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Uncertainties in projected impacts of climate change on European agriculture and terrestrial ecosystems based on scenarios from regional climate models

J. E. Olesen · T. R. Carter · C. H. Díaz-Ambrona · S. Fronzek · T. Heidmann · T. Hickler · T. Holt · M. I. Minguez · P. Morales · J. P. Palutikof · M. Quemada · M. Ruiz-Ramos · G. H. Rubæk · F. Sau · B. Smith · M. T. Sykes

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Abstract The uncertainties and sources of variation in projected impacts of climate change on agriculture and terrestrial ecosystems depend not only on the emission scenarios and climate models used for projecting future climates, but also on the impact models used, and the local soil and climatic conditions of the managed or unmanaged ecosystems under study. We addressed these uncertainties by applying different impact models at site, regional and continental scales, and by separating the variation in simulated relative changes in ecosystem performance into the different sources of uncertainty and variation using analyses of variance. The crop and ecosystem models used output from a range of global and regional climate

J. E. Olesen (✉) · T. Heidmann · G. H. Rubæk
Danish Institute of Agricultural Sciences, Department of Agroecology, Research Centre Foulum, P.O. Box 50, 8830 Tjele, Denmark
e-mail: JorgenE.Olesen@agrsci.dk

T. R. Carter · S. Fronzek
Finnish Environment Institute, Box 140, 00251 Helsinki, Finland

C. H. Díaz-Ambrona · M. I. Minguez · M. Quemada · M. Ruiz-Ramos
Depto. de Producción Vegetal, Universidad Politécnica de Madrid, Avda. Compluense s/n, 28040 Madrid, Spain

T. Hickler · P. Morales · B. Smith · M. T. Sykes
Centre for Geobiosphere Science, Department of Physical Geography and Ecosystems Analysis, Lund University, Sölvegatan 37, 22362 Lund, Sweden

T. Holt
Climatic Research Unit, University of East Anglia, University Plain, NR4 7TJ Norwich, UK

J. P. Palutikof
Hadley Centre, Met Office, Fitzroy Road, Exeter, Devon EX1 3PB, UK

F. Sau
Depto. de Biologia Vegetal, Universidad Politécnica de Madrid,
Avda. Complutense s/n, 28040 Madrid, Spain

models (GCMs and RCMs) projecting climate change over Europe between 1961–1990 and 2071–2100 under the IPCC SRES scenarios. The projected impacts on productivity of crops and ecosystems included the direct effects of increased CO_2 concentration on photosynthesis. The variation in simulated results attributed to differences between the climate models were, in all cases, smaller than the variation attributed to either emission scenarios or local conditions. The methods used for applying the climate model outputs played a larger role than the choice of the GCM or RCM. The thermal suitability for grain maize cultivation in Europe was estimated to expand by 30–50% across all SRES emissions scenarios. Strong increases in net primary productivity (NPP) (35–54%) were projected in northern European ecosystems as a result of a longer growing season and higher CO_2 concentrations. Changing water balance dominated the projected responses of southern European ecosystems, with NPP declining or increasing only slightly relative to present-day conditions. Both site and continental scale models showed large increases in yield of rain-fed winter wheat for northern Europe, with smaller increases or even decreases in southern Europe. Site-based, regional and continental scale models showed large spatial variations in the response of nitrate leaching from winter wheat cultivation to projected climate change due to strong interactions with soils and climate. The variation in simulated impacts was smaller between scenarios based on RCMs nested within the same GCM than between scenarios based on different GCMs or between emission scenarios.

1 Introduction

General circulation models (GCMs) are capable of providing information on most of the climate variables of interest in modelling impacts on crops, trees and natural vegetation (e.g., air temperature, precipitation, humidity, radiation and wind speed), but at horizontal spatial scales of several hundreds of kilometres, which is considerably coarser than the typical scale of the impacts (Mearns et al. 2001). The outputs from GCMs are most often unsuitable as direct inputs to impact studies due to their inability to resolve sub-grid scale processes such as those affecting the regional precipitation (Mearns et al. 2003). For this reason GCM outputs are typically extracted at a monthly time scale, and differences between modelled present-day and future climate are used to perturb an observed reference climate.

As there is an increasing need to evaluate the impacts of climate change on agriculture and ecosystems at a regional level, the coarse resolution of GCMs has been cited as a serious limitation (O'Brien et al. 2004). Climate scenarios with higher spatial resolution can be obtained by statistically downscaling GCM projections, by using outputs from high or variable resolution GCMs, or by dynamical downscaling with high resolution regional climate models (RCMs) driven by initial and boundary conditions supplied by a GCM (Mearns et al. 2001, 2003). Impacts obtained using downscaled information from GCMs can be different from those obtained using scenarios based on GCM outputs alone (e.g., Carbone et al. 2003; Tsvetsinskaya et al. 2003). However, since there are uncertainties associated with various downscaling procedures, there can be no guarantee that scenarios developed at higher resolution are any more reliable or accurate than those based on direct GCM outputs (Mearns et al. 2003).

Besides the uncertainties involved with the generation of climate change scenarios, there are a number of additional uncertainties in climate change impact studies, which also need attention (Fig. 1). The socio-economic drivers that influence greenhouse gas emissions (e.g., population, economic development and level of technology) also provide the context in which the impacts of climate change occur and adaptation takes place. The emissions, in

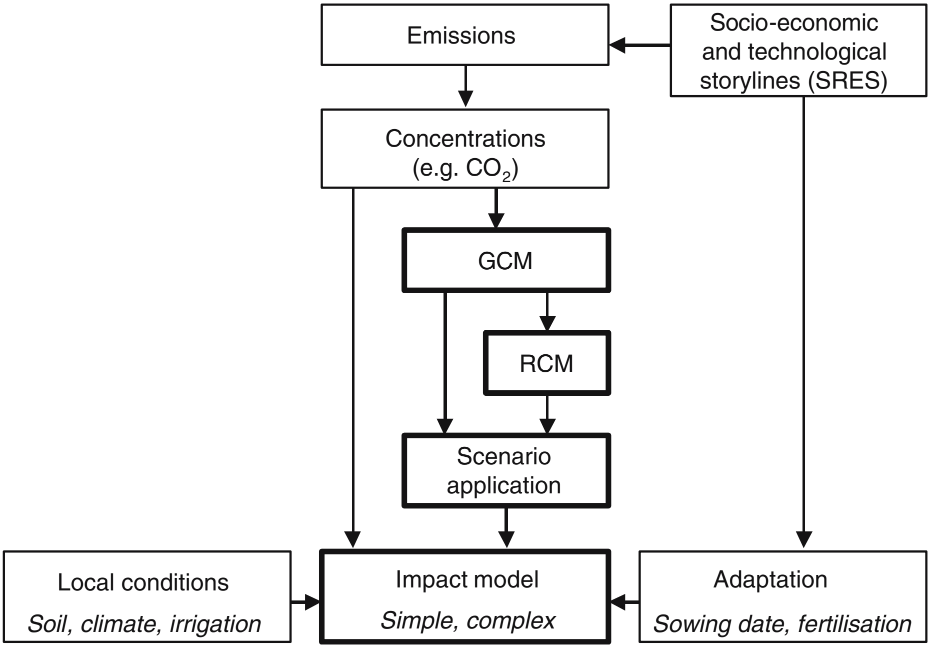

Fig. 1 Some sources of uncertainties in climate change impact studies. The items shown in *italics* were specifically considered in the analyses. *Arrows* indicate flow of information. *Thick frames* indicate the focal areas of the PRUDENCE project

