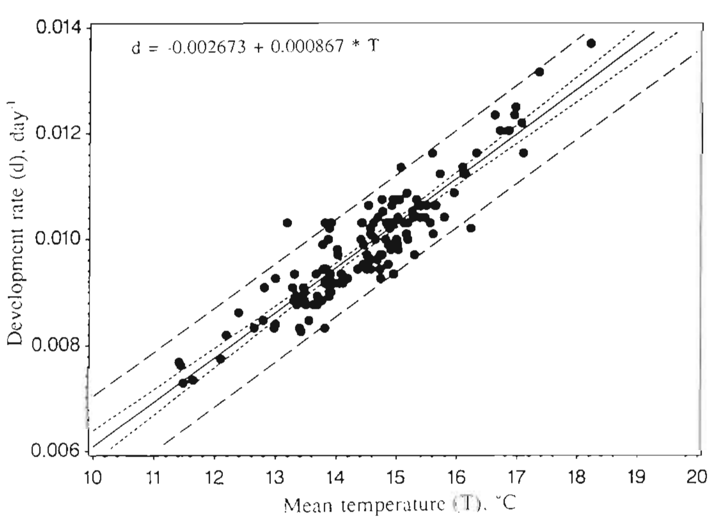

Fig. 1. Relationship between mean development rate (d^{-1}) and mean temperature (°C) in spring wheat cv. Ruso for the sowing to yellow ripening phase. Curves are 95% confidence limits of the mean phasal development rate (----) and of individual observations (– – –). Data source: Official Variety Trials, Agricultural Research Centre of Finland

2.2. Favourable growing season. Before crop development can be estimated at any location, a period with favourable growth conditions needs to be identified. The beginning of that period was specified as the day when smoothed daily mean air temperature exceeds 8°C in the spring, based on sowing date information from experimental sites (Carter & Saarikko 1996). The favourable period is terminated when daily mean air temperature falls below 12°C in the autumn. This autumn cutoff represents roughly a 25% risk of the first occurrence of hard frost, when daily minimum air temperature is below 0°C (Carter & Saarikko 1996).

2.3. Regional crop development and thermal suitability. In order to assess the regional pattern of thermal suitability, the models were applied across a 10 × 10 km regular grid covering Finland (Carter & Saarikko 1996). Monthly mean air temperatures for each year of the baseline period 1961–1990 were interpolated to grid box centres from between 122 and 151 meteorological stations (the exact number depending on the year) by the kriging method. This accounts for the local modifying effects on temperature of mean altitude and proximity to surface waters such as lakes and the Baltic Sea (Henttonen 1991). The accuracy of this procedure, which varies from year to year according to both the number of stations and the weather conditions, can be assessed using the standard error of the predicted temperatures averaged across all grid boxes (Henttonen 1991). This was generally lowest in the early autumn (0.2 to 0.4°C in September) and highest in the winter months (0.3 to 0.9°C in January). However, these mean values disguise a large variation in the standard error geographically, with the highest values (maximum 1.9°C) occurring in upland regions of northwestern Finland, where the station coverage is very poor.

Since the models require daily mean temperature as an input variable, smoothed values were derived from the gridded monthly mean temperatures using a sine curve interpolation method (Brooks 1943). The absence of realistic day-to-day variability in the temperature data has some implications in interpreting the model results, and is discussed further below.

In each 10 km grid box, annual suitability was evaluated by first estimating the favourable growing season duration (i.e. the maximum number of days available for the crop to grow). The mean temperature during this period was computed next, and the regression equation (Fig. 1) used to infer the number of days the crop would require to develop from sowing to yellow ripening at that temperature. A grid box was classified as suitable if the required duration did not exceed the growing season duration. By computing thermal suitability for each year of the baseline period, 30 yr probabilities of successful crop yellow ripening could be estimated.

In addition, the uncertainty of the suitability classification was also evaluated at each grid box by computing the respective crop requirements for development from the 95% confidence intervals about the regression line (cf. Fig. 1). In this way, 2 types of model uncertainty could be expressed spatially: (1) the uncertainty surrounding the mean relationship between temperature and suitability, and (2) the uncertainty surrounding individual predictions of suitability at single locations.