turn, determine the levels of atmospheric CO_2 concentration that influence plant photosynthesis and water use. Impact models themselves vary in structure and complexity giving rise to different projected impacts, although for ecosystem productivity, models most often given similar results (e.g., Semenov et al. 1996). The response to climate change is often closely tied to the prevailing soil and climatic conditions in a particular location or region (Wassenaar et al. 1999). Additionally, adaptation, in particular in agriculture, may offset negative impacts or increase benefits compared with assuming unchanged (baseline) management (e.g., Alexandrov et al. 2002). All of these issues will add to the uncertainties in projected impacts of climate change.

This paper estimates the uncertainties involved in projecting impacts of climate change on European agricultural and terrestrial ecosystems. It also explores the merits of alternative methods of scenario construction and application for use in impact assessments. The large ensemble of RCM outputs generated for Europe in the PRUDENCE project for the periods 1961–1990 and 2071–2100 (Christensen et al. 2007) are used to compare variations in impacts obtained for scenarios based on many different RCMs, for the variation between RCMs and their driving GCMs, and between RCM-based and GCM-based scenarios assuming alternative greenhouse gas emissions scenarios. A range of different impact models and indices are used for this purpose, with the primary objective to examine the uncertainties involved in applying outputs from RCMs and GCMs in impact studies, compared with the uncertainties involved in scenario application, type of impact model, and effects of location conditions (e.g., soil and irrigation).

2 Materials and methods

The analyses were designed to explore some of the sources of uncertainty shown in Fig. 1. A range of impact models was applied at different scales. Not all impact studies considered the full range of uncertainty sources, but together the results give a comprehensive picture of the uncertainties in climate change impacts on agriculture and terrestrial ecosystems, although the interaction with technological improvements and socio-economic drivers was not considered in the analyses.

Models of ecosystem impacts were applied at different temporal and spatial scales to simulate present day and future conditions. Climate changes were represented using scenarios based on a range of RCMs, each driven by outputs from one or more GCMs describing baseline climate conditions for 1961–1990 and climate under the SRES A2 and B2 emissions scenarios for 2071–2100 (Nakicenovic et al. 2000). Additional comparisons were made with alternative GCMs and with the A1FI and B1 emissions scenarios for 2071–2100.

2.1 Impact models

Site-based crop models (Daisy, CERES and CropSyst) were applied to study impacts of climate change on crops and cropping systems in Denmark and Spain, reflecting northern and southern European conditions, respectively. These models require daily climate data, detailed data on soil conditions and information on crop management. The response of terrestrial ecosystem net primary productivity (NPP) across Europe was evaluated using the LPJ-GUESS ecosystem model. The response of potential water availability (PWA) in the Mediterranean region was analysed using a simple water balance model. At the European level, simple indices were used to analyse the suitability for grain maize cultivation, the yield (YLD) of winter wheat and the nitrate leaching (NL) from winter wheat cultivation. These latter models on (sub-)continental scale made use of the CRU 0.5° latitude × 0.5° longitude interpolated monthly observational climate data set (New et al. 1999, 2000).

2.1.1 Site-based crop models

The Daisy dynamic soil-plant-atmosphere model (Hansen et al. 1991; Olesen et al. 2004) was used to analyse the interaction of climate change and nitrogen (N) cycling for continuous winter wheat in Denmark. An adaptive response was introduced by assuming the sowing date to be delayed by 5 days for each 1°C increase in mean temperature (Olesen et al. 2000). The model was run for five different rates of fertiliser N (50–250 kg N ha^{-1}), and the optimal N fertiliser rate was estimated for maximum profit at a grain price of 100 € Mg^{-1} for grain with 85% dry matter and a fertiliser price of 0.5 € kg^{-1} N (Petersen 2005). The grain yield and N leaching were then estimated for the optimal N fertiliser rate. The study used daily climate data from site based climate stations as baseline data for the period 1961–2000 for perturbing with the climate model outputs (see Section 2.3). Data was used for specific climate stations giving site specific responses in grain yield (YLD_s) and N leaching (NL_s).

The study of crop production on the Iberian Peninsula applied the CERES dynamic models for wheat (Ritchie and Otter 1985) and maize (Jones and Kiniry 1986) as included in DSSAT v. 3.5 (Tsuji et al. 1994). These models have previously been calibrated and validated for various locations in the Iberian Peninsula (Mínguez and Iglesias 1996; Quemada and Tajadura 2001). The crop management was set for either rain-fed or irrigation, and no nitrogen limitation was assumed. Current sowing dates were assumed for each region. The study used 34 representative soil types, and the link between the geographical distribution of climate and soil data was handled in a GIS. The simulated climate data from the RCM and GCM control runs representing 1961–1990 were used for the baseline climate data. The model was used to simulate regional grain yields (YLD_r).

2.1.2 Ecosystem model

LPJ-GUESS is a process-based model of the dynamics of ecosystem structure and functioning at scales from the site to the globe (Smith et al. 2001; Hickler et al. 2004). It incorporates generalised representations of plant physiology and ecosystem biogeochemistry, derived from the LPJ dynamic global vegetation model (Sitch et al. 2003) and representations of plant population dynamic processes as commonly adopted by forest gap models (Smith et al. 2001). Vegetation in LPJ-GUESS is represented as a mixture of plant functional types (PFTs), differentiated by physiognomic, physiological, phenological and life-history attributes. The model simulates coupled changes in ecosystem function (water, energy and carbon exchange) and vegetation structure (distribution, PFT composition, size/age structure) in response to scenarios of changes in climate and atmospheric CO_2 concentrations.

Simulations of net primary productivity (NPP) for potential natural vegetation were performed in this study; anthropogenic land use and land management were not taken into account. Simulations began from bare soil (no plant biomass present) and were then “spun up” for 300 model years to achieve near equilibrium with respect to carbon pools and vegetation structure. A 100-year mean disturbance interval, corresponding to typical disturbance regimes for natural vegetation in Europe, was implemented over the entire model domain and simulation period.

The model was driven by an observed climatology for the period 1901–1998 from the CRU05 monthly dataset. Climate data for the gap between the observed data and climate input for the scenario period (1991–2070) were derived by first standardizing observed climate data from CRU05 (1961–1990), which were then repeatedly unstandardized using linear trends in means and standard deviations between the RCM output for the control (1961–1990) and the scenario (2071–2100) period. This retains the observed inter-annual variability, but means and variances evolve linearly between the two periods of climate data. RCM data were rescaled such that mean values and standard deviations for the control period (1961–1990) corresponded with the observed data from CRU05. Global atmospheric CO_2 concentrations from 1901 to 1998 from the Carbon Cycle Model Linkage Project (McGuire et al. 2001) were used.