Table 1. Parameters of the development model for the phases sowing-heading (S-H) and sowing-yellow ripening (S-YR)

Variety/phase	T_b (°C)	a (× 10^{-2})	b (× 10^{-2})
Kadett			
S-H	-4.2	0.4492	0.1077
S-YR	2.6	-0.2057	0.0790
Ruso			
S-H	-2.4	0.2885	0.1217
S-YR	3.1	-0.2673	0.0867

Finally, the durations of the S-H and H-YR phases were computed in those grid boxes classified as suitable. Conditions during the S-H phase are known to influence the population density and size of the ear in wheat, while the grain weight is mainly determined during the grain filling period, which is a major part of the H-YR phase (Hay & Walker 1989). Thus, phase durations, and their timing in relation to weather events and light conditions, can have important effects on the harvestable yield.

Durations of the S-H and S-YR phases were simulated using Eqs. (1) & (2) (Table 1). The duration of the H-YR phase was calculated by subtracting the estimated heading date from the estimated yellow ripening date rather than by using a separate model for that phase. This was because the date of yellow ripening is most accurately predicted with a single model starting from sowing (Saarikko & Carter 1996). The effect of a delayed sowing (by 1 wk) on phase durations and thermal suitability was also examined.

2.4. Scenarios of climate change. Thermal suitability was first computed for the baseline climate, using both the 30 yr mean climate and data from each individual year to examine the effects of climatic variability. Next, as a means of testing the sensitivity of suitability zones to changing temperature, baseline temperatures throughout the year were adjusted systematically by +1, +2, +3, +4 and +5°C increments. Subsequently, the analysis was repeated for 2 sets of scenarios of altered temperatures: first, low and high estimates of temperature change for Finland by 2050, accounting for different sources of uncertainty (SILMU scenarios, see below), and second, 2 regional scenarios of temperature change based on outputs from general circulation models (GCMs).

2.4.1. SILMU scenarios: In order to provide an impression of the range of future climate projections for Finland, seasonal scenarios applicable to the whole country were developed as part of the Finnish

Research Programme on Climate Change (SILMU, Carter et al. 1995). These attempt to embrace the range of uncertainty in projections of greenhouse gas emissions and of global climate sensitivity reported by the Intergovernmental Panel on Climate Change (IPCC 1992) by using a set of simple models (MAGICC, Hulme et al. 1995) combined with regional estimates over Finland from coupled ocean-atmosphere GCMs.

Extreme low and high estimates of global temperature change by 2050 were first obtained with MAGICC for the extreme low IPCC emissions scenario IS92c and low climate sensitivity assumption (+1.5°C) and for the respective extreme high emissions scenario IS92f and high climate sensitivity assumption (+4.5°C). Estimates of the cooling effect of sulphate aerosol concentrations, consistent with the emissions scenarios, were also included at a global scale in the simulations with MAGICC. Outputs from 3 transient GCMs (forced with greenhouse gases but not sulphate aerosols) were then used to identify seasonal temperature changes over Finland corresponding to the low and high global temperature change estimates. Changes from the 3 GCMs were averaged to produce the SILMU Low and SILMU High scenarios, giving a range of mean annual warming of between 0.6 and 3.6°C by 2050 (Table 2). The SILMU scenarios therefore provide a range of projections that account for a large part of the global uncertainty (due to emissions and climate sensitivity), but not necessarily encompassing all of the regional uncertainty, which is expressed in the differences between GCM estimates. As such, formal confidence levels cannot be attached to these (or any other) climate change scenarios, but at least the uncertainties they embrace are readily identifiable.

2.4.2. GCM-based transient climatic scenarios: In addition to the SILMU scenarios, which were prepared exclusively for Finland, 2 other scenarios based directly on outputs from GCMs were also adopted. The scenarios were based on transient simulations with 2 coupled ocean-atmosphere models: the United Kingdom Meteorological Office (UKTR, Murphy & Mitchell 1995) and Geophysical Fluid Dynamics Laboratory (GFDL, Manabe et al. 1991) transient experiments. Decadal mean temperature changes relative to the control for Years 66 to 75 of the UKTR simulation (UKTR6675) and Years 55 to 64 of the GFDL simulation (GFDL5564) were used. These decades produced the same global mean warming (1.76°C) in both models. Temperature changes were linearly interpolated to the Finnish 10 km grid from the GCM grid box centres over Finland (15 from the UKTR model and 6 from the GFDL model). More sophisticated methods of statistical downscaling from these GCM outputs to selected locations in Europe are reported elsewhere (Barrow et al. 1996, this issue), but were not applied here given the large number of 10 km grid boxes (3827) over Finland. The baseline climate was adjusted for these scenarios by adding the interpolated monthly temperature changes to the interpolated baseline values. Seasonal and annual scenario temperature changes are shown in Table 2 for sample 10 km grid boxes in southern, central and northern Finland.

The GCM-based scenarios were adopted for 2 reasons: first, to illustrate some of the differences between GCM estimates at the regional and monthly level that are not represented by the SILMU scenarios, and second, to allow comparison with other agricultural impact studies in which the same scenarios were also used as part of a European-wide research project (Harrison et al. 1995). The timing of each scenario depends on various assumptions about future rates of radiative forcing and of climate response, and is different from the timing of the SILMU scenarios.

Table 2. Scenarios of seasonal and annual temperature change relative to 1990 (°C) for the whole of Finland by 2050 (SILMU) and at 3 locations (GCM-based). Site locations are shown in Fig. 2a

Scenario/ site	Spring (MAM)	Summer (JJA)	Autumn (SON)	Winter (DJF)	Year
SILMU Low	0.6	0.45	0.6	0.75	0.6
SILMU High	3.6	2.7	3.6	4.5	3.6
UKTR6675					
Jokioinen	3.6	2.2	2.9	4.4	3.3
Jyväskylä	3.2	2.2	3.2	4.8	3.4
Rovaniemi	2.6	2.3	3.1	4.8	3.2
GFDL5564					
Jokioinen	1.9	2.4	3.4	2.7	2.6
Jyväskylä	1.8	2.4	3.6	2.8	2.6
Rovaniemi	1.2	2.2	3.7	2.4	2.4

3. RESULTS

3.1. Thermal suitability under present-day climate

During the 30 yr of the baseline period 1961–1990 the estimated probability of successful yellow ripening was greatest in southern Finland and declined northwards. The northernmost regions of actual spring wheat cultivation coincide roughly with the 60% probability limit of estimated ripening of cv. Ruso. In this study, a strict limit of 80% probability, i.e. crop failure in no more than 2 years per decade, was adopted to describe thermal suitability, recognizing, however, that some farmers may accept a higher risk and cultivate the crop outside the region of estimated suitability.

Fig. 2a shows the calculated pattern of thermal suitability of both cultivars, Ruso and Kadett, alongside the

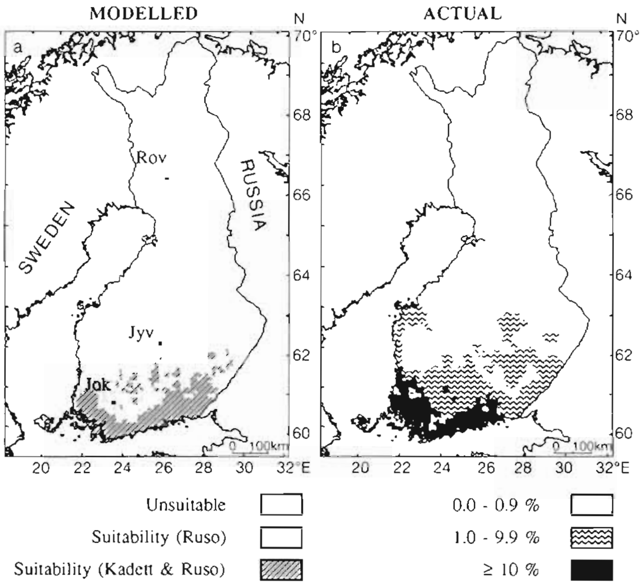

Fig. 2. (a) Modelled thermal suitability (≥80% probability of ripening) of late-maturing (Kadett) and early-maturing (Ruso) spring wheat cultivars under baseline temperatures (1961–1990) in Finland. Sites for which temperature scenarios are given in Table 2 are also shown (Jok = Jokioinen, Jyv = Jyväskylä, Rov = Rovaniemi). (b) Area of spring wheat by commune in 1990 as a percentage of cultivated land. Data source: Finnish Board of Agriculture