2.1.3 Potential water availability for the Mediterranean region

The potential water availability (PAW) was calculated from a simple balance of potential evapotranspiration (PET) and precipitation. PET was derived from temperature and daylength using the methodology of Palutikof et al. (1994), which takes account of relative humidity, wind speed, and sunshine. PAW was calculated by subtracting the monthly total PET from the monthly total precipitation for each grid square.

2.1.4 Maize suitability

The thermal suitability for the successful cultivation of grain maize was estimated with the effective temperature sum (ETS). Daily mean temperatures above 10°C were cumulated for all days of the year. A location was classified as suitable for grain maize if a threshold of 850 °Cd was attained (Carter et al. 1991), which put the focus on the northern limit of thermal suitability as an indicator of sensitivity to climate warming.

As the observed gridded database was available only in monthly time steps, we used a method suggested by Kauppi and Posch (1988) to approximate the ETS, requiring information about the standard deviation of daily mean temperatures about the monthly mean. We derived this by interpolating station data obtained from the European Climate Assessment (Klein Tank et al. 2002) for the observed baseline, and by applying estimates based on daily data for the scenario period 2071–2100 simulated by the HadAM3 GCM.

2.1.5 Winter wheat yield and nitrate leaching

The Daisy model (Section 2.1.1) was run at nine climate stations across Europe with varying soils, N fertiliser and climate changes in order to develop an empirical function for N leaching as affected by soils, climate and CO_2 concentration. Only a rain-fed winter wheat monoculture without straw incorporation was considered. The model was run for 98 years for each scenario combination and the average yield and N leaching were estimated for each combination. Based on the simulated N response, the optimal N fertiliser rate was calculated for each climate-soil combination and this was used to estimate a multiple linear regression model of N leaching (NL_o) and yield (YLD_o) at optimal N rate on soil and climate variables. The N leaching was fitted to the expo-linear equation (Goudriaan and Monteith 1990):

$$\mathrm{NL} = \mathrm{NL}_b + a/b\ \ln\{1 + \exp\left[b(\mathrm{N} - \mathrm{N}_b)\right]\} \tag{1}$$

where NL is mean nitrate leaching (kg N ha^{-1}), N is nitrogen fertiliser input (kg N ha^{-1}), and NL_b, a, b and N_b are parameters. NL_b corresponds to the nitrate leaching at no fertiliser input, and a is the proportion of N input that leaches at high N input. This value was fixed at a=0.6. The other parameters in Eq. 1 were estimated using the NLIN procedure of SAS (SAS Institute 1996), and these parameters were regressed on the soil and climate variables. The variables considered in the multiple linear regression models were atmospheric CO_2 concentration, soil water capacity, and seasonal mean values of temperature and rainfall. Only statistically significant variables were included in the regression models.

A temperature constraint for mean minimum temperature in January of no less than −11.5°C was used to represent areas where severe winters will hinder survival and effective establishment (Harrison et al. 1995). In addition, successful winter wheat cultivation is generally constrained by an annual precipitation greater than 1,000 mm (Bunting et al. 1982). Therefore, the regression indices for winter wheat yield and nitrate leaching were not applied in grid boxes where these two simple constraints were exceeded. A European database of soil water-holding capacity was applied for both baseline and future applications (Groenendijk 1989).

2.2 Climate change scenarios

The impact models were driven by outputs from a range of regional climate models (RCMs) (Table 1). The RCMs were run both for a control period (1961–1990) and for a future time period (2071–2100). The emission scenarios were the IPCC SRES A2 and B2 scenarios, representing rather high and more modest future greenhouse gas emissions, respectively (Nakicenovic et al. 2000). The RCMs were driven by boundary conditions

Table 1 Regional climate models (RCM) driven by different general circulation models (GCM) and different SRES emissions scenarios used with the different biophysical models

RCM	GCM	SRES	No. ensembles	Biophysical models[1]
	CGCM2	Four[2]	1 each	M
	CSIRO-Mk2	Four[2]	1 each	M
	GFDL-R30	Four[2]	1 each	M
	ECHAM4/OPYC3	Four[2]	1 each	M
	NCAR-PCM	Four[2]	1 each	M
	HadCM3	Four[2]	1 each	M
Arpège[a]		B2	3	M
Arpège[a]		A2	3	C, M
	HadAM3H	A2	1	M, D
HIRHAM (50 km)	HadAM3H	A2	3	C, D, L, P, M, W
HIRHAM (25 km)	HadAM3H	A2	1	D
HadRM3H	HadAM3H	A2	1	C, D, L, M, W
CHRM	HadAM3H	A2	1	C, D, M, W
CLM	HadAM3H	A2	1	C, D, L, M, W
REMO	HadAM3H	A2	1	C, D, L, M, W
PROMES	HadAM3H	A2	1	C, W
RegCM	HadAM3H	A2	1	C, D, W
RACMO	HadAM3H	A2	1	C, D, M, W
RCAO (50 km)	HadAM3H	A2	1	D, L, P, M, W
RCAO (25 km)	HadAM3H	A2	1	D
RCAO (50 km)	HadAM3H	B2	1	L, M
RCAO (50 km)	ECHAM4/OPYC3	A2	1	D, L, M
RCAO (50 km)	ECHAM4/OPYC3	B2	1	L, M
HIRHAM (50 km)	ECHAM4/OPYC3	A2	1	D, L, M
HIRHAM (50 km)	ECHAM4/OPYC3	B2	1	L, M
HadRM3P	HadAM3P	A2	3	D, P

Some of the RCMs used different spatial resolutions and were applied for a number of ensemble runs.

[1] Biophysical models: *D* (Daisy), *C* (CERES), *L* (LPJ-GUESS), *P* (potential water availability), *M* (maize suitability) and *W* (winter wheat productivity and N leaching).

[2] A2, B2 (modelled) and A1FI, B1 (pattern-scaled).

[a] Arpège is a variable resolution atmospheric GCM operating at high resolution over Europe and employing sea surface temperatures from either the HadCM3 or the Arpège models.

taken from two different global models, HadAM3H and ECHAM4/OPYC3 (Jacob et al. 2007). However, the runs of the HadRM3P regional model used the HadAM3P for boundary conditions (Table 1). The Arpège stretched grid simulations has a global coverage, but with a spatial resolution similar to the RCMs over Europe. Not all impact models applied all climate model simulations (Table 1). Some of the RCMs had multiple ensembles using different initial conditions, but identical bounding conditions.

The atmospheric CO_2 concentrations were taken as the estimates used in the climate modelling experiments, which on average were 333 ppm for the 1961–1990 baseline, and 718 and 566 ppm for 2071–2100 for the A2 and B2 scenarios, respectively.

For the analysis of maize suitability additional outputs from six coupled atmosphere-ocean general circulation models (AOGCMs) for the SRES A2 and B2 scenarios were obtained from the IPCC Data Distribution Centre. The models utilized are HadCM3, ECHAM4/OPYC3, CSIRO-Mk2, NCAR-PCM, CGCM2 and GFDL-R30. These were used directly as input to impact models, and were also pattern-scaled to represent regional climates under the full range of SRES emissions scenarios from B1 (lowest) to A1FI (highest) (Ruosteenoja et al. 2007).

2.3 Methods of scenario application

Two methods of constructing and applying RCM-based scenarios were tested. The *Direct* method uses the daily outputs from the RCMs directly for both the control and future scenarios. The *Δ-change* method uses the observed climate series for the baseline climate, and for the future scenarios the observed baseline data are adjusted for the mean monthly differences (for temperatures) or ratios (for precipitation and radiation) between climate model outputs for future and control climates. For the analyses of potential water availability, maize suitability and winter wheat production and N leaching, differences were used for both temperature and (where applicable) precipitation.

2.4 Statistical analyses of sources of uncertainty

Uncertainties in impact model estimates attributable to different RCMs, different GCMs, and different emissions scenarios were assessed by an analysis of variance using the GLM procedure of the Statistical Analysis System, SAS (SAS Institute 1996). The contribution of each source to the uncertainty was evaluated by the Mean Squared Error (MS) calculated as the Type III Sum of Squares divided by the associated degrees of freedom (df), and the significance was evaluated by F-tests. A high MS of one factor compared with other factors show that this factor contributes greatly to explaining the total variation in the simulated results. However, this may still not be significant, if the overall variation explained by the statistical model is low, or if the degrees of freedom of the particular factor are small. The amount of variation in model results explained by the attributed factors is given by the coefficient of determination (R^2), and the size of the error in residuals is given by the root mean squared error (RMSE). Factors contributing to the uncertainty should primarily be evaluated in terms of statistical significance (P value) and secondly in their MS. Thus, for example significant P values for RCMs show that different RCMs give different results, which therefore makes it important to consider a range of different RCMs in impact analyses for obtaining a valid range of the projected impacts for the particular variable.

3 Agricultural crops at the national scale

3.1 Winter wheat in Denmark

Both the *Direct* and the *Δ-change* methods for scenario application were used in the analyses of climate change effects on winter wheat production in Denmark. A range of different GCM and RCM projections for the A2 emissions scenario were used to simulate winter wheat production at two sites and for four different soil types (sand, irrigated sand, loamy sand and sandy loam) in Denmark (Table 2). The variation in both indicators (grain

Table 2 Analyses of variance of mean relative changes in site based grain yield (YLD_s) (%) and nitrate leaching (YLD_s) (%) of winter wheat at optimal N fertiliser rate from 1961–1990 to 2071–2100 for the SRES A2 scenario at two sites in Denmark (Jyndevad and Roskilde), four soil types

Factor	d.f.	MS	P
Change in grain yield			
GCM	4	136	0.3010
RCM	8	565	<0.0001
Ensembles	2	44	0.6752
Scenario application	1	19,089	<0.0001
Location	1	19,614	<0.0001
Soils	3	3,383	<0.0001
Change in N leaching			
GCM	4	2,505	0.6627
RCM	8	8,952	0.0320
Ensembles	2	485	0.8902
Scenario application	1	124,767	<0.0001
Location	1	51,419	0.0005
Soils	3	16,905	0.0077

Nine different RCMs were nested within different combinations of the HadAM3H, HadAM3P and ECHAM4/OPYC3 model, and the Arpège model was included as the fourth GCM. The ensembles reflect repeated runs of HIRHAM and HadRM3P RCMs. Two different methods for scenario application (*Direct* and *Δ-change*) were used for each climate model. Model R^2 =0.65 and RMSE=10.5 for N grain yield, and R^2 =0.25 and RMSE=64.6 for N leaching.

yield and N leaching) was dominated by differences between methods of scenario application, locations and soils, whereas there was much less variation between the tested GCMs, RCMs and the different ensembles of these climate model runs.

The mean grain yield was increased by 37% with the *Direct* method and 21% for the *Δ-change* method, whereas the respective increases in N leaching were 16 and 57%. The generally higher increases in grain yield under the *Direct* compared with the *Δ-change* method were due to lower simulated grain yields for some of the GCM and RCM climate runs for the baseline period, primarily due to differences in mean rainfall during the main growing season (April–July) for the climate model control runs. Such effects of errors in simulation of the control climate are not introduced in the *Δ-change* method.

For both methods, the increases in grain yield were larger for Roskilde compared with the Jyndevad climate (data not shown). Roskilde is located in east Denmark with a drier climate than Jyndevad in west Denmark, and this probably affected simulated crop production under the baseline climate. The variation between soil types in average grain yield and N leaching varied 23–39% and 24–58%, respectively.

3.2 Wheat and maize in Spain

The *Direct* method for scenario application was used in the analyses of climate change effects on crop production in Spain, because there were no observed climatic datasets available for all the regions studied. The response of simulated grain yield varied considerably between cereal species at three regions in Spain (Table 3). There was a mean yield increase of 90% for spring wheat, but a yield decrease of 21% for both winter wheat and irrigated grain maize. The variation attributable to different GCMs and RCMs also varied considerably between crop types. Little of the large variation in yield change of spring wheat could be attributed to either climate models or regions, but rather to the

Table 3 Analysis of variance of mean relative changes in regional grain yield (YLD_r) (%) of spring wheat, winter wheat and irrigated maize from 1961–1990 to 2071–2100 for the A2 emissions scenario for three regions in Spain (Navarra in Northern Spain, Castilla La Mancha in Central Spain and Badajoz in South-Western Spain)

Factor	d.f.	MS	P
Spring wheat			
GCM	1	1,700	0.6384
RCM	8	3,825	0.8304
Region	2	11,147	0.2501
Winter wheat			
GCM	1	1,129	0.0512
RCM	8	2,834	<0.0001
Region	2	2,456	0.0015
Irrigated maize			
GCM	1	124	0.3541
RCM	8	300	0.0803
Region	2	248	0.1928

Nine different RCMs were used nested within the HadAM3H model. Model R^2 =0.29 and RMSE=86.3 for spring wheat, R^2 =0.87 and RMSE=16.1 for winter wheat, and R^2 =0.54 and RMSE=11.7 for irrigated maize.

interaction between climate models and local soil and climatic conditions. In contrast most of the variation in yield change for winter wheat and grain maize was attributable to differences between climate models, in particular RCMs. The smaller variation attributed to GCMs may be related to the fact that both the HadAM3H and the Arpége models were driven by sea surface temperatures of the same AOGCM (HadCM3).

The yield of winter wheat was reduced more in the scenarios in the south (Badajoz) than in the north of Spain (Navarra). Winter wheat is currently cultivated in central and northern areas of the peninsula but not in the South, because the requirements for low temperatures for flower induction (vernalisation) are not fulfilled, and the projected warming enhances this problem. Spring wheat is also sown in late autumn, and the milder winters promote greater crop growth during winter leading to yield increases under the A2 emission scenario (Mínguez et al. 2007).