actual pattern of spring wheat cultivation in 1990 (Fig. 2b). The 1990 pattern is shown here because this was the year in which a special detailed survey was conducted at the municipality level by the Finnish Board of Agriculture. Its representativeness is supported by annual information at a larger (agricultural district) scale, which indicates that the 1990 pattern of spring wheat cultivation is very similar to other years in the 1980s (National Board of Agriculture various dates). Of course, the actual distribution of spring wheat is influenced by many factors other than temperature, for example moisture conditions, soil type, terrain and land use as well as socioeconomic considerations. It is worth noting, however, that wheat does tend to be cultivated close to its physiological limits in Finland, because its profitability is competitive relative to other cereals if good quality can be assured. For this reason, and with these other caveats in mind, there is some justification in comparing the estimated pattern of thermal suitability with actual patterns.

3.1.1. Model and data uncertainties

The geographical zones of thermal suitability shown in Fig. 2a have associated uncertainty bounds which are based on the confidence limits of the development model (Fig. 1). These too can be expressed geographically for the baseline period by combining assessments from 30 individual years (Fig. 3). On both maps the diagonal stripes represent those regions in which the modelled crop is suitable with greater than 97.5% confidence in at least 24 years, whilst the dark shade depicts the 95% confidence limits. Hence, in regions lying outside the shaded areas, where the crop is designated as not ripening in at least 7 years out of 30, there is a 2.5% probability or less that the crop might actually ripen in one of those 7 years. The confidence range shown in Fig. 3a, demarcating a geographical zone approximately 1 grid box or 10 km in width, represents the uncertainty in the position of the mean limit of thermal suitability. The corresponding range in Fig. 3b (some 180 to 220 km in width) expresses the uncertainty surrounding individual predictions of suitability and is considerably wider than the range shown in Fig. 3a, as would be anticipated from inspection of Fig. 1. In this study the main interest is in estimating average zones of suitability rather than making predictions of suitability for individual grid boxes at specific dates. Thus, the uncertainty bounds of most relevance are those shown in Fig. 3a.

A further potential source of error is the use of smoothed daily temperatures (derived from monthly mean temperatures). This was tested by computing phase durations at experimental sites using both smoothed and observed daily temperatures from sowing. Differences between the 2 methods were very small (less than 1 d). A more important effect of using

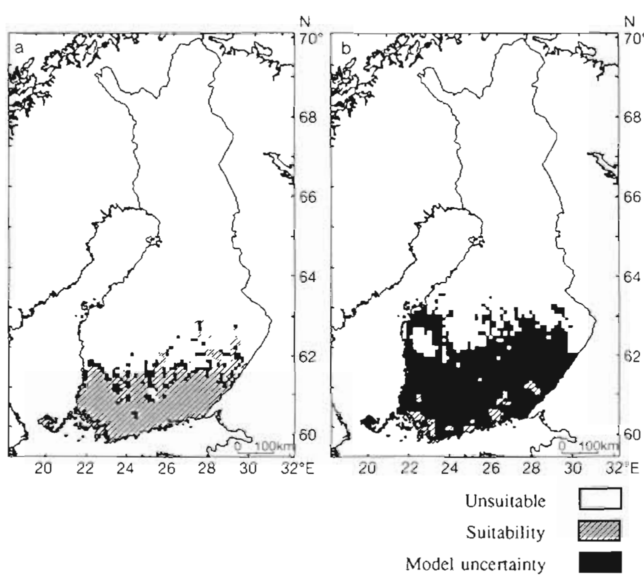

Fig. 3. Spatial uncertainty of modelled thermal suitability for spring wheat cv. Ruso in Finland under baseline temperatures, based on the 95% confidence intervals of the development model for: (a) mean suitability, (b) individual predictions

smoothed temperatures, however, concerns model extrapolation (see below).

3.1.2. Effects of sowing date assumptions

Another source of uncertainty is errors in the indices defining the favourable growing season. Likely errors in the temperature-based index for the end of the growing season were not investigated. Some verification of the sowing date index was obtained by comparing estimated sowing dates with observed dates of onset of sowing by rural districts during 1961–1985 (National Board of Agriculture various dates). The model estimates were 0.4 d late on average (rms error = 6.4 d) with no systematic differences in prediction accuracy between districts, except in some coastal areas where most of the predictions were too late. At a district level, therefore, the predictions appeared to be reasonable under the present-day conditions, even though factors other than mean daily air temperature also affect the optimal date of sowing (e.g. seed bed moisture and temperature, precipitation and frost occurrence). Moreover, under a warmer climate it is plausible to expect the state of the soil to be suitable for sowing earlier than at present, so a temperature-based sowing date index such as this provides a simple way of simulating such a change.