4 Water availability in the Mediterranean region

Results are presented for projected changes in winter and summer potential water availability (PAW) over the Mediterranean region (Fig. 2). Each set of results shows the mean difference between 1961–90 and 2071–2100, averaged over all ensemble members for all models, and the bootstrapped estimates of uncertainty in the mean differences. Thus, each analysis is based on averaging and bootstrapping seven sets of results, three RCMs of which two had three ensembles (Table 1). The uncertainty is expressed as the absolute difference between the upper and lower confidence limits at the 5% significance level. These results show differences under the A2 emission scenario only. For example, Fig. 2a indicates that, under the A2 scenario, southern France is projected to have about 300 mm less PAW in summer in 2070–2099 compared with 1961–1990. Figure 2b shows that the uncertainty range in this estimate is about 40 mm. In other words, PAW in southern France is projected to decline by about 300 (±20 mm, or half the uncertainty range). The spatial

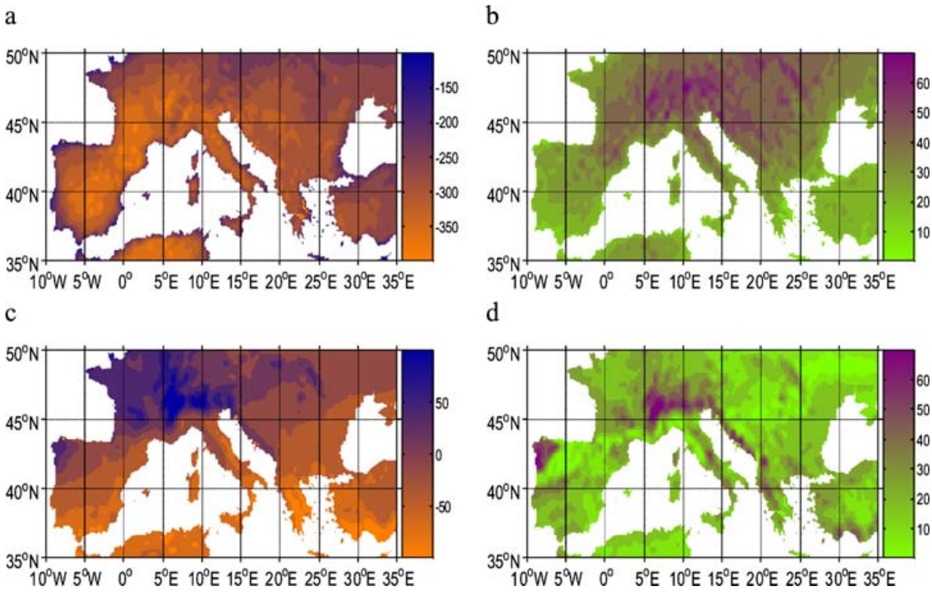

Fig. 2 Mean change in summer (**a**) and winter (**c**) potential water availability (PAW) (mm) over the Mediterranean region for the A2 emissions scenario for 2071–2100 compared with 1961–1990 and the associated uncertainty range (mm) for summer (**b**) and winter (**d**). The uncertainty is expressed as the absolute difference between the upper and lower confidence limits at the 5% significance level

patterns under the more moderate B2 scenario are essentially the same, but with much smaller differences (data not shown).

Summer PAW can be expected to decline by 300–400 (±20 mm) in most Mediterranean countries (Fig. 2a), with Iberia, southern France, and northern Africa being the worst affected areas. In winter (Fig. 2c), Western Europe north of the Mediterranean can expect an increase in PAW of 50–100 (±10–30 mm). The countries bordering the Mediterranean are projected to experience winter deficits in PAW of 50–100 (±10 mm).

It is worth noting that the uncertainty in winter PAW generally follows the same spatial structure as the changes in mean PAW. This is not the case for summer PAW, where the uncertainties are largest in Central Europe, whereas the reductions are largest in southern and south-eastern Europe. This emphasises the significance of the projected reductions in summer PAW over Iberia and most of the rest of the Mediterranean region.

Table 4 Analysis of variance of mean relative changes in NPP (%) for 2071–2100 compared with 1961–1990 across five European sub-regions simulated by LPJ-GUESS using outputs of five different RCMs nested within HadAM3H and ECHAM4/OPYC3 for two emissions scenarios (A2 and B2)

Factor	d.f.	MS	P
Emission scenario	1	1	0.8241
GCM	1	113	0.0562
RCM	4	93	0.0313
Region	4	827	<0.0001
Region × Emission	4	19	0.5913
Region × GCM	4	30	0.3701
Region × RCM	16	16	0.8132

Model R^2 =0.96 and RMSE=5.1

5 Impacts at the European scale

5.1 Ecosystem productivity

LPJ-GUESS predicted an overall increase in ecosystem NPP for Europe, but with large variations across regions (Fig. 3; Table 5). NPP increases were most pronounced at high elevations (in the Alps) and at northern latitudes, ranging from 35 to 54% across all scenarios for the northern region. In these areas, higher temperatures, leading to an extended growing season, and elevated atmospheric CO_2 concentrations interacted positively to enhance NPP, often leading to a shift in dominance from coniferous to broadleaved deciduous trees in forest. Tree-line advance is projected in the Fennoscandian Alps.

In southern Europe, NPP was projected to decline or increase only slightly relative to present-day conditions (Fig. 3). The simulated ecosystem response in the south of Europe was largely driven by projected changes in water availability.

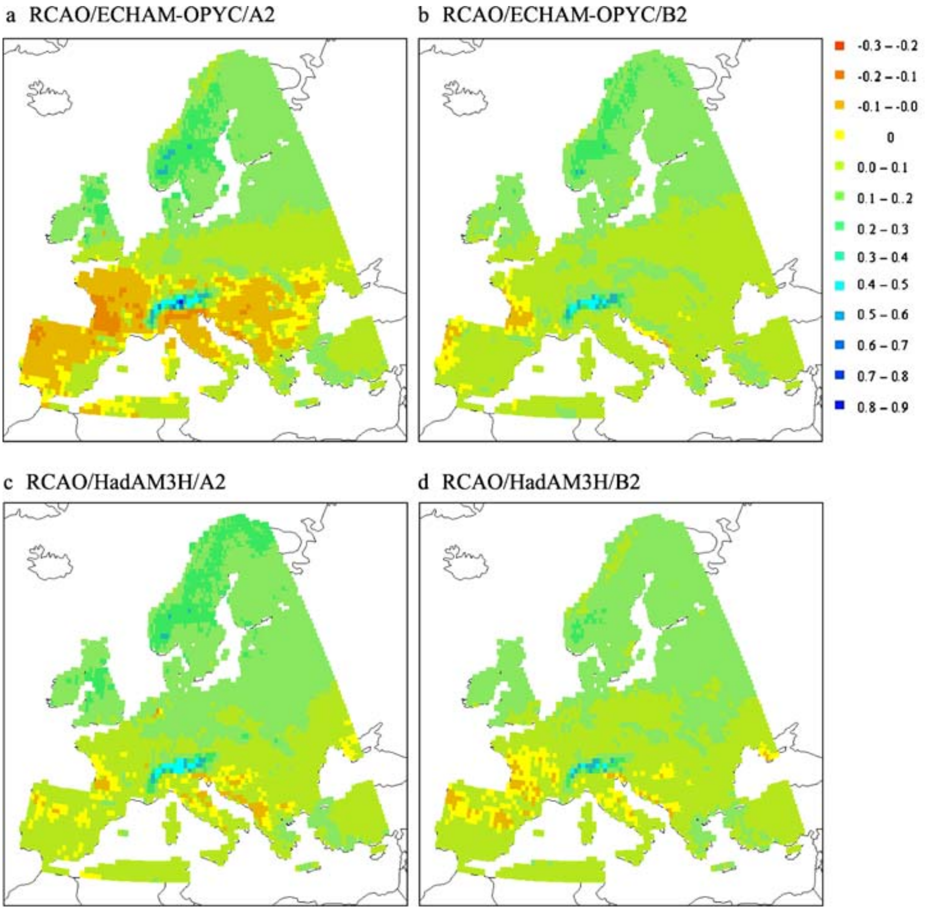

Fig. 3 Mean change in net primary production (NPP, kg C m^{-2} yr^{-1}) over Europe for 2071–2100 compared with 1961–1990 simulated by LPJ-GUESS, driven by the RCAO RCM with two different bounding GCMs, ECHAM4/OPYC3 (**a, b**) and HadAM3H (**c, d**), and two different emissions scenarios, A2 (**a, c**) and B2 (**b, d**)

Table 5 Analysis of variance of expansion of the suitable area for cultivation of grain maize (%) in Europe for different groups of climate scenarios from RCM, AGCM and AOGCM simulations under four different emissions scenarios (A1FI, A2, B1 and B2) in the period 2071–2100 compared with the baseline (1961–1990)

Factor	d.f.	MS	P
Emission scenario	3	72.8	<0.0001
GCM	8	13.0	0.0298
RCM	9	2.1	0.5404
Ensembles	2	10.9	0.0230

Three different ensemble members were available for the Arpège model. Model R^2 =0.91 and RMSE=1.5.

The relative importance of different environmental driving forces for the ecosystem response is well illustrated by differences in simulated NPP under the A2 and B2 scenarios generated by the RCAO/ECHAM4/OPYC3 model realization (Fig. 3a, b). The A2 scenario is associated with greater overall warming, but a stronger decrease in water availability in the South, compared to the B2 scenario. This results in a lower or negative projected increase in NPP in southern Europe (where the water supply dominates the ecosystem response), but higher NPP in the north (where temperatures are more limiting for production than the water).

The very different responses to climate change in different European regions, meant that the overall variation in results were dominated by regional differences (Table 4). However, there were also differences between emission scenarios and climate models with this variation being dominated by the differences between the driving GCMs. There were no significant interactions between region in Europe and the emission scenarios or climate models, indicating that the main differences between climate models are that of overall changes in NPP overlaid on regional differences in response.

5.2 Maize suitability

For the observed baseline, the areas fulfilling the condition of thermal suitability for the cultivation of grain maize have their northern border in central Europe, reaching to the north of France through Belgium, and to parts of Germany, Poland and Belarus (Fig. 4). This is close to the actual limit of cultivation shown by Carter et al. (1991).

Estimates based on climate scenarios for 2071–2100 show a substantial northward shift of the northern limits of grain maize suitability. However, the extent of this shift varies considerably across climate scenarios. Figure 4a shows the range of shifts estimated from climate scenarios based on seven RCMs that were nested in the same GCM (HadAM3H) for the A2 emissions scenario. The extension of the area thermally suitable for grain maize that is common to all seven scenarios reaches to Ireland and Scotland, and covers most of Southern Sweden and Finland. The uncertainty attributable to different RCMs is illustrated by the area of expansion that is not common for all scenarios. The climate model uncertainty range is largest over central Finland, due to the gentle topography with a relatively weak temperature gradient northwards. The uncertainty range for shifts in maize suitability predicted from six GCMs for the A2 scenario is wider than the RCM range (not shown). However, the widest range is spanned under the four SRES emissions scenarios for the six GCMs (Fig. 4b).

The changes in area of suitability in Europe estimated from different groups of climate scenarios were mostly determined by emission scenario (Table 5). The mean relative increase in suitable area for grain maize was 47, 44, 39 and 42% for the A1FI, A2, B1 and

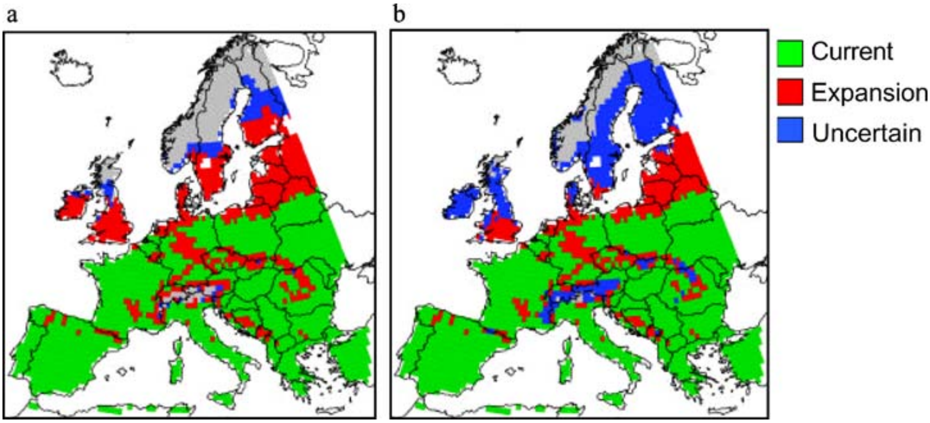

Fig. 4 Modelled suitability for grain maize cultivation during the baseline (1961–1990) and future (2071–2100) periods for: **a** 7 RCM scenarios driven by HadAM3H for the A2 emissions scenario and **b** 24 scenarios from 6 GCMs for each of the A1FI, A2, B1 and B2 emissions scenarios. *Green areas* show the suitable area for the baseline, *red* depicts the expansion common under all scenarios and *blue* the uncertainty range of the respective scenario group. *Grey areas* are unsuitable under all scenarios

B2 scenarios, respectively. There were much wider ranges of shifts between different GCMs than between RCMs nested within some of these GCMs.

All RCMs produced expansion that was reduced (or in one case, slightly increased) relative to expansion induced by the bounding HadAM3H model (data not shown). This indicated stronger growing season temperature increases in the driving GCM than in the RCMs. This observation was repeated for other temperature-based impacts models that are reported elsewhere (Fronzek and Carter 2007).