Aside from the prediction error surrounding onset dates for sowing, it should also be noted that in actual farm practice cereal crops are not normally sown at the earliest available date, as modelled, due to farm management decisions unrelated to climate. The sensitivity of mapped thermal suitability to sowing date was examined by estimating the pattern of baseline suitability for cv. Ruso assuming a sowing date delayed by 1 wk relative to the estimated sowing date. The limit of suitability (not presented here) lies some 30 to 50 km south of that shown in Fig. 2a. Since it is common for sowings to be carried out over a period of several weeks, the large magnitude of this sensitivity should not be overlooked. However, for the purposes of this study the use of a fixed criterion for the sowing date is both valid and necessary if other aspects of uncertainty are to be quantified.

The wider spread of the observed sowing dates than those simulated also has subtle implications for interpreting simulated phase durations. The duration of the S–H phase was estimated in most cases to be longer than that of the H–YR phase, in contrast to observations at experimental sites, where both phases were approximately the same in duration. However, delaying the sowing by 1 wk shortens the modelled duration of the S–H phase by approximately 2 to 4 d compared to 0 to 2 d for the H–YR phase, thus reducing the discrepancy between the durations of the 2 phases.

3.2. Model sensitivity to systematic changes in temperature

This section examines the modelled effects of climatic warming on the regional pattern of thermal suitability and on phasal development. To assist in interpreting the results, it is instructive first to consider the effects of warming at a single location.

3.2.1. Warming and crop development

Fig. 4 illustrates the timing of 2 development phases of cv. Ruso under 30-year mean baseline temperatures and under temperatures 4°C above the baseline in a single grid box (Jokioinen, cf. Fig. 2a). One notable effect of warming is to shift the sowing date earlier (by 17 d in this example). As a result, the early period of crop development proceeds in temperatures comparable to the corresponding values in the baseline climate. Hence, although the mean annual climate warms by 4°C, the S–YR phase is completed in a mean temperature that is only 2.1°C warmer than for the baseline. The mean temperature of the S–H phase under the adjusted temperatures is only 0.9°C greater than under baseline conditions. In contrast, the subsequent H–YR phase is subjected to a mean temperature 4.3°C higher than in the baseline. Since another effect of warming is to shorten the duration of development phases, this explains why the duration of the H–YR phase displays a greater sensitivity to climatic warming than the S–H phase (a respective foreshortening of 14 d compared to 3 d in Fig. 4).

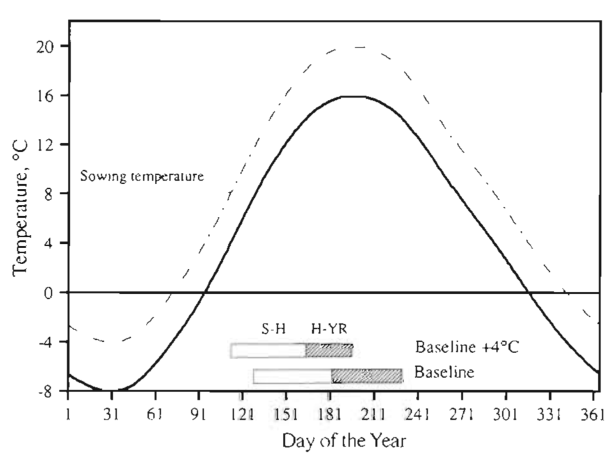

Fig. 4. Modelled phasal development (sowing–heading and heading–yellow ripening) of spring wheat cv. Ruso at Jokioinen grid box under baseline temperatures (mean for 1961–1990) and for a uniform annual warming of 4°C

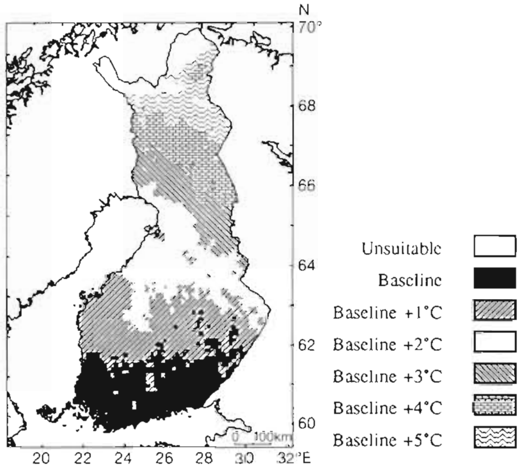

Fig. 5. Shifts in modelled thermal suitability of spring wheat cv. Ruso in Finland under temperature increases of 1, 2, 3, 4, and 5°C relative to the baseline

3.2.2. Spatial shifts in thermal suitability

The effect of an incremental warming on the pattern of thermal suitability (i.e. regions with at least an 80% expectation of successful maturation) for Ruso spring wheat is shown in Fig. 5. Each 1°C of warming induced a northward shift in the limit by, on average, approximately 160 km in the west (along longitude 24° E) and 180 km in the east (longitude 29° E) of Finland. The effect of warming up to 2°C relative to the baseline is more marked in western than in eastern Finland. This probably reflects the combined effects of lower altitude and proximity to the coast in the west. The rate of northward extension for cv. Kadett is broadly similar to that for cv. Ruso.

3.2.3. Changes in phase durations

Durations of the S–H and H–YR phases in the regions of baseline suitability (yellow ripening in at least 24 years) were calculated as the mean of the 24 years with the shortest growing times in each grid box to enable regional comparisons. Since this method accounts for only 80% of all years, mean durations in both phases were approximately 1 d shorter than those computed separately for the 30 yr average climate.

The S–H phase shortened on average by 1 d or less per 1°C increase in annual temperature up to a +5°C warming (Table 3). Shortening of the H–YR phase was greatest under the first 1°C warming (3 to 6 d), progressively diminishing with further temperature increments (Table 3). Regionally, the phasal shortening was greatest near the northern limit of the baseline suitability, where the longest phase durations are found

Table 3. Estimated phase duration (in days) for the baseline climate and shortening under successive 1°C increments of warming with modal values in parentheses

	Sowing-heading	Heading-yellow ripening
Baseline duration	52–55 (53)	42–50 (46)
Shortening for warming between:		
Baseline-1°C	0–2 (1)	3–6 (4)
1–2°C	0–1 (1)	2–4 (4)
2–3°C	0–1 (0)	1–3 (2)
3–4°C	0–1 (1)	1–3 (2)
4–5°C	0–1 (0)	1–2 (1)

under the baseline climate. It is not clear what effect a shortening of the S–H phase would have on grain production, but a marked shortening of the H–YR phase under climatic warming could be expected to curtail grain filling, hence reducing yield (Nonhebel 1993).

3.3. Effects of projected climate change

3.3.1. Effects on regional suitability and phase duration

Under the 2 transient scenarios, modelled thermal suitability of cv. Ruso extended northwards by about 580 km in western and 330 km in eastern Finland under the UKTR6675 scenario (Fig. 6a) and 520 km

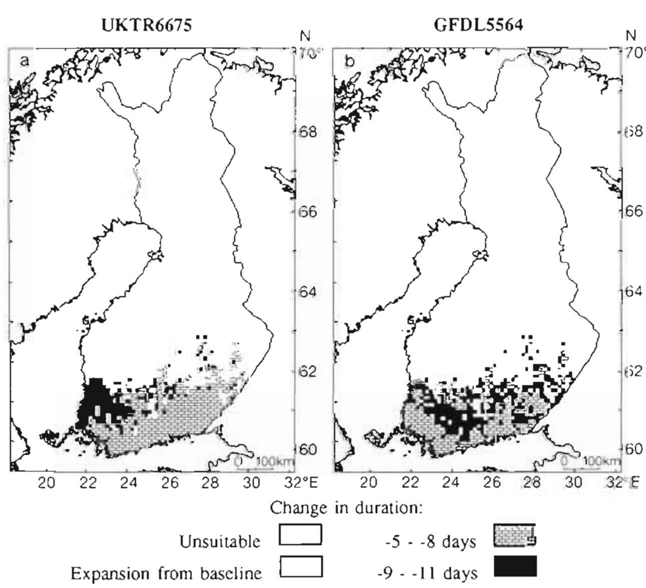

Fig. 6. Change in simulated duration of the heading-yellow ripening phase in spring wheat cv. Ruso relative to the baseline in regions of baseline thermal suitability and estimated extension of suitability under 2 GCM-based climatic scenarios: (a) UKTR6675 transient, (b) GFDL5564 transient