5.3 Winter wheat yield and nitrate leaching

The highest yields of rain-fed winter wheat under the baseline climate (1961–1990) are estimated in central Europe with more than 8 t ha^{-1} in France and parts of England (Fig. 5a). Smaller yields down to 4 t ha^{-1} were estimated for north-eastern and southern Europe, in agreement with other European-scale assessments of the productivity of winter wheat (Harrison et al. 1995). Estimates of the changes in productivity for 2071–2100 were very consistent among the nine RCM scenarios with increases in most areas north of the Alps and decreases in southern Europe, especially over the Iberian Peninsula (Fig. 5b).

The estimates of nitrate leaching from winter wheat cultivation for the baseline remained below 10 kg N ha^{-1} for most parts of Europe. The highest estimates were given for Southern Sweden, some areas in Eastern Europe, most notably in Belarus, and some areas in Northern Italy (Fig. 5c). The spatial pattern of changes by 2071–2100 is far patchier compared to the estimated changes in wheat yield. Decreases in N leaching predominate over large parts of Eastern Europe and some smaller areas in Spain, whereas increases occur in the UK and in smaller regions over many other parts of Europe (Fig. 5d). The areas where different climate scenarios resulted in a different direction of change in nitrate leaching were relatively large and occurred across all study regions. Model results were therefore very sensitive to even small changes in temperature and precipitation.

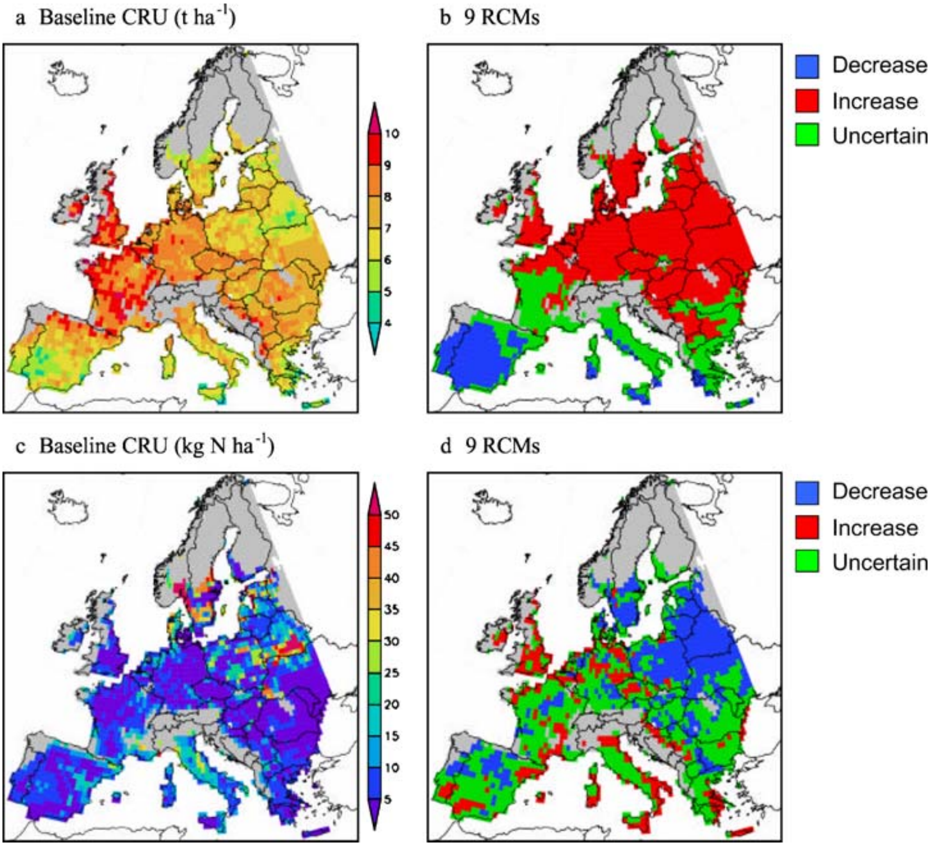

Fig. 5 Estimated winter wheat yield (YLD_o) (**a, b**) and nitrate leaching (NL_o) at optimal N fertiliser rate from winter wheat cultivation (**c, d**) for the baseline 1961–1990 period (**a, c**), and qualitative changes for 9 RCMs with HadAM3H as bounding GCM for the A2 emissions scenario (**b, d**) with scenario results all showing decreases (*blue*), all showing increases (*red*) and showing conflicting directions of response (*green*). *Grey areas* are estimated to be unsuitable for winter wheat

6 Discussion

We have addressed the uncertainties in projected impacts of crop production and ecosystem productivity using different impact models at different scales and separating the variation in simulated relative changes into the sources of variation shown in Fig. 1. The variation in simulated changes in crop yield, NPP and N leaching attributed to climate models were generally smaller or of the same size as the variation due to local conditions. The methods used for applying the climate model outputs played a larger role for the site-based analyses than the choice of the GCM or RCM. The variation in results between emission scenarios was larger than the variation attributed to the climate models, when the full range of SRES scenarios was considered, whereas there was little difference in simulated change in simulated NPP between the A2 and B2 scenarios. However, the simulated water balance for the Mediterranean region was more negative for the A2 compared with the B2 scenario.

6.1 Emission scenarios

The uncertainty that is attributed to any given source of variation in Fig. 1 depends on the range explored within each of these categories. This is clearly illustrated for the emission scenarios, which only explained a very small part of the variation in NPP (Table 4), because this study only included the A2 and B2 scenarios, and these scenarios showed very little difference in average impact on NPP. When the full range of IPCC emission scenarios for 2071–2100 were explored as in the analysis of expansion of suitable area for grain maize, the emission scenario became the dominant source of variation (Table 5). However, even with this large range of emission scenarios, there was a modest variation of 39–47% in mean increase in the thermal suitable area for grain maize. However, when adding the variation due to climate models, the uncertainty increased, although a substantial area in Europe would still increase in suitability for grain maize (Fig. 4).

The emission scenarios affected modelled NPP in terrestrial ecosystems through different processes in different regions: the strongest NPP increase was modelled in the North, where higher temperatures and CO_2 fertilisation (Cramer et al. 2001; Long et al. 2004) positively affected production. In southern Europe, changes in water availability were more important for the simulated ecosystem response than changes in temperature as also illustrated by the simulated changes in PAW (Fig. 2).

6.2 Climate models and downscaling

The analysis of the northward expansion of cropping zones in Europe was focused on grain maize, since the northern limit of suitability is overwhelmingly temperature related (Carter et al. 1991; Kenny et al. 1993). The results demonstrate that RCMs only cover a small proportion of the full uncertainty range in climate projections (Fig. 4 and Table 5). This is particularly true when comparing with a range of GCM simulations for different emissions scenarios. However, for the RCM experiments nested in HadAM3H for the A2 scenario, most scenarios were found to give smaller temperature changes than the bounding GCM. If this is a general result, then it implies that the sub-GCM-grid-scale processes incorporated in RCMs may produce systematic differences in projected climate from the GCMs in which they are nested.

The variation attributed to different GCMs was smaller than the variation between RCMs, when only considering the GCMs included in the PRUDENCE project, i.e., HadAM3H, HadAM3P, ECHAM4/OPYC3 and Arpège. However, when the span of GCMs was expanded with a broader range of GCMs in the study of grain maize suitability, the variation attributed to GCMs became considerably larger than the variation between RCMs. This shows that the variation among GCMs included in PRUDENCE only represents a small part of the full variation in climate model outputs, and that this variation may be considerably more important to capture than the variation between RCMs.

The variation attributed to different ensemble runs varied considerably between the study on winter wheat in Denmark (Table 2), where very little variation was attributed to different ensembles, and the maize suitability study (Table 5), where the variation between ensembles were just as large as between different GCMs. This can probably be attributed to the different sources of sea surface temperatures that formed the basis for the different ensemble runs. In the study on winter wheat, the different ensembles were based on different runs with the same AOGCM, whereas in the study on maize suitability different AOGCMs were used to provide sea surface temperatures for the Arpège model.

The simulation of plant productivity and N cycling in natural and managed systems is very sensitive to changes in temperature and rainfall. Small changes in spring and summer rainfall can have large effects on simulated yields, if the rainfall verges on being insufficient for sustaining plant growth (van Ittersum et al. 2003). This is demonstrated by the use of different methods for applying the scenario data as input to a model of wheat production in Denmark (Table 2). The use of the GCM and RCM outputs directly as input to the crop models results, in some cases, in very low yields, primarily due to slightly underestimated precipitation relative to the observed climate. The sensitivity of the simulation models to small differences in rainfall makes the impact assessments vulnerable to the method used for applying climate model outputs, and the use of the climate model outputs directly in the simulation models should be avoided, if possible. The RCM model outputs were used directly as input to the CERES crop model for simulating cereal productivity in Spain, and this in combination with the sensitivity to variation in rainfall probably contributed considerably to the large variation between climate models in simulated yield increases. This variation was particularly large for spring wheat, where thresholds in the temperature responses play a critical role for crop development and yield.

6.3 Impact models

The response of winter wheat yield and N cycling to climatic change under the A2 scenario was analysed using simulation models (DAISY and CERES) and simple regression based indices. The results of the different approaches at regional scale generally agree by showing consistent yield increases across RCMs and GCMs in northern Europe (Denmark) and reductions in yield in parts of southern Europe (Spain). Previous attempts to estimate the effects of global warming on European winter wheat yields have also shown larger increases in northern Europe (Harrison et al. 1995). Continental-scale projections of ecosystem NPP were sensitive to the choice of climate models, but the spatial pattern, including the major driving forces of change in different regions, were rather robust across all scenarios. A similar pattern in productivity changes was projected by the ATEAM project (Schröter et al. 2005). The general agreement among multiple impact models and studies as to the overall direction and broad spatial pattern of future productivity changes in Europe suggests that these (qualitative) features of the projections might be of value as a basis for decision making at the European level. The absolute level of future changes, on the other hand, remains sensitive to the combination of emission scenarios, climate models and impact models employed.

The uncertainty in the modelling of impacts probably also depends on the type of impact being modelled. Uncertainties are probably smaller for estimates of NPP and crop productivity under optimal conditions, whereas simulation of actual yields under water and nutrient limitations may involve considerably higher uncertainties (Jamieson et al. 1998). The simulation of climate change impacts on second order effects such as nitrate leaching, probably involves even higher uncertainties, although information on this is to our knowledge not available.

6.4 Local conditions

The changes in winter wheat yields were relatively insensitive to the choice of the RCM model. In contrast, estimates of nitrate leaching from winter wheat cultivation under different RCM-based scenarios showed spatial patterns of change that were highly sensitive to specific combinations of climate change and soil type (Fig. 5). However, the results indicate a risk of increases in N leaching in large parts of northwest Europe, which currently have intensive winter wheat cultivation. Large differences between sites and soil types with respect to the response of N leaching to climate change were seen for the simulation model results for Denmark (Table 2). The N leaching is determined by a complex interaction between transport and transformation processes in soil and plants being influenced by changes in temperature, precipitation and CO_2 concentration (Olesen et al. 2004). This results in large regional and local variations in sensitivity to climate.

The large spatial differences obtained in simulated response of N leaching under the A2 scenario has consequences for the protection of freshwater and coastal ecosystems. The effect of the spatial resolution of the RCM on ecosystem responses needs to be further investigated. It may well be that the spatial resolution of the climate model is of particular importance for impacts, which are sensitive to small changes in climatic conditions, such as nitrate leaching from agricultural systems in northern Europe and rainfed cereal production in the Mediterranean region.

6.5 Spatial differences

There were distinctly different responses in simulated crops and vegetation for northern versus southern Europe to the GCM and RCM projections for the SRES A2 and B2 emissions scenarios for 2071–2100. In northern Europe there is an expansion of suitable cropping areas, as illustrated by maize, increases in crop yields and increases in terrestrial ecosystem NPP. The simulated increases in crop yields and NPP in southern Europe are generally much smaller, and in some regions decreases were simulated, e.g., in parts of the Iberian Peninsula. However, these regional decreases in Southern Europe vary among the impacts studied. This is partly a result of differences in seasonal and spatial changes in water availability (Fig. 2).

Under the A2 scenario for 2071–2100, the consensus of the RCMs used here is that in summer the Mediterranean will experience temperature increases of around 5°C, a reduction in rainfall of 50–100 mm, leading to severe reductions in soil moisture. The potential for offsetting the severe depletion of water resources in summer by increasing storage in winter will be reduced by the year-round reduction in water availability. Because of the changes in temperature and water availability, it is likely that agricultural production will experience a shift in season. This was indicated by the increase in yield of spring wheat grown during winter in Spain under the projected climate change.

7 Conclusion

The variation in simulated impacts was smaller between RCMs nested within the same GCM than between different GCMs or between emission scenarios, when the full range of SRES emission scenarios and available GCMs were used. However, when the comparisons were limited to the A2 and B2 emission scenarios and the narrow range of GCMs available in the PRUDENCE project, the variation in simulated impacts were larger between RCMs than between GCMs and emission scenarios.

The variation associated with different methods for applying the climate model outputs and with differences in local climate and soil conditions were in most cases larger or equal to the uncertainties in emission scenarios and climate models. This emphasises the need in impact studies to focus on the need for proper consideration of local environmental conditions as well as adaptation of management for agricultural crops, since the uncertainties associated with these components may be of larger importance than the variation due to projected climate change.

The ecosystem simulation models are in general very sensitive to variation in temperature and rainfall. This limits the application of RCM output for direct use in the simulation models, since there are often biases in the RCM's representation of current temperature and precipitation climate. For some ecosystem responses like nitrate leaching there is a need for detailed regional spatial analyses. This may necessitate a higher spatial resolution of the RCMs.

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