and 330 km, respectively, under the GFDL5564 scenario (Fig. 6b). These extensions can be converted to rates of shift if calendar dates are attached to the transient scenarios. For example, if it is assumed that these scenarios reflect the regional climate response under the IPCC central estimates of greenhouse gas emissions and climate sensitivity (IPCC 1992) then their timing can be estimated as the mid-2060s (Barrow et al. 1996). This would imply rates of northward shift in suitability for both scenarios of approximately 45 to 75 km per decade.

Fig. 6 also depicts the scenario change in duration of the H-YR phase of cv. Ruso relative to the baseline in the region of baseline suitability. The phasal shortening was 5 to 11 d under the UKTR6675 scenario (Fig. 6a) and 6 to 10 d under the GFDL5564 scenario (Fig. 6b). The S-H phase also shortened under these scenarios, by 0 to 3 d (UKTR6675) and 2 to 5 d (GFDL5564). The shortening was most pronounced in grid boxes having the longest phase durations under the present-day climate.

3.3.2. Uncertainties in scenario estimates of thermal suitability

The GCM-based scenarios represent only a subset of climate projections for the Finnish region. A better impression of the range of uncertainties attached to future climate projections over Finland and their implications for assessing thermal suitability can be obtained by applying the SILMU Low and SILMU High scenarios (Table 2).

The estimated northward shift in the limit of cv. Ruso suitability by 2050 under these 2 SILMU scenarios is shown in Fig. 7. It ranges from about 40 to 90 km under the Low scenario to about 390 to 610 km under the High scenario. This converts to a rate of northward shift of between about 10 and 80 km per decade, an 8-fold difference. It was stated earlier that it is not possible to assign confidence limits to the uncertainty ranges represented by the SILMU scenarios. However, if it is assumed that a large proportion of the uncertainty is captured by these scenarios, then a tentative comparison is possible between Fig. 7 and the 2 maps showing 95% confidence intervals of the model in Fig. 3. Clearly, the uncertainties surrounding future climate projections, when expressed spatially, far exceed the model uncertainty surrounding the mapped limit of mean suitability, and are greater even than the uncertainty of individual predictions of suitability.

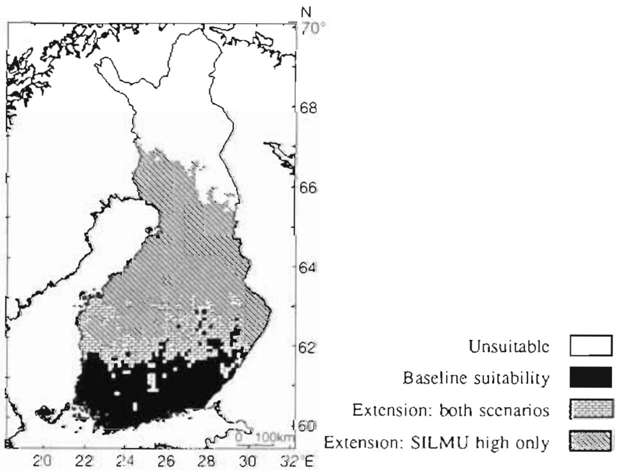

Fig. 7 Range of uncertainty in the extension of estimated thermal suitability of spring wheat cv. Ruso in Finland by 2050 relative to the baseline. Limits based on the SILMU Low and SILMU High scenarios

4. DISCUSSION

The 3 main results of this study can be summarised as follows:

(1) The thermal suitability for spring wheat cultivation in Finland could shift markedly northwards under the anticipated climatic warming of future decades.

(2) Under higher temperatures, the timing of crop development is shifted earlier in the year and there is a shortening of development phases in regions of present-day suitability.

(3) The range of uncertainty in the position of the northern limit of thermal suitability under alternative scenarios of temperature change by 2050 is substantially greater than the range of model uncertainty in the simulated mean limit for a fixed climate.

The first 2 findings provide further confirmation of results from previous studies of regional suitability (e.g. Carter et al. 1991, Kenny et al. 1993). The third result illustrates how the uncertainties surrounding climate change impacts can be assessed. The spatial expression of uncertainty is a useful device, since it offers a clear visual method of describing and comparing different sources of uncertainty. It could also allow policy issues to be explored in terms of impacts. For example, the SILMU scenarios attempt to encompass the extreme range of future greenhouse gas emissions and global climate response. It would be a simple matter to substitute the extreme emissions scenarios for more moderate ones so as to explore the uncertainties in mapped response attributable to alternative emissions scenarios.

A number of important caveats still need to be considered in interpreting these results further. These relate to model extrapolation, possible effects of photoperiod, and other limitations of the approach.

4.1. Model extrapolation

A warming of the mean climate, assuming no change in climatic variability, will logically lead to an increased frequency of extremely warm days and a corresponding reduction in frequency of extremely cold days. The crop development models used in the present study are based on observed mean daily temperatures, and it is inevitable that a climatic warming will bring high temperatures that lie outside the range used in model construction, requiring extrapolation of the modelled relationships. Indeed, since the models are based on a limited number of site observations, there are probably some locations in Finland at which higher daily temperatures have already been observed under the baseline climate.

However, the need for extrapolation of daily temperatures is obscured in the analysis in 2 ways. First, since the relationship obtained between daily temperature and development rate was linear, it was possible to substitute the mean temperature of the sowing to yellow ripening phase as a predictor for mean development rate. As was shown above (cf. Fig. 4), because the timing of development is shifted under a climatic warming the mean phasal temperature does not increase by as much as the mean annual temperature. In fact, under a mean annual warming of 5°C the mean temperature of the sowing to yellow ripening phase only exceeds the observed range of phasal mean temperatures in 3 years out of 30, and then only in some grid boxes.

A second complicating factor was the use of smoothed daily temperatures over the grid to simulate phase durations. Without realistic day-to-day temperature variability in the data, extreme high (and low) temperature events were omitted from the analysis. These are precisely the occurrences for which problems of extrapolation would be expected under a climatic warming. One solution to this problem might be the application of a stochastic weather generator over the grid, to simulate realistic daily temperatures under the baseline and changed climate. This possibility is being pursued in ongoing work with a weather generator developed for Finland (CLIGEN, Carter et al. 1995).

The importance of extrapolation in influencing the validity of the results is difficult to assess. However, even if the linear relationship between temperature and development rate does not hold outside the observed range, it seems unlikely that a handful of supra-optimal temperature events would greatly affect the conclusions of this study. It is worth noting that, in any case, farmers would be unlikely to use the same cultivars under a substantially warmer climate since other cultivars would be better suited to the changed conditions. Ultimately, the only method of testing the validity of the development models is to conduct controlled experiments that simulate high temperature effects on development. Such experiments are planned as part of continuing European collaboration.

4.2. Possible effects of photoperiod

The relative stability of the sowing–heading phase estimated for a climatic warming was mainly a result of an earlier sowing date. However, with an earlier sowing the daylength would be shorter than under present-day cultivation, and this may delay crop development before flowering. Values of 13 to 16 h d^{-1} have been suggested as a threshold photoperiod for delay in barley (Roberts et al. 1988), but this limit has been little examined in high latitude environments. Under average baseline conditions the earliest computed sowing dates fall in early May when the daylength in southern Finland (60° N) is already close to 18 h (including civil twilight). However, a warming of 5°C would shift the earliest average sowing date to the middle of April, which means that crops would be exposed to approximately 16 h days. Therefore, effects of photoperiod may also need to be examined in future experimental work.

4.3. Refining the approach

Finally, it should be recognised that the zones of suitability mapped in this study are based on temperature alone. No account was taken of other factors that might restrict cultivation. These include physical constraints such as soils, surface waters, terrain and land cover characteristics, economic considerations of profitability and comparative advantage, and other constraints on land use. Since digital regionalised data on some of these characteristics are available for Finland, a more detailed and realistic geographical analysis of land capability under a changing climate that accounts for these other limitations is planned.

The modelling approach presented here has considered suitability only in terms of successful maturation of the crop. The most important consideration in economic terms is the amount and quality of the harvested grain. Work is in progress to apply process-based crop growth simulation models to the 10 km grid in order to estimate the sensitivity of crop yield to a changing climate.

